Nutrient Fluxes between Sediment and Water in the Shatt Al-Arab Estuary, Northwestern Arabian Gulf

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Abstract

Nutrient exchange occurred at four stations located downstream of the Shatt Al-Arab River and in the northwestern Arabian Gulf. The stations (Al-Ashar, Abu Flous, Al-Seeba, and Al-Faw) were studied over four seasons (autumn, winter, spring, and summer) of 2024–2025. These samples were then analyzed for total nitrogen (TN), total phosphorus (TP), nitrite (NO_2), nitrate (NO_3), and (PO_4). The seasonal water results will show significant spatial and temporal changes in nutrient levels driven by seasonal river discharge, seawater intrusion, and human activities such as farming and urban runoff. The concentrations of TN, TP, NO_2, NO_3, and PO_4 are high at the downstream stations (24.08 mg/l – 0.281 mg/l – 0.9322 mg/l – 0.009 mg/l), whereas low readings were recorded at the upstream stations (1.12 mg/l – 0.0042 mg/l – 0.007116 mg/l – 0.0143 mg/l – 0.001 mg/l). The sediment samples yielded results that varied widely. They gave higher concentrations than water (16.8 mg/l – 221.72 mg/l – 2.6921 mg/l – 1.136 mg/l – 0.037 mg/l). Moreover, it gave the lower concentrations (0.84 mg/l – 86.75 mg/l – 0.0081 mg/l – 0.0133 mg/l – 0.017 mg/l). The results demonstrate that the exchange of water and sediments helps limit nutrient cycling and reduce the risk of eutrophication in the study area. The findings of this study provide essential baseline data for ongoing monitoring and appropriate management of nutrient enrichment. Identifying nutrient enrichment status in the waters of the Shatt Al-Arab and the northern Arabian Gulf is expected to aid in protecting ecosystem health and the efficient use of water resources for future strategies.

Keywords: Nutrients, water, sediment, Shatt Al-Arab River, the Arabian Gulf.

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Introduction

Nutrients such as nitrogen and phosphorus affect the quality and stability of aquatic systems. Nutrients regulate primary productivity and drive the onset of eutrophication, which can induce harmful algal blooms, oxygen depletion, and biodiversity loss (Conley *et al.*, 2009). The water column and sediment are both nutrient reservoirs where dissolved and particulate matter exchange. These exchanges influence ecosystem functioning, productivity, biodiversity, and long-term resilience.

However, sediment is highly dynamic in the water column and can act as either a source or a sink, depending on environmental conditions (Engelsen *et al.*, 2008; Yu *et al.*, 2017). Nitrogen and phosphorus can be found in water as dissolved or particulate organic or inorganic materials. Physical, chemical, and biological drivers govern their mobilization across the sediment-water interface (SWI). The water column receives ammonium, nitrate, and nitrite generated in sediments, which degrade water quality. Denitrification reduces nitrogen loading but produces the potent greenhouse gas nitrous oxide (N2O) (Quick *et al.*, 2019). When dissolved oxygen levels are low, temperatures are high, and microbial activity is enhanced, sediments tend to release nutrients into the overlying water (Hou *et al.* 2013; Pang *et al.* 2022).

The processes of “remineralization” enhance these fluxes, which are especially prevalent during eutrophication or in water bodies unaffected by human influence (Khatri and Tyagi, 2015; Savic *et al.*, 2022). Algal growth is often limited by phosphorus in freshwater studies, but in coastal and estuarine environments, nitrogen can become similarly limiting due to seasonal and spatial variability (Conley *et al.*, 2009).

Nutrient fluxes are strongly influenced by hydrodynamics. Enhanced water currents and turbulence can reduce the thickness of the diffusive boundary layer, thereby increasing nitrogen and phosphorus release several times higher than under stagnant conditions (Reidenbach *et al.*, 2010; Hou *et al.*, 2013; Yu *et al.*, 2017; Mereta *et al.*, 2020; Jeong, 2024). Wang *et al.* (2010) and Xia *et al.* (2017) emphasised that the equilibrium process is closely linked to hydrological characteristics, including flow velocity, sediment transport, and water residence time, which control microbial functions and biogeochemical pathways. Moreover, wetlands reduce the transport of nitrogen and phosphorus to rivers and estuaries significantly (Fisher and Acreman, 2004; Golden, 2019). However, agriculture, land-use change, hydrological alteration, and other anthropogenic pressures can impair the many functions that wetlands perform, turning them from nutrient sinks to sources during high-flow or flood events (Wiegman, 2024; Moustafa, 2025). The average phosphorus retention efficiency is 30 to 40%, but this capacity is highly variable to environmental stressors (Wiegman, 2024).

Salt and temperature differences lead to layering in estuarine and coastal systems, which complicates nutrient behaviour. Stratification prevents the mixing of surface and bottom waters, leading to bottom-water oxygen depletion (Reidenbach *et al.*, 2010; Jeong, 2024).

