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Original article

Spatial and Seasonal Distribution of Nitrate and Phosphate Contamination in Groundwater in Wadi Al-Tarfawi, Northeastern Libya

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Abstract
This study aimed to evaluate the quality of groundwater in Wadi Al-Tarfawi, Libya, through the assessment of its physicochemical characteristics, with particular emphasis on nitrate and phosphate concentrations and their spatial and seasonal variations in relation to international health standards. Groundwater Wells were collected from five wells during the summer and winter seasons of 2025, with three replicates per well. Laboratory analyses were conducted following standard methods and included measurements of temperature, pH, total dissolved solids (TDS), and electrical conductivity (EC), in addition to the determination of nitrate and phosphate concentrations using spectrophotometric techniques. Descriptive statistical analysis and one-way ANOVA were applied to assess seasonal differences at a significance level of ($p < 0.05$). The results revealed clear spatial and seasonal variability in the studied parameters. Groundwater temperature ranged between 22 and 27°C, while pH values varied from 7.2 to 7.9, all within locally and internationally permissible limits. Total dissolved solids ranged from 595 to 1102 mg/L, whereas the highest electrical conductivity reached 2285 µS/cm during the summer season. Phosphate concentrations recorded a maximum value of 0.77 mg/L in summer, exceeding the recommended global guideline (0.5 mg/L) in several wells, while the minimum value (0.06 mg/L) was observed in winter. Nitrate concentrations ranged from 21 to 64 mg/L, with exceedances of the WHO drinking water limit (45 mg/L) detected in two wells during the summer season. These findings indicate the influence of intensive agricultural activities, shallow groundwater depth, and local hydrogeological conditions on groundwater quality. The study highlights the need for continuous monitoring programs and improved fertilizer management practices to protect groundwater resources and public health.
Keywords. Groundwater Quality, Nitrate, Phosphate, Agricultural Pollution.

Introduction

Groundwater is considered one of the most important sources of freshwater upon which humans depend for various life activities, particularly in arid and semi-arid regions where surface water resources are scarce, such as Libya. Agricultural production in Libyan lands relies primarily on groundwater not only for irrigation but also across multiple sectors. With the expansion of agricultural activities and the increased use of chemical fertilizers based on nitrates and phosphates—aimed at compensating for nutrient losses caused by plant uptake and reduced soil organic matter, as well as serving as a means of vertical intensification in crop production—growing concerns have emerged regarding the contamination of groundwater aquifers by these compounds. Their leaching through soil into groundwater poses a serious threat to water quality and its suitability for human and agricultural use [1-3].

Recent studies indicate that nitrates represent the most common form of nitrogen contaminant in groundwater due to their high solubility and ease of transport with percolating water, particularly in intensively cultivated agricultural areas. In such regions, nitrate concentrations may exceed internationally permissible limits for drinking water, posing a direct threat to public health [4]. Several studies have linked chronic exposure to nitrate-contaminated drinking water with severe health effects, including methemoglobinemia (blue baby syndrome), certain types of cancer, and developmental disorders [5].

Phosphates, although essential nutrients for plant growth, can cause significant environmental disturbances when accumulated in groundwater and surface water systems. One of the most notable consequences is eutrophication, which contributes to water quality degradation and ecosystem imbalance, ultimately undermining the sustainability of water resources and food security [6]. Contemporary literature emphasizes that groundwater contamination by agricultural nutrients is not limited to environmental and health impacts but also indirectly affects agricultural productivity and food quality, particularly in regions where irrigation depends almost entirely on groundwater resources [7].

Multiple studies have demonstrated that the distribution of nitrate and phosphate concentrations in groundwater is influenced by complex spatial and temporal factors, including soil characteristics, aquifer depth, land-use patterns, and the intensity of agricultural activities. Consequently, spatiotemporal analysis has become an essential tool for understanding contamination dynamics and identifying areas most vulnerable to environmental and health risks [8].

