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Original Article

Environmental Fate of Nutrients in the Karun River Using the AQUATAX Model

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Abstract

Background: The fate of nutrients plays a crucial role in the environmental management of aquatic ecosystems.

Methods: This study, performed in 2024, investigated the environmental fate of nutrients in the Karun River using the AQUATOX model. The water samples were collected from 10 locations across all seasons. Phosphate and nitrate concentrations were measured, along with dissolved oxygen (DO), electrical conductivity (EC), pH, and total suspended solids (TSS), following standard methods for the AQUATOX modeling. Two scenarios were simulated: S1 (a 15% reduction in nutrient levels) and S2 (a 15% increase). The Shannon, Simpson, Camargo, and Brillouin indices were calculated as biological indicators under these scenarios.

Results: The average values of the Shannon, Simpson, Camargo, and Brillouin indices were 1.295, 0.585, 0.308, and 1.247, respectively, indicating low biodiversity and a high dominance of specific species in the Karun River ecosystem. The AQUATOX model estimated annual average phosphate and nitrate concentrations at 4.55 and 23.64 mg/L, respectively. DO and algal biomass were measured at 2.31 mg/L and 1.16 g/L. The simulation results highlighted the direct impact of nutrient fluctuations on ecosystem dynamics. In Scenario 1, the total nutrient concentration reached 223.9 mg/L, while in Scenario 2, it decreased to 32.42 mg/L. A 15% reduction in nutrient concentrations significantly improved biodiversity.

Conclusion: The findings showed that variations in nutrient levels can profoundly influence biodiversity in aquatic ecosystems.

Keywords: Environmental fate modeling, Aquatic ecosystems, Biodiversity, Nutrients, AQUATOX model, Water pollution

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Introduction

Rivers, as vital arteries of the Earth, play a major role in sustaining the planet's life cycles. It is predicted that in the coming century, the importance of water will increase to such an extent that it may become a primary source of conflict and a central driver of national development worldwide.[1-5] Nutrients such as nitrogen and phosphorus are essential for the growth and development of plants and animals in both groundwater and surface water. However, increasing pollution from human activities—particularly the influx of these nutrients into aquatic ecosystems—poses a significant threat to environmental health and water quality.[6-10]

Global statistics indicate that approximately 80% of the world's surface waters are affected by nutrient pollution, leading to adverse phenomena such as algal blooms and decreased dissolved oxygen (DO) levels. These conditions, in turn, harm aquatic life and compromise drinking water quality.[11-14] A variety of industrial, agricultural, and natural processes contribute to the pollution of surface water resources. Among them, wastewater discharge and the use of chemical fertilizers containing phosphates and nitrates are among the most prominent sources of contamination.[15-17]

One of the key challenges in protecting and restoring rivers is understanding the complex interactions between their physical and chemical environments and the living organisms they support.[18,19] To deal with this various models have been developed to simulate the fate of pollutants in aquatic systems, including ECOFATE,[20,21] STELLA,[22] and QUAL2K.[23] Among these, AQUATOX stands out as an ecosystem-based model capable of predicting the fate of nutrients and organic chemicals, as well as assessing their direct and indirect effects on aquatic biota.[24] AQUATOX is a simulation tool designed to forecast the behavior of excess nutrients and pollutants in water bodies and to evaluate their impacts on aquatic ecosystems—including fish, invertebrates, and aquatic plants.[25] It has proven to be a valuable resource for ecologists, biologists, and environmental managers involved in aquatic ecological risk assessment.[26] The model is designed to simulate ecosystem dynamics even with limited site-specific data and is compatible with a variety of data formats. This flexibility allows researchers to explore the effects of human activities on water quality and to recommend appropriate management strategies.[27]

Several studies have successfully applied the AQUATOX model. For example, Talukdar et al used the model to assess the effects of agricultural pollutants in a Bangladeshi watershed, finding that chemical fertilizers increased nitrate and phosphate concentrations, thereby harming the aquatic ecosystem.[28] Similarly, Sarkar et al employed AQUATOX to evaluate lake water quality in Bangladesh, revealing that industrial and domestic waste had reduced biodiversity and altered plankton community structures.[29] In India, Kibria et al used the model to explore climate change impacts on river water quality, concluding that rising temperatures and erratic rainfall patterns could exacerbate pollutant loads.[30] Moreover, Zhang et al examined nutrient runoff from agricultural activities in China and emphasized the importance of effective water resource management to mitigate environmental damage.[7]