The N:P ratio indicates which nutrient limits algal growth in water bodies. Ratios below 16 usually indicate nitrogen limitation. On the contrary, ratios of 16 or higher indicate phosphorus limitation (Savic *et al*., 2022). Therefore, monitoring this ratio in water and sediments is important to ensure understanding and management. Research on river estuaries in Syria indicates that nutrients are typically concentrated at the mouth. Nutrient patterns influence primary productivity, as indicated by chlorophyll-a concentrations. These concentrations often peak seasonally, associated with nutrient availability. When viewed together, these insights indicate that sediments and the overlying water column cannot be studied in isolation. It is an integrated, dynamic system in which hydrodynamics, biogeochemistry, and ecosystem structure interact to determine water quality and ecological health. It is really vital to reverse the impact of eutrophication, not just target nitrogen or phosphorus, but both (Conley *et al*., 2009; Savic *et al*., 2022).

Several studies have evaluated the pollution status in the Shatt Al-Arab (Hassan, 2013; Al-Dabbas and Al-Jaberi, 2014; Mahdi, 2015; Alhello *et al*., 2019; Aoubid and Opp, 2023). Nevertheless, none of these researchers addresses seasonal variation in nutrient concentrations. Understanding how exchanges occur at the sediment-water interface can inform better management strategies. In addition, it enhances the resilience of wetlands and estuaries.

This study aims to determine nutrient concentrations, such as Nitrogen and phosphorus, at four stations in Basra Governorate, Al-Ashar, Abu Flous, Al-Seeba, and Al-Faw, during the four seasons in the Shatt Al-Arab Estuary to understand internal loading dynamics.

Materials And Methods

The Shatt Al-Arab River is the primary freshwater system in southern Iraq. It flows about 190 km before reaching the Arabian Gulf. This river is vital to agriculture, navigation, and drinking water supply; however, its hydrology and water quality have been increasingly influenced by upstream interventions, climate variability, and tidal intrusion from the Gulf (Al-Darraji *et al*., 2023; Al-Baghdadi *et al*., 2024). Four stations were selected to determine nutrient concentrations, the Nitrogen and phosphorus, at four stations in Basra Governorate, Al-Ashar, Abu Flous, Al-Seeba, and Al-Faw, during the four seasons in the Shatt Al-Arab Estuary in this study (Fig. 1), Table 1 shows the coordinates of the study sites..

The first station is located in Al-Ashar within the Basra City Center. Ashar has long served as a central commercial hub with bustling river navigation that includes traditional wooden boats and large cargo vessels, transporting goods between Basra and the Arabian Gulf. The second station is located in Abu Flus, about 30km south of Ashar. This port serves as a key logistics and trade hub, handling the movement of goods such as construction materials, food, supplies, and industrial equipment. Increasing water pollution has affected the local fishing industry in recent years. The third station is at Al-Seeba, about 60 km south of Abu Flus. There has been a recent increase in salinity due to seawater intrusion and a reduction. The fourth station is at Al-Faw, at the southern end of Iraq, where the Shatt Al-Arab meets the Arabian Gulf; it is home to Iraq's main port, Al-Faw Grand Port. The area is heavily influenced by tides and salinity, making it one of the most environmentally sensitive along the Shatt al-Arab.

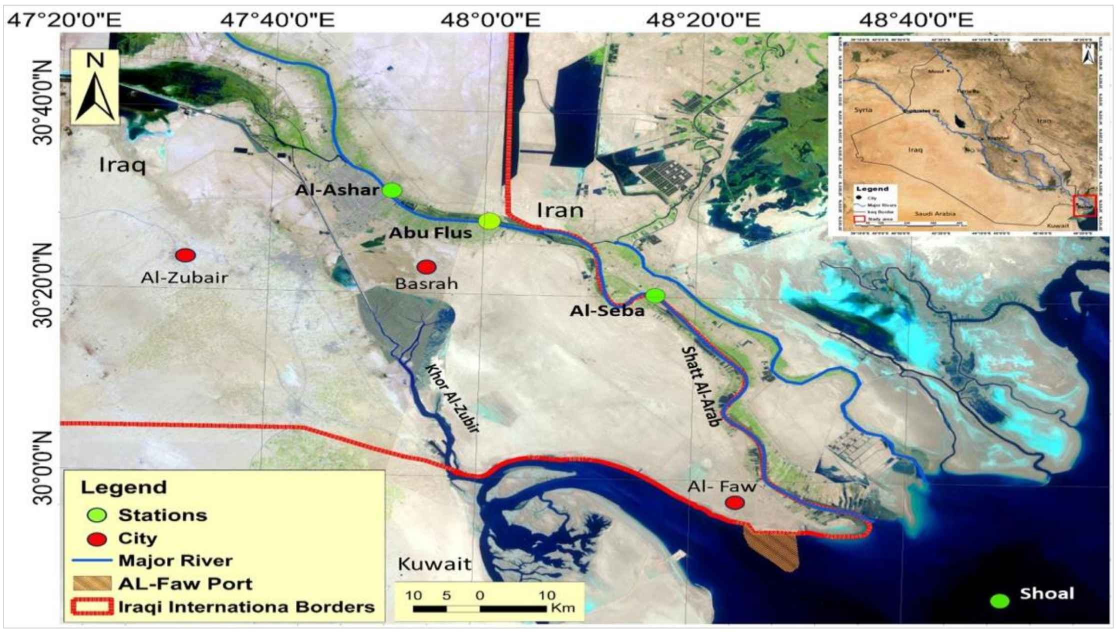

Figure 1. Map of the study area and the sampling stations along the Satt Al-Arab Estuary.