A recent study conducted in various regions of western Libya confirmed significant spatial variability in groundwater quality, with elevated nitrate concentrations recorded at several sites exceeding permissible

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limits according to Libyan standards and World Health Organization guidelines, particularly in areas affected by agricultural activities [9]. These findings highlight the potential health risks associated with long-term use of nitrate-contaminated groundwater, especially for vulnerable groups such as infants and pregnant women. The study also emphasized the need to strengthen periodic monitoring programs and integrate chemical assessments with spatial analysis to identify high-risk contamination zones. Such evidence underscores the importance of conducting detailed local studies that account for the unique geographical and hydrogeological characteristics of each region.
Despite the increasing global attention to groundwater contamination by nitrates and phosphates, agricultural regions in Libya, including Wadi Al-Tarfawi, remain insufficiently studied, particularly from an integrated spatiotemporal perspective. The problem addressed in this study lies in the growing risk of groundwater contamination resulting from intensive fertilizer use and unregulated agricultural practices in areas that depend primarily on groundwater for drinking and irrigation, raising serious environmental and public health concerns in the absence of systematic water quality monitoring programs. The significance of this study stems from its contribution to evaluating nitrate and phosphate contamination levels in groundwater and their associated environmental, health, and agricultural implications, providing reliable scientific data to support sustainable groundwater management and informed decision-making. Accordingly, the present study aims to provide a comprehensive assessment of nitrate and phosphate contamination in groundwater in Wadi Al-Tarfawi through seasonal laboratory analyses and spatiotemporal evaluation, while comparing the results with established environmental and health standards. Accordingly, the present study aims to provide a scientifically robust evaluation supported by seasonal laboratory analyses and to compare the findings with established environmental and health standards, thereby contributing to filling this research gap and supporting sustainable groundwater management efforts in the region.

Methods

Study Area

The study area is in northeastern Libya. The climate of the study area is characterized as semi-arid, originating from an arid climate influenced by the adjacent Mediterranean climate. The average temperature during the summer season reaches approximately 25.2 °C [10]. Geographically, the study area lies between longitudes 36°24′–38°24′ E and latitudes 30°32′–31°58′ N, as illustrated in (Figure 1).

Well Collection

Groundwater Wells were collected during two different seasons. The first sampling campaign was conducted in winter (February 2025), while the second was carried out in summer (August 2025). Five groundwater wells were selected for sampling, with three replicates collected from each well. The depths of the selected wells ranged between 6 and 15 m.

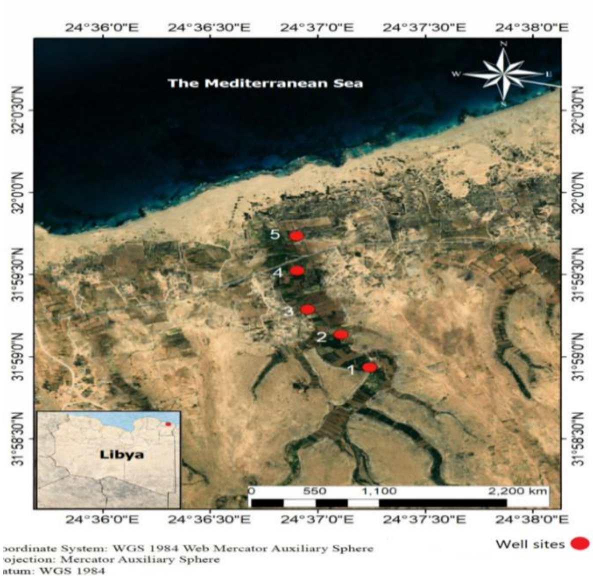

Figure 1. Study area and locations of the investigated wells.

Physical and Chemical Analysis Methods

Temperature (T)

Water temperature was measured in situ at the sampling sites using a calibrated mercury thermometer with a measurement range of 0–100 °C.

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pH
The pH of the water Wells was measured immediately after collection using a digital pH meter (Model AR-50-HACH, 4 plastuly).

Total Dissolved Solids (TDS)
Total dissolved solids were determined using a TDS meter (Model AR-50-HACH) and expressed in mg/L.