The Karun River is the largest, longest, and most water-abundant river in Iran, stretching 950 kilometers and passing through ten cities. It supports a wide range of plant and animal species and is a critical source of water for drinking, agriculture, and industry in southwestern Iran.[31] In recent years, numerous reports have highlighted increasing pollution in the Karun River. Hence, in this study, we assess the river's pollution status with a focus on nutrient levels (nitrates and phosphates), its physicochemical characteristics within Khuzestan province, and relevant hydrographic parameters. We also explore the interrelationships among these factors. The findings of this research are expected to make a valuable contribution to the environmental management and restoration efforts for the Karun River.

Materials and Methods

Study Area

The Karun River is the longest and most water-rich river in Iran, extending approximately 950 kilometers and encompassing a watershed area of 65 230 km^2. Currently, 11 dams and hydropower plants are either operational, under construction, or in the planning phase along the Karun River. Upon completion, these structures will collectively have a total storage capacity of approximately 21.559 bn m^3. The river's average daily, monthly, and ecological flow rates are estimated at 536, 631, and 290 m^3/s, respectively. These values underscore the river's critical role in supplying water resources for drinking, agriculture, industry, and power generation in southwestern Iran. Field investigations have revealed a progressive decline in the Water Quality Index (WQI) along the river, particularly starting from 140 km north of Ahvaz, primarily due to the discharge of substantial volumes of industrial and agricultural wastewater.[31] The location of the Karun River and the sampling points used in this study have been shown in Figure 1.

Sampling Strategy and Data Collection

This study was categorized as applied research, grounded in both theoretical and practical foundations. The selected study area along the Karun River extended from Ahvaz to Khorramshahr. Sampling was conducted during January, April, July, and October 2023, resulting in a total of 40 samples. Sampling locations were chosen based on their distance from the city of Ahvaz, ranging from 80 km north to 40 km south. Water samples were collected at various depths using a Nansen sampler, while sediment samples from the riverbed were obtained using an Ekman grab sampler. Phosphate concentrations were determined via a reaction with molybdate ions, while nitrate levels were measured after reduction with cadmium to nitrite, followed by a reaction with sulfanilic acid. Nitrite concentrations were also measured using sulfanilic acid. Both nitrate and phosphate levels in sediments were analyzed by spectrophotometry according to standard methods. Nitrate ion concentrations were assessed using Program 355 at a wavelength of 500 nm, while Program 371 was used at 507 nm for nitrite ions, applying the Nitraver 3 reagent. Additional parameters—including nutrient levels, pH, total suspended solids (TSS), DO, and electrical conductivity (EC)—were measured seasonally at the ten sampling sites. Data on aquatic species (plants, invertebrates, and fish) were collected from the Environmental Protection Agency. Hydraulic parameters (such as flow velocity, inflow, and discharge) were provided by the Water and Wastewater Organization, and climatic data (e.g., temperature and wind speed) were obtained from the Meteorological Organization.

Nutrients and Water Quality Analysis

To determine the concentrations of phosphate and nitrate in the water samples, a Hach DR2800 spectrophotometer was used. Prior to analysis, the samples were filtered and diluted as necessary. A 10 mL aliquot of each sample was placed into the appropriate cuvettes, and the device was set to measure phosphate (PO_4^{3-}) concentrations. For nitrate analysis, ultraviolet (UV) absorbance was measured at a wavelength of 220 nanometers (nm). Since organic compounds also absorb at this wavelength, a secondary measurement at 275 nm was conducted to correct for organic interference. Phosphate concentrations were measured at a wavelength of 720 nm.[32] Additional water quality parameters were measured using standard instruments and methods: pH was determined using a pH meter; TSS were measured using the gravimetric method; and EC was measured with an EC-meter, with results reported in μS/cm.