Table 1. Coordinates of study stations.

stations	North	East
St. 1	30.5122319	47.8515292
St. 2	30.4650465	48.0101288
St. 3	30.3374656	48.2605821
St. 4	29.792053	48.827153

Water samples were collected seasonally during 2024 and 2025 using a water sampler at a depth of 5-10cm below the surface. The samples were collected in a plastic dim container, stored in a refrigerator at 4°C, and kept in a cold place to minimize volume changes due to evaporation (APHA, 1992). Then, they were sent to the laboratories of the Marine Scientific Center at the University of Basra for analysis.

Sediment samples were collected from the riverbed using a Van Veen grab sampler, placed in plastic bags, stored in a cooling container, and transported to the laboratory. The samples were air-dried at room temperature, ground in a ceramic mortar and pestle to disintegrate and homogenize them without altering their physical or chemical properties, and then sieved through a 75µm mesh to isolate the fine fraction for further analysis, following international procedures (APHA, 1992).

Results and Discussion

The region is a key area for organisms and humans. Hence, the water and sediment samples were analyzed, as nutrients are important in the area. Nutrient characteristics of samples collected from four stations (S1, S2, S3, and S4) were assessed. The different water stations represent various water environments, and the selection aims to represent a range of water types. The tests included nitrite (4500-NO_2 B), Nitrate (4500-NO_3 D), phosphate (4500-P C), total nitrogen (4500-Norg B) and total phosphorus (4500-P D).

Water samples

Total nitrogen (TN) in water at all stations and seasons ranged from 1.12 mg/L (Spring and Summer) to 24.08 mg/L (Winter) (Fig. 2). The highest TN values were recorded during the winter months, with the highest at Abu Flous (Station 2). Increased runoff and sediment resuspension are likely responsible for nitrogen release from sediments into the water column (Li *et al*., 2021; Zhang *et al*., 2023). Lower TN levels in spring and summer at Al-Seeba (station 3) indicate greater biological uptake and denitrification, as well as reduced external loading (Wang *et al*., 2021; Ghaffour *et al*., 2021).

The concentration of total phosphorus (TP) in water across all stations and seasons showed apparent temporal and spatial variation, ranging from 0.0042 mg/L in autumn to 0.281 mg/L in winter. The lowest values of TP were generally found in autumn, spring, and summer (0.03-0.042 ppm)(Fig. 3). In comparison, the highest value was 0.281 ppm in winter at Al-Ashar (station 1), likely due to increased TP concentrations resulting from increased surface runoff and sediment resuspension (Rasheed and Hassan, 2021; Al-Saadi *et al*., 2023) during rainy and high-flow periods.

The nitrite (NO_2) levels at the first three stations were not consistent with the seasonal modal value. The lowest value, 0.007 mg/L, was observed in the fall. In the spring season, the highest value (0.9322 mg/L; in Al-Seeba, Station 3) was found (Fig. 4) (Al-Kubaisi *et al*., 2020; Ghasemi *et al*., 2021). Nitrate (NO_3) at the first three stations (Al-Ashar, Abu Flous, and Al-Seeba) showed seasonal variation, with the highest value in autumn at 0.324 mg/L and the lowest in winter at 0.143 mg/L (Fig. 5). The spring and summer stations displayed moderate values, which are common in river and wetland systems influenced by natural phenomena and human activities (Al-Lami *et al*., 2022; Mohamed *et al*., 2021).

The first three stations (Al-Ashar, Abu Flous, and Al-Seeba) had low phosphate (PO_4) concentrations, with the highest recorded in autumn at Abu Flous (0.009 mg/L) and the lowest values at Faw (0.001 mg/L)(Fig. 6). This may be due to either a decline in nutrient inputs or a higher biological uptake of nutrients by micro-organisms and algae (Othman *et al*., 2020; Al Obaidy, 2022).

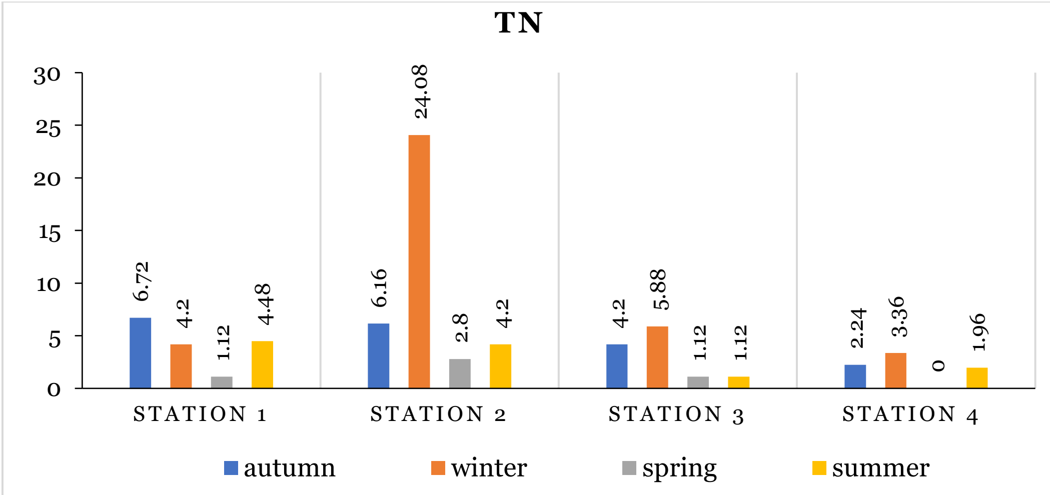

Figure 2. Water TN levels along the stations in different seasons.