Electrical Conductivity (EC)
Electrical conductivity (EC) of the water Wells was measured using a conductivity meter, following the procedure described in [11].

Nitrate (NO_3^-)
Nitrate concentrations in the water Wells were determined according to the method described in [12] using a UV/Visible spectrophotometer (PU8625 Series, PHILIPS) at a wavelength of 220 nm.

Phosphate (PO_4^{3-})
Phosphate concentrations were measured following the method outlined in [12] using a UV/Visible spectrophotometer (PU8625 Series, PHILIPS) at a wavelength of 470 nm.

Statistical Analysis
Descriptive statistical analysis was applied to evaluate the physical and chemical parameters of groundwater Wells, including the calculation of means and standard deviations. One-way analysis of variance (One-way ANOVA) was employed to compare the recorded values between summer and winter seasons for each parameter individually, at a significance level of $p < 0.05$. All statistical analyses were performed using SPSS software (Version 27) to identify statistically significant seasonal variations.

Results and Discussion

Temperature
The results presented in Table 1 indicate that the mean groundwater temperature ranged from 22 °C, recorded as the lowest value in wells (1 and 3) during the winter season, to 27 °C, representing the highest value observed in wells (4 and 5) during the summer season. This variation reflects the direct influence of seasonal climatic changes and ambient air temperature, particularly in shallow wells.
Temperature is considered a key factor influencing the physical and chemical properties of water, as it directly affects salt solubility, the rate of chemical reactions, and microbial activity [13]. Indirectly, temperature also contributes to accelerating nitrification processes and increasing nitrogen losses [14]. Despite the observed seasonal variability, the recorded temperature values fall within the natural range expected for groundwater in arid regions.

Table 1. Seasonal variation of physicochemical parameters of groundwater in the study area.

TDS (mg/L)		EC (µS/cm)		pH		T		Elevation above sea level	Depth	Well number
winter	summer	winter	summer	winter	summer	winter	summer			
968	1102	1875	2285	7.4	7.3	22	25	14	15	1
661	735	1264	1376	7.2	7.4	23	26	11	13	2
597	680	1124	1294	7.3	7.5	22	25	7	9	3
608	646	1194	1267	7.4	7.6	23	27	7	8	4
595	623	1089	1126	7.7	7.9	24	27	5	6	5
1000 mg/L		-		8.5-6.5				Libya [15]		
1000 mg/L		2300 µs/cm		8.5-6.5				WHO [16]		

pH
Referring to the results presented in (Table 1), the pH values ranged from 7.2, recorded in well (2) during the winter season, to 7.9 in well (5) during the summer season. These values indicate that the groundwater in the study area exhibits a neutral to slightly alkaline nature. The results further show that all Wells fall within the permissible limits according to both Libyan standards and World Health Organization guidelines, suggesting the absence of direct health risks associated with pH levels.
These findings are consistent with those reported by [9] regarding groundwater quality in western Libya, where pH values ranged from 6.7 to 7.25, reflecting relatively stable chemical conditions of groundwater in arid and semi-arid environments. Such stability is commonly attributed to the geological formations of the aquifer and the presence of bicarbonates, which act as a buffering system regulating pH values.

Total Dissolved Solids (TDS)
The results shown in (Table 1) indicate that the lowest TDS value (595 mg/L) was recorded in Well (5) during

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the winter season, whereas the highest value (1102 mg/L) was observed in Well (1) during the summer season. Total dissolved solids are considered an important indicator of water quality and its suitability for drinking and irrigation, as elevated concentrations may adversely affect crop growth and agricultural productivity.
The increased TDS concentration observed in Well (1) during the summer season may be attributed to seawater intrusion, as this well is located closest to the coastline, in addition to prolonged and intensive groundwater abstraction. Furthermore, the heavy reliance of local farmers on groundwater resources, as well as the geological composition of the aquifer in the study area, may have contributed to the elevated salinity levels [17]. Accordingly, all TDS values recorded in this study—except for Well (1)—fall within the safe limits established by Libyan standards and the World Health Organization for drinking and irrigation purposes.