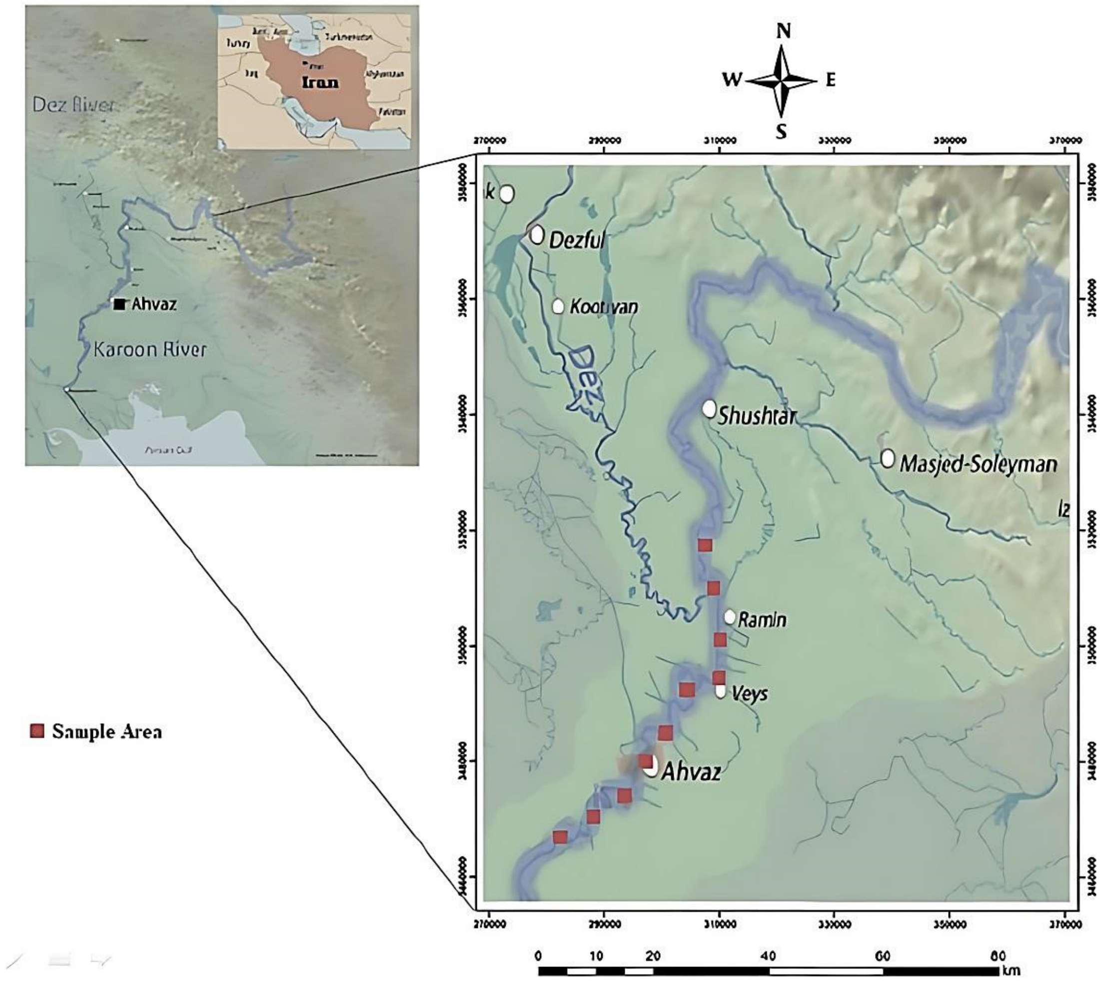

Figure 1. Geographical Location of Karun River and Sampling Points

AQUATOX Model Calibration and Verification

Before applying the AQUATOX model to assess the environmental fate of nutrients and analyze their impacts on aquatic organisms and ecosystem conditions in the study area, it was essential to calibrate and validate the model. This process focused on accurately simulating nutrient concentrations as well as hydraulic flow characteristics, including flow rate and water depth. For the calibration and validation of nutrient concentration simulations, data obtained from the sampling campaigns conducted during the study period were used. In contrast, the validation of flow rate and depth simulations was based on measurements recorded at regional hydrometric stations. To assess the model's performance and accuracy, both graphical comparisons (between observed and simulated values) and statistical metrics were employed. These included the root mean square error (RMSE), Nash–Sutcliffe efficiency (NSE) coefficient, and mean absolute error (MAE), among others.[33] The steps involved in modeling the biological fate of nutrients in the Karun River using the AQUATOX model are outlined in Table 1.

The type of aquatic ecosystem intended for simulation is a "Stream," which refers to a river characterized by flowing water. The AQUATOX model is capable of accurately simulating the dynamics of water flow, nutrient transport, and their impacts on the aquatic ecosystem.[34] In this study, the simulation period was set from September 20, 2022, to September 20, 2023. The average nitrogen concentration 2.76 mg/L, while phosphorus averaged 0.89 mg/L. The dominant plant species in this ecosystem was Eunotia.[35]

Invertebrates present in the ecosystem include Peri Hi-Nut Dia warm, freshwater snail (*Lymnaea stagnalis*), leech (*Hirudo medicinalis*), and segmented worms (Polychaeta).[36]

Peri Hi-Nut Dia warm: This invertebrate may serve as an indicator of water quality and nutrient levels.