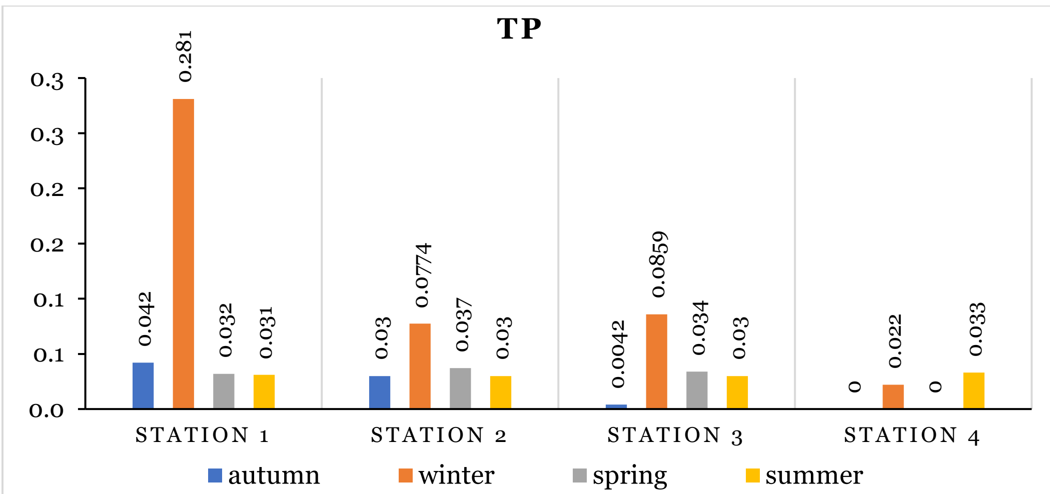

Figure 3. Water TP levels along the stations in different seasons.

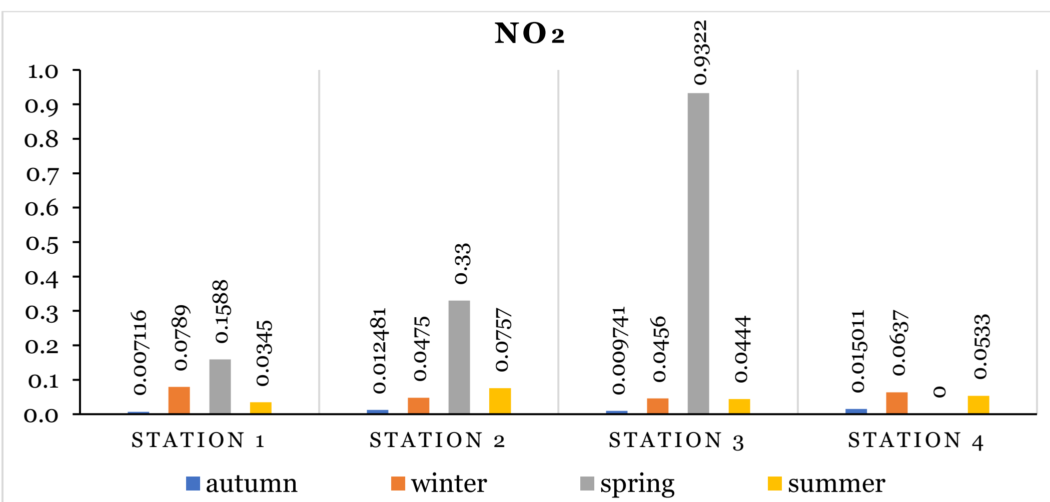

Figure 4. water NO_2 levels along the stations in different seasons.

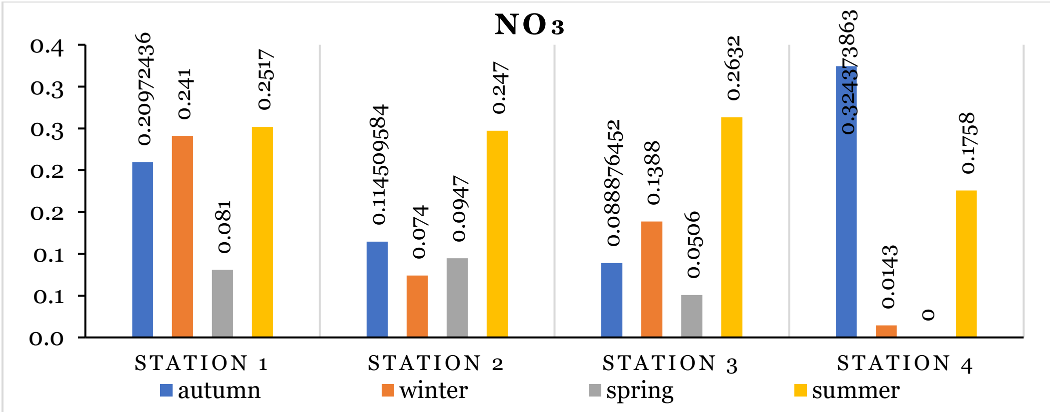

Figure 5. water NO3 levels along the stations in different seasons.