Electrical Conductivity (EC)
According to (Table 1), the mean electrical conductivity values ranged from a maximum of 2285 µS/cm in Well (1) during the summer season to a minimum of 1089 µS/cm in Well (5) during the winter season. The EC values obtained in the present study are lower than those reported by [18] in their investigation of groundwater quality in the Dafniya area, where all measured conductivity values exceeded permissible limits.
Similarly, the current findings are lower than those reported by [19], who classified most of the analyzed groundwater Wells as highly saline based on elevated electrical conductivity values. This discrepancy may be attributed to differences in hydrogeological conditions, land use patterns, and the intensity of groundwater exploitation across the studied regions.

Phosphate (PO_4^{3-})
The spatial distribution maps (Figures 2 and 3) reveal a heterogeneous pattern of phosphate concentrations across the study area during both seasons. Higher concentrations were mainly observed along the northern and southern margins of the area, whereas lower values were recorded in the central zones. A noticeable reduction in phosphate concentrations was observed during the winter season compared to the summer season.
As shown in (Table 2), the highest phosphate concentration (0.77 mg/L) was recorded in well (5) during the summer season, while the lowest concentration (0.06 mg/L) was detected in well (1) during the winter season. When compared with World Health Organization guidelines, which recommend a phosphate concentration limit of 0.5 mg/L, the results indicate that phosphate levels exceeded the permissible limits in all wells except wells (1, 2, and 3) during the winter season.
The phosphate concentrations reported in this study are higher than those reported by [20], who found that all phosphate values were within permissible limits, with a maximum concentration of 0.16 mg/L. The elevated phosphate levels observed in the present study may be attributed to the findings of [21], who reported that phosphate derived from organic fertilizer application decreases with increasing soil depth. In the present study, well depths ranged from 6 to 15 m, whereas the wells investigated in [20] ranged from 100 to 200 m in depth.
In a similar context, [22] reported that phosphate concentrations in all studied wells exceeded WHO permissible limits, attributing the elevated levels to long-term excessive agricultural use of phosphate-based fertilizers. In contrast, the results of the present study differ from those reported by [23], who observed increased phosphate levels following rainfall events due to enhanced surface runoff and groundwater recharge. This discrepancy may be explained by variations in hydrological conditions, land-use practices, phosphate sources, and transport mechanisms into groundwater systems. Although phosphate is generally less mobile than nitrate, it remains a significant contributor to eutrophication when transported into surface water bodies [14].

Table 2. Seasonal variation of nitrate (NO_3^-) and phosphate (PO_4^{3-}) concentrations in groundwater wells.

PO^{3-}_4 (mg/L)		NO^-_3 (mg/L)		Elevation above sea level	Depth	Well number
winter	summer	winter	summer			
0.06	0.74	21	35	14	15	1
0.12	0.66	24	32	11	13	2
0.09	0.63	35	30	7	9	3
0.61	0.52	22	47	7	8	4
0.65	0.77	41	64	5	6	5
		4 mg/L		Libya		
(0.5) mg/L		45 mg/L		WHO		

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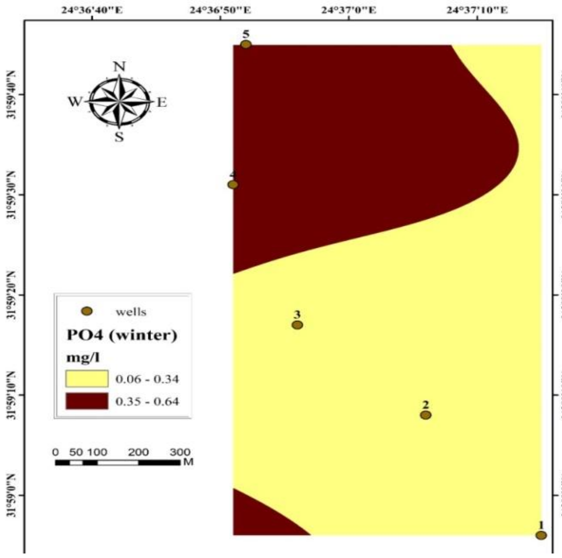