Freshwater snail (*Lymnaea stagnalis*): These snails act as primary consumers in the food chain and can aid in the decomposition of organic matter.[37]

Leech (*Hirudo medicinalis*): This type of worm is utilized as a biological indicator for assessing biodiversity and water quality.[38]

Segmented worms (Polychaeta): These worms also play a role in nutrient cycling and the decomposition of organic materials.

The next section focuses on the fish species inhabiting the Karun River. The mentioned fish include Tigris asp (*Leuciscus vorax*), Yellow Barbell (*Carasobarbus luteus*), Yellowfin (Luciobarbus xanthopterus), Common Carp

Table 1. Stages of Modeling the Biological Fate of Nutrients in the Karun River by the AQUATOX Model

Input Parameters	Input Data
Simulation type	Stream
Simulation period	20/09/2022- 20/09/2023
Nutrients (mg/L)	N = 2.76 P = 0.89
Vital gases	$CO_2 = 0.5$ $O_2 = 5.7$
Sediments	Labelle detritus: 13.5 g/m^2 dry Refractory: 67.5 g/m^2 dry
Plants	Eunotia Peri Hi-Nut Dia Warm
Invertebrates	Freshwater snail (*Lymnaea stagnalis*), Leech (*Hirudo medicinalis*), Segmented worms (*Polychaeta*)
Fish	Tigris asp *(Leuciscus vorax*), Yellow Barbell (*Carasobarbus luteus*), Yellowfin (*Luciobarbus xanthopterus*), Common Carp (*Cyprinus carpio*), Anguilloidei (*Anguilla anguilla*)
Site characteristics	Length of river: 950 km Surface area: 24.7 km^2 Mean depth: 3.7 m Max depth: 21 m Mean evaporation: 2500 mm/year
Water volume	14 billion cubic/meters
Water temperature	24 °C
Wind loading	5.8 m/s
Light loading	518 Ly/d
Water pH	7.51
Inorganic solids	TSS: 93.6 mg/L
Chemicals	31 types
Inflow precipitation	Daily inflow
Direct precipitation	267 mm
Point-source loading	Oil & Steel
Nonpoint-source loads	Vehicles

(*Cyprinus carpio*), and Anguilloidei (*Anguilla anguilla*).

The total volume of water in the Karun River is considered to be 14 bm^3 per year, serving as a one-year input for the study. The volume of water has a direct impact on the concentration of nutrients and pollutants present in the river. The average annual water temperature in the Karun River, as reported in this study, is 24 °C. The wind speed is measured at 5.8 m/s. Wind speed can significantly influence gas exchange (such as oxygen) and surface water movements, which can facilitate the distribution of nutrients and pollutants across the water's surface. The light intensity is recorded at 518 lumens per day. Light is a vital factor for the photosynthesis of aquatic plants, and the amount of light received can directly affect primary production and the growth of these plants, ultimately influencing nutrient cycling.

The pH level of the water is 7.51, and the TSS concentration stands at 93.6 mg/L. Point source loading includes pollution from oil and metal industries, while non-point source loading is attributed to vehicles. Non-point source pollution typically arises from human activities, such as road traffic, which can lead to the introduction of pollutants into the river. This type of loading is generally more diffuse and less controllable.

These parameters and data play a crucial role in determining the environmental fate of nutrients in the Karun River. Utilizing the AQUATOX model with these inputs allows for more accurate simulations and deeper analyses of the river's environmental status.

In addition to the main scenario, two alternative scenarios have been defined for modeling purposes:

- Scenario 1 (S1): A 15% reduction in total nutrients (nitrates and phosphates) in the water of the Karun River.
- Scenario 2 (S2): A 15% increase in total nutrients (nitrates and phosphates) in the water of the Karun River.

The selection of these scenarios was based on long-term fluctuations in nutrient levels. The results obtained from these two scenarios were also compared.

Biodiversity Indicator Determination

To better assess the ecological status of the Karun River and evaluate the effects of nutrient levels on aquatic life, four biodiversity indices were employed: Shannon, Simpson, Camargo, and Brillouin. These indices were selected based on their relevance and compatibility with the output variables generated by the AQUATOX model.