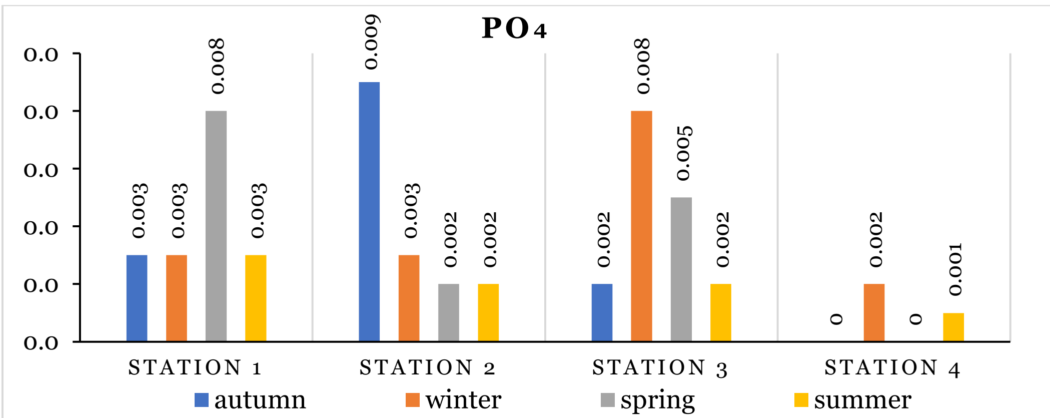

Figure 6. PO4 levels along the stations in different seasons.

Sediment samples

The total nitrogen (TN) concentration in sediment fluctuated seasonally and spatially, ranging from 0.84 mg/L in summer to 16.8 mg/L in winter. The TN levels in winter (16.8 mg/L) were generally higher than in spring and summer (0.84 mg/L)(Fig. 7). This pattern aligns with findings from recent studies in Iraq, which show that sediments accumulate nitrogen during periods of enhanced organic matter input and precipitation, especially during the cold season (Shakir *et al.*, 2022; Al-Saadi *et al.*, 2023). The concentrations of total phosphorus TP in sediment revealed that they varied widely. The Winter concentration was 86.75 mg/L, whereas the summer concentration reached a maximum of 221.72 mg/L(Fig. 8). Research estimates indicate that phosphorus concentrations are likely to peak during autumn and winter. Peaks during this season may be due to increased runoff and the input of organic matter during rainy months, which enhances phosphorus accumulation in sediments (Abdulnabi, 2016; Rasheed *et al.*, 2021). The TP values during spring and summer were generally lower and more stable, possibly due to increased biological uptake and mineralization at higher temperatures. (Ministry of Environment, 2021; Al-Saad *et al.*, 2023).

Nitrite (NO_2) concentrations were highest in Autumn in Al-Faw (Station 4), of 2.6921 mg/L, and lowest in Summer in Seeba (Station 3), of 0.0081 mg/L(Fig. 9). The high concentration of nitrite in autumn may be attributed to increased decomposition of organic matter coupled with anoxic conditions. On the other hand, the lower values during summer suggest microbially mediated conversion of NO_2 to nitrate (Al-Khafaji and Al-Timimi, 2020; Zhang *et al.*, 2023). Nitrate (NO_3) also showed differences. The highest concentration was recorded in Summer in Ashar (Station 1) at 1.136 mg/L, while the lowest was in Winter in Seeba (Station 3) at 0.0133 mg/L (Fig. 10). The summer increase may be due to higher temperatures, which promote nitrification. The low values during winter may be due to reduced pollutant microbial activity, resulting from dilution by increased water flow (Al-Fatlawy *et al.*, 2022). Sediments at all stations show moderate variation in phosphate (PO_4). The highest value was observed at Autumn in Faw (Station 4) of 0.037 mg/L. The lowest at Spring in Faw as well as 0.00 mg/L(Fig. 11). This trend could be attributed to increased autumn runoff and organic matter inputs, which may drive phosphate accumulation (Liu *et al.*, 2021; Al-Saadi *et al.*, 2023). In spring, PO_4 levels are likely to decrease due to increased biological uptake by microorganisms and algae (Jiang *et al.*, 2022).

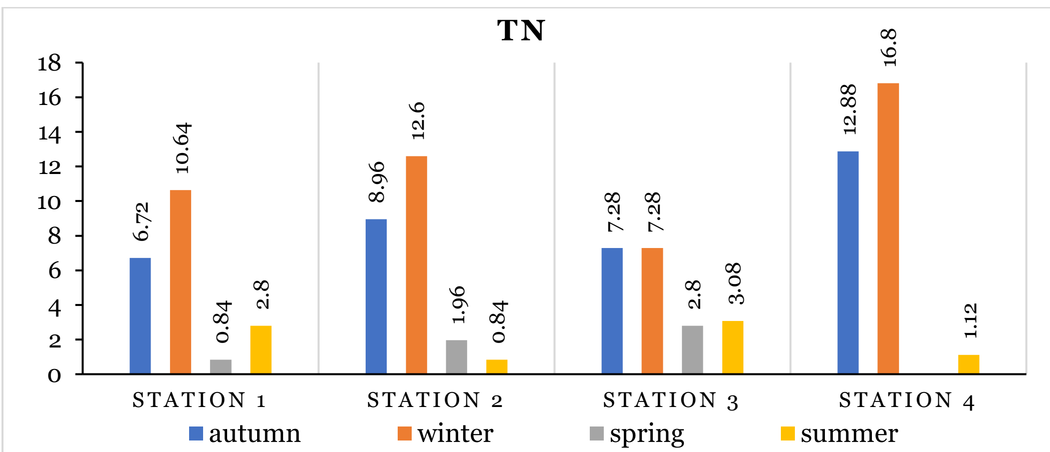

Figure 7. sediment TN levels along the stations in different seasons.