Figure 2. Spatial distribution of nitrate concentrations (NO_3^-) in groundwater during the winter season.
Source: ArcMap

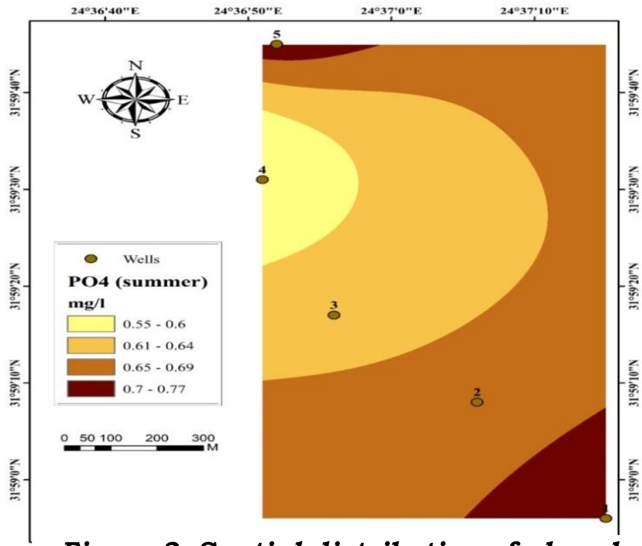

Figure 3. Spatial distribution of phosphate concentrations (PO_4^{3-}) in groundwater during the summer season.
Source: ArcMap

Nitrate (NO_3^-)

The spatial distribution maps (Figures 4 and 5) of nitrate concentrations reveal a pronounced spatial variability across the study area. Higher nitrate levels were recorded in certain northern and southern parts, whereas lower concentrations were observed in the central zones. In addition, nitrate concentrations were generally higher during the summer season compared to the winter season.

According to the results presented in (Table 3), the highest nitrate concentration (64 mg/L) was recorded in well (5) during the summer season, while the lowest concentration (21 mg/L) was observed in well (1) during the winter season. Comparison of the obtained results with World Health Organization guidelines indicates that all Wells were within the permissible limits in both seasons, except for wells (3) and (5) during the summer season.

The elevated nitrate concentrations observed during the summer season may be attributed to the excessive application of nitrogen-based fertilizers, in addition to intensive irrigation practices driven by higher temperatures. These conditions enhance the percolation of irrigation water enriched with nitrogen compounds into the groundwater system, which is consistent with the findings reported by [24]. The increased nitrate levels in these wells may also be related to the sandy nature of the soil, as sandy soils—due to their higher porosity—facilitate greater nitrate leaching into groundwater compared to clayey soils [25]. Furthermore, [26] reported that shallow aquifers associated with shallow wells are more vulnerable to nitrate contamination than deeper aquifers.

The findings of the present study are consistent with those reported by [9], who indicated that elevated nitrate concentrations tend to intensify during drought periods due to reduced dilution. In contrast, the results differ from those reported by [27], who found that nitrate concentrations increased following irrigation and rainfall seasons as a result of fertilizer leaching. Such variability among studies can primarily be attributed to differences in climatic conditions, land-use patterns, and the intensity of agricultural activities, as well as soil characteristics and local hydrogeological systems. These factors collectively govern the behavior and transport of nitrate within groundwater environments.