Shannon Index Calculation

This index not only considers the number of species but also considers their abundance distribution. The higher the H value, the greater the biodiversity. Its values are calculated based on equation 1:

$$H' = -\sum (p_i \cdot \ln(p_i)) \qquad (1)$$

Where p_i = the frequency ratio of species i to the total frequencies; $H > 1 > 0$: low diversity; $H > 3 > 1$: moderate diversity; and $H' > 3$: high diversity.[39]

Simpson Index Calculation

Simpson's index refers to the probability that two random samples from the same population are selected from the same species. This index specifically focuses on dominant species and can help identify the extinction risk of certain species. Its values are calculated through equation 2:

$$D = \sum (p_i^2) \qquad (2)$$

Where p_i = frequency ratio of species *i* to total frequencies; D close to 0: high diversity; and D close to 1: diversity is low.[40]

Camargo Index Calculation

The Camargo index is designed to evaluate water quality and the state of aquatic ecosystems. This index examines biodiversity with water quality and pollution. This index is calculated through equation 3:

$$C = \frac{NS}{NT} \tag{3}$$

Where:
NS = Number of pollution-sensitive species
NT = Number of total species
C < 0.5: low quality
0.5 < C < 0.75: medium quality
C > 0.75: High quality.[41]

Brillouin Index Calculation

The Brillouin index is another biodiversity index that is especially used in small and rare populations. This index is calculated according to the number of species and their abundance. This reed index is calculated based on equation 4:

$$H_b = \ln\left(\frac{N}{\Pi_{n_i}}\right) \tag{4}$$

Where: N = total number of samples; n_i = number of samples related to species *i*; and Interpretation: higher values indicate more diversity and a more complex population structure.[42]

In addition to the main scenario, the index values were determined and compared in two possible scenarios.

Results and Discussion

In this research, the environmental fate of nutrients in the Karun River was investigated using the AQUATAX model. The results obtained from biological indicators in 10 sampling areas in Figure 2 show the state of biodiversity and the quality of the water ecosystem of this river.

The average Shannon index value (Figure 2A) was 1.295, with a standard deviation of 0.067. The highest value was recorded at sampling site 1 (upstream of Ahvaz), reaching 1.417, while the lowest was observed at site 7 (near the Fifth Bridge) with a value of 1.213. These figures indicate a moderate to low level of biodiversity within the Karun River ecosystem. In comparison, Chowdhury et al in 2011 reported a Shannon index of 3.13 for the Naaf River in Bangladesh, suggesting high biodiversity.[43] Similarly, Shahnawaz et al in 2010 reported values ranging from 2.8 to 3.2 in the Bhadra River, India.[44] In another study, in 2022 Shapoori et al reported a Shannon index of 1.92 for the Karaj River.[45] These comparisons highlight the relatively low biodiversity levels in the Karun River. The Simpson index (Figure 2B) showed variability across stations: 0.439, 0.541, 0.510, 0.753, 0.603, 0.662, 0.689, 0.545, 0.587, and 0.539. The highest value (0.689) was observed at site 7, while the lowest (0.439) was at site 1. The average Simpson index was 0.585, with a standard deviation of 0.0586. Higher values suggest the dominance of a few species, indicating reduced biodiversity. This trend may reflect environmental stressors or altered ecological conditions in urban sampling zones.[46] Similar patterns were observed in studies by Xu et al[47] and Nur Hasyimah et al,[48] suggesting species dominance in areas experiencing nutrient fluctuations or pollution, such as those affected by algal blooms.[49] Camargo index values (Figure 2C) for