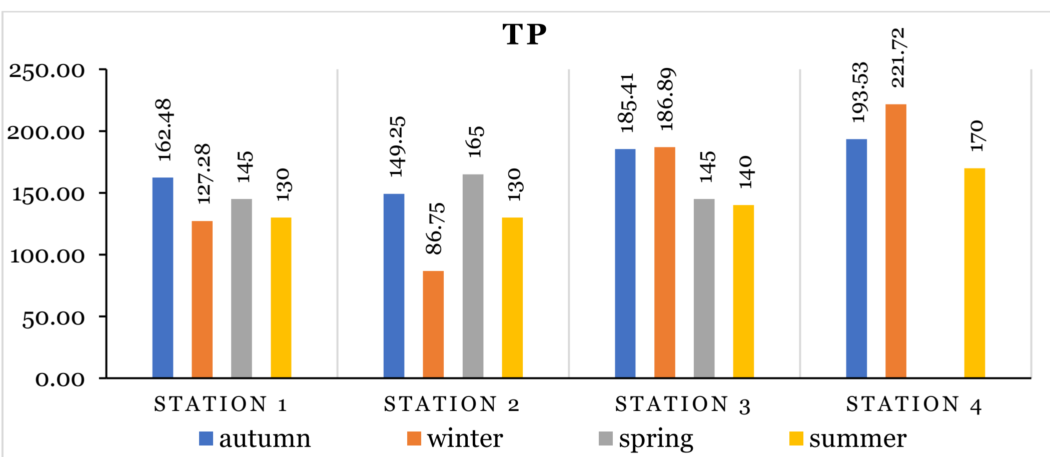

Figure 8. sediment TP levels along the stations in different seasons.

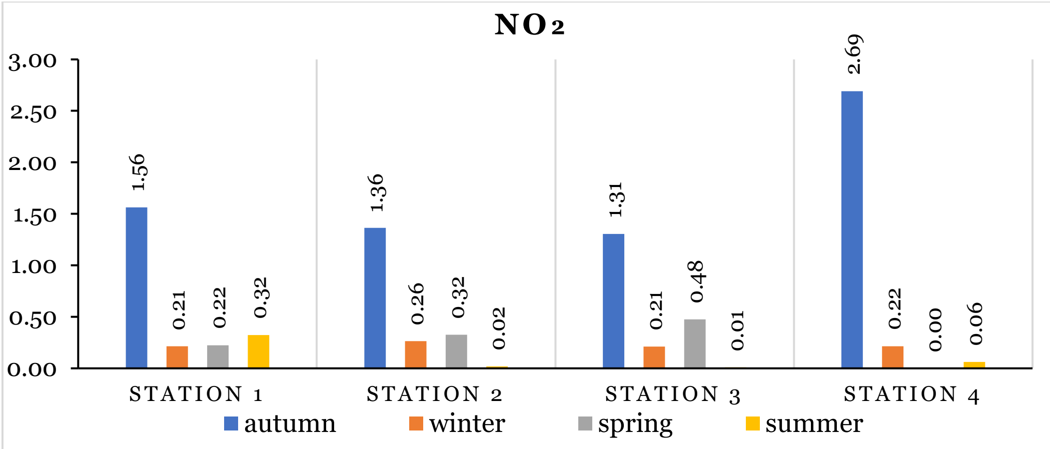

Figure 9. sediment NO2 levels along the stations in different seasons.

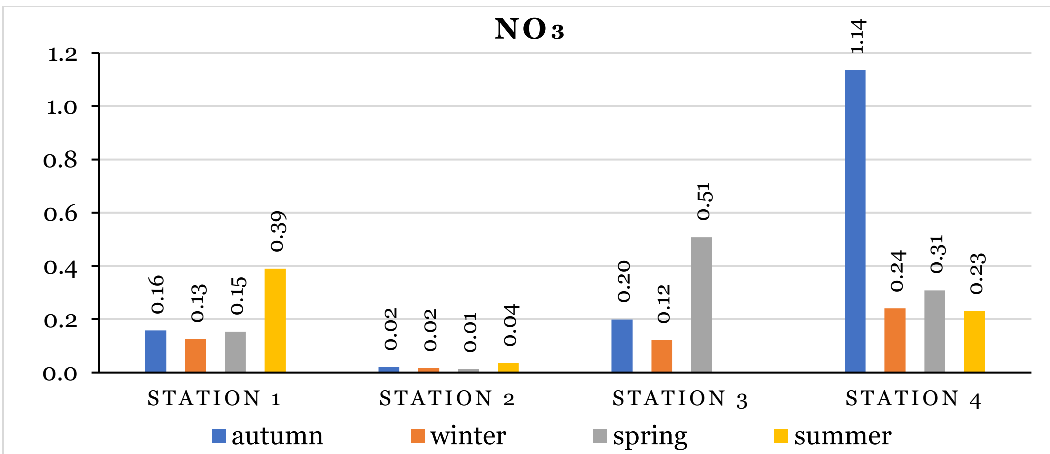

Figure 10. sediment NO3 levels along the stations in different seasons.