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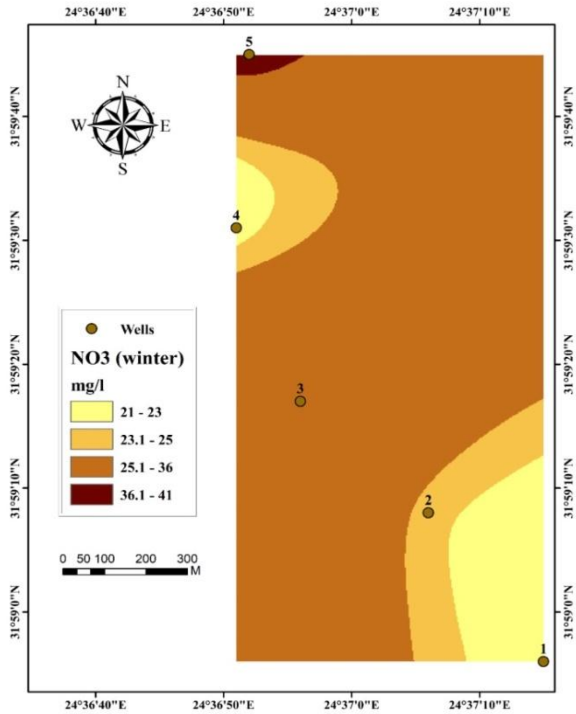

Figure 4. Spatial distribution of nitrate concentrations (NO_3^-) in groundwater during the winter season. Source: ArcMap.

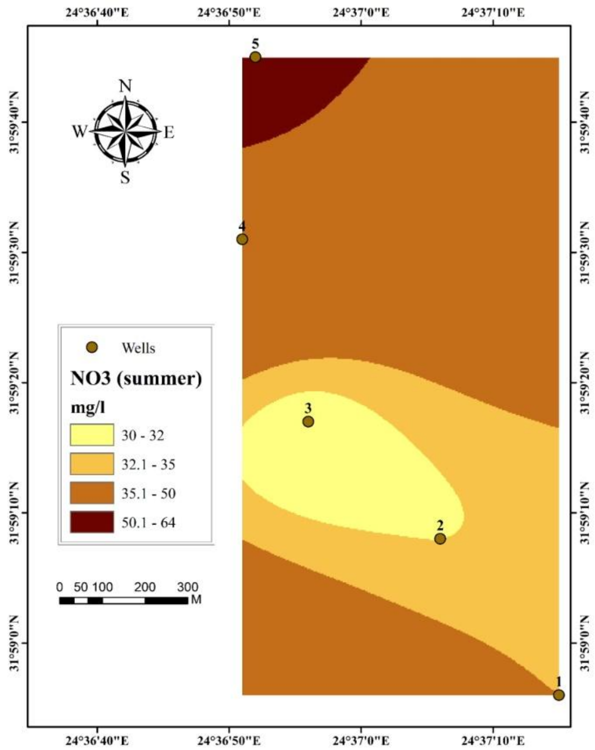

Figure 5. Spatial distribution of nitrate concentrations (NO_3^-) in groundwater during the summer season. Source: ArcMap.

Conclusion

This study revealed clear spatial and seasonal variations in nitrate and phosphate concentrations in groundwater within the Wadi Al-Tarfawi area. Higher concentrations were generally recorded during the summer season, particularly in wells located near intensively cultivated agricultural zones. These patterns are mainly attributed to increased fertilizer application, intensive irrigation practices, shallow aquifer depths, and the hydrogeological characteristics of the study area. Although most groundwater Wells complied with Libyan standards and World Health Organization guidelines, exceedances were observed in some wells during the summer season, indicating localized contamination risks that warrant attention. The findings highlight the importance of strengthening regular groundwater monitoring programs, integrating chemical assessments with spatial analysis, and promoting sustainable agricultural practices to mitigate nutrient pollution and ensure the long-term protection of groundwater resources.

Recommendations

The study recommends establishing a regular groundwater quality monitoring program in the Wadi Al-Tarfawi area, with particular emphasis on nitrate and phosphate concentrations. It also highlights the need to rationalize the use of chemical and organic fertilizers and to adopt sustainable agricultural practices to reduce contaminant leaching into the aquifer. Increasing the depth of newly drilled wells is advised to minimize vulnerability to surface contamination, while wells exhibiting elevated nitrate and phosphate levels should be treated or restricted from use for drinking purposes. Additionally, raising awareness among farmers and local communities about the environmental and health risks associated with groundwater contamination is essential for ensuring long-term water resource protection.

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Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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