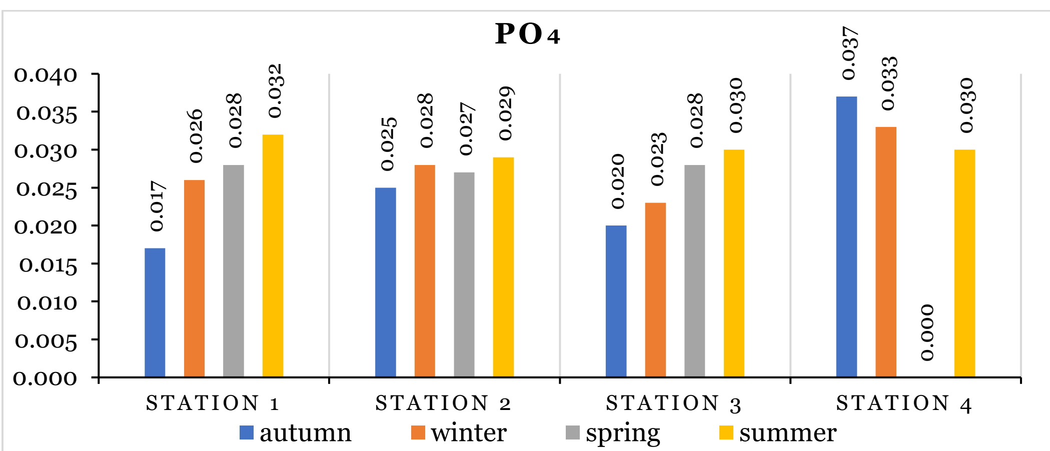

Figure 11. sediment PO4 levels along the stations in different seasons.

There is an interrelation between water and sediments. Sediment-water interface enrichment of N and P or depletion depends on environmental conditions. The exchange of nutrients between the sediment and water column is influenced by hydrodynamics, redox state, sediment composition, and microbial processes (Al-Baldawi *et al*., 2021; Zhang *et al*., 2023). The sedimentation process often uses nitrogen and phosphorus. During high-runoff events, organic inputs and external sediment loads are often the first to act as nutrient sinks. When this happens, the water column exerts the force, conveying nutrients and organic material to the sediments, which gradually settle and can store these substances (Abdulnabi, 2016; Ministry of Environment, 2021). On the other hand, environmental changes, e.g., loss of oxygen, increased temperatures, or increased physical disturbance (e.g., resuspension during storms or high-flow events) can shift sediments from sinks to sources. Under these conditions, sediments release nitrogen (as ammonium or nitrate) and phosphorus (as orthophosphate) back into the overlying water, which can feed the water column and fuel an eutrophication event (Jiang *et al*., 2022; Chen *et al*., 2022). In the water column, phosphate (PO_4) concentrations were generally low across seasons and stations, with the lowest values observed during periods of high bio-productivity. The pattern indicates either efficient uptake by phytoplankton and bacteria or negligible external input. PO_4 in sediments was also found to be low to moderate and is expected to increase after disturbances and/or under hypoxic conditions, when iron-bound phosphorus is released to porewater and then to the overlying water (Islam *et al*., 2020; Radwan *et al*., 2022). Sediment TN decreased in spring and summer, suggesting increased biological uptake by benthic organisms and aquatic plants. Furthermore, microbial mineralization and denitrification processes released nitrogen to the water column and may have removed it as gas (Saleh *et al*., 2021; Liu *et al*., 2021). On the other hand, the elevated sediment TN observed in winter and autumn reflects increased organic input and runoff. Therefore, under conditions of high flow or low oxygen, it may become an internal nitrogen source.

Water TN values followed these trends: winter and autumn showed high TN concentrations, mainly after storm events or due to agricultural runoff; spring and summer values were low due to river flow dilution and biological assimilation (Al-Mayah *et al*., 2020; Sharif *et al*., 2021). Likewise, TP concentrations in sediment and water showed pronounced seasonal and spatial variation. The lower values of TP in both matrices, especially in spring and summer, show that under the influence of Sediment-water interface, a phosphorus sink often occurs. TP is retained in sediments due to binding to oxic iron, aluminum, or calcium, and to uptake by benthic algae and microbes. However, winter peaks in sediment and water TP suggest that sediments can become an important internal source of phosphorus during disturbance, resuspension, and hypoxia, which would otherwise alter phosphorus retention and trigger release to the water column. Nitrite (NO_2) and nitrate (NO_3) also varied considerably. In water, NO_2 concentrations were typically low, except under accelerated organic matter breakdown or low oxygen conditions, where peaks may reflect incomplete nitrification. Sediment NO_2 levels are mostly transient, but they can accumulate under anoxic conditions. Water has high NO_3 during the autumn and winter months. Table 2 shows the statistics for the factors studied.

Table 2. Statistical analysis of variance of environmental factors across stations and seasons

Statistical analysis of Variance					
Variables, stations and seasons		water		sediment	
		F	P	F	P
NO_2	Season	48310.21	<0.001	1.873E+07	<0.001
	Station	18628.72	<0.001	4.227E+05	<0.001
	Season-station	20430.25	<0.001	1.134E+06	<0.001
NO_3	Season	2.848E+05	<0.001	1.659E+06	<0.001
	Station	48180.49	<0.001	5.811E+05	<0.001
	Season-station	78942.52	<0.001	7.993E+05	<0.001
PO_4	Season	11.70	<0.001	27.68	<0.001
	Station	42.49	<0.001	1.71	<0.001
	Season-station	28.40	<0.001	39.91	<0.001
TN	Season	57150.56	<0.001	1.249E+05	<0.001
	Station	49753.85	<0.001	6613.45	<0.001
	Season-station	24294.81	<0.001	8058.10	<0.001
TP	Season	1314.09	<0.001	16974.56	<0.001
	Station	755.13	<0.001	4887.03	<0.001
	Season-station	451.05	<0.001	21788.35	<0.001

The higher NO_3 during this time is due to increased runoff and nitrification of ammonium. In the other months, such as spring and summer, NO_3 was comparatively low, which may be due to denitrification or plant uptake. Sediments can accumulate NO_3 under oxic conditions, but once the oxygen in the sediment is exhausted, NO_3 is rapidly reduced to nitrogen gas (Al-Rubaye *et al.*, 2021; Zhao *et al.*, 2022).

Conclusions

Nitrogen and phosphorus dynamics were studied at four stations (Al-Ashar, Abu Flous, Al-Seeba, and Al-Faw) during the four seasons. In both the water and sediments, spatial and seasonal variations in total nitrogen and total phosphorus were observed. This shows that the water column and sediments are tightly coupled, with each acting as a source or sink depending on environmental conditions.

The results provide an overall picture of the system's nutrient status and interactions. It would serve as a valuable reference for future monitoring and management of the area, as well as for developing strategies to control eutrophication and maintain ecosystem health.

Recomindation

Regular monitoring of NO_3^-, NO_2^-, PO_4^{3-}, TN, and TP should be included within routine environmental monitoring programs. Such monitoring should consider both the water column and sediments to better understand nutrient behavior and reduce enrichment within the Shatt Al-Arab system.

Disturbance of sediments in nutrient-rich and high-energy areas should be limited as much as possible. This can be achieved by controlling dredging activities and regulating vessel movement, especially in locations that are frequently affected by resuspension and tidal action.

Improving wastewater treatment facilities is necessary to reduce the long-term accumulation of nutrients in sediments and to enhance surface water quality. In addition, further studies are needed to examine the role of tidal processes in sediment resuspension and nutrient transport, with particular attention to seasonal variations.

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تبادل المغذيات بين الرواسب والمياه في مصب شط العرب وشمال غرب الخليج العربي

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المستخلص

حدث تبادل غذائي في أربع محطات تقع أسفل مجرى نهر شط العرب وفي شمال غرب الخليج العربي. دُرست المحطات (العشار، وأبو فلوس، والسيبة، والفاو) على مدار أربعة فصول (الخريف، والشتاء، والربيع، والصيف) للفترة 2024-2025. جمعنا عينات من المياه والرواسب موسمياً، ثم حُللت هذه العينات لقياس النيتروجين الكلي (TN)، والفوسفور الكلي (TP)، والنتريت (NO_2)، والنترات (NO_3)، و (PO_4) تُظهر نتائج المياه الموسمية تغيرات مكانية وزمانية هائلة في العناصر الغذائية نتيجةً لتصريف الأنهار الموسمي، وتسرب مياه البحر، والأنشطة البشرية كالزراعة والجريان السطحي الحضري. كانت كمية TN و TP و NO_2 و NO_3 و PO_4 مرتفعة في محطات المصب (24.08 ملغم/لتر- 0.281 جزء في المليون - 0.9322 جزء في المليون- 0.009 جزء في المليون)، بينما سُجلت قراءات منخفضة عند (1.12 ملغم/لتر - 0.0042 جزء في المليون- 0.007116 جزء في المليون- 0.0143 جزء في المليون- 0.001 جزء في المليون). أظهرت عينات الرواسب نتائج متباينة للغاية. فقد أظهرت تركيزات أعلى من الماء (16.8 ملغم/لتر - 221.72 جزء في المليون - 2.6921 جزء في المليون - 1.136 جزء في المليون - 0.037 جزء في المليون). بينما أظهرت تركيزات أقل (0.84 ملغم/لتر - 86.75 جزء في المليون - 0.0081 جزء في المليون- 0.0133 جزء في المليون- 0.017 جزء في المليون). تُظهر النتائج أن تبادل المياه والرواسب يُسهم في الحد من دورة المغذيات، ويُقلل من خطر غزو المغذيات الزائدة لمنطقة الدراسة. تُوفر نتائج هذه الدراسة بياناتٍ أساسيةً يُمكن استخدامها للرصد المستمر والإدارة المُناسبة لإثراء المغذيات. ومن المُتوقع أن يُسهم تحديد حالة إثراء المغذيات في مياه شط العرب وشمال الخليج العربي في حماية صحة النظام البيئي، والاستخدام الأمثل للموارد المائية في الاستراتيجيات المُستقبلية.

الكلمات المفتاحية: المغذيات، المياه، الرواسب، نهر شط العرب، الخليج العربي.