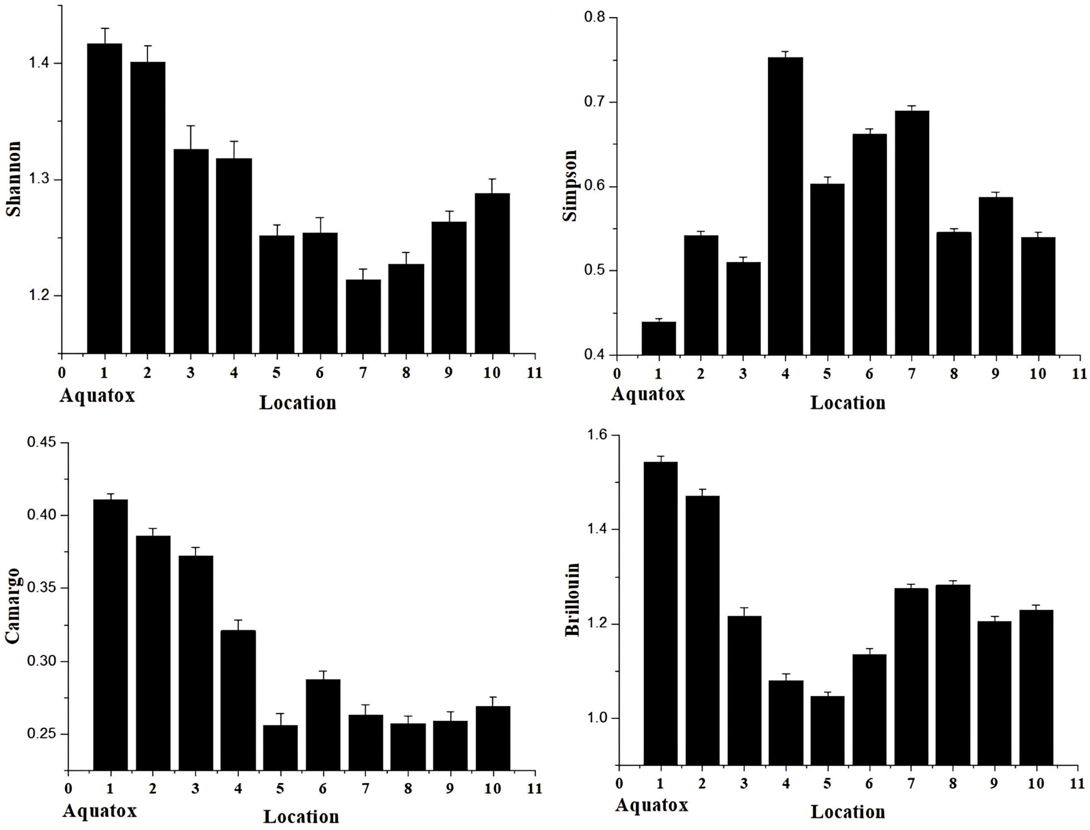

Figure 2. Results of the Values of Biological Indicators in 10 Sampling Areas of Karun. Index of Shannon (2A), Simpson (2B), Camargo (2C) and Brillouin (2D)

the ten sites were: 0.411, 0.386, 0.372, 0.321, 0.256, 0.287, 0.263, 0.257, 0.259, and 0.269. The average was 0.3081, with a standard deviation of 0.057. These low values point to reduced biodiversity and potential ecological degradation, likely owing to pollution or habitat disruption.[50] Brillouin index values (Figure 2D) ranged from 1.045 to 1.543, with the average at 1.247 and a standard deviation of 0.132. Higher values were found at sites with better environmental conditions, supporting the inference that biodiversity is higher upstream and declines in urban or polluted areas. In conclusion, the biodiversity indices collectively indicate a moderate to low biodiversity status in the Karun River. The upstream sections near Ahvaz exhibited more favorable conditions and biodiversity, while downstream urban areas showed increased species dominance, likely driven by anthropogenic stressors.

AQUATOX Model Results

After entering the data into the model based on the items mentioned in the materials and methods section, the estimated output values for nitrate, phosphate, DO, and algal biomass are presented. The simulation period was from September 20, 2022, to September 20, 2023. Therefore, the forecast period was related to the same time from 2023 to 2024. The estimated values for nutrients, algal biomass, and DO have been presented in Figure 3.

The findings indicate that the average annual concentrations of phosphate in the Karun River water were estimated at 4.55 mg/L, while the nitrate concentration was approximately 23.64 mg/L. Analysis of the simulation curves revealed that nitrate and phosphate levels peaked during October. The autumn rains, which wash nutrients from agricultural lands into the river, are likely contributing factors to these elevated levels.[51] In addition, agricultural activities tend to increase during this season, and the use of chemical fertilizers can further elevate nitrate and phosphate concentrations in the water.[52] In contrast, nitrate and phosphate levels reach their lowest points in January, February, and March. The increased river flow during this period plays a crucial role in diluting nutrient concentrations. Overall, the results from the AQUATOX model demonstrated seasonal fluctuations in nitrate and phosphate levels in the Karun River, influenced by both natural and anthropogenic factors. These fluctuations can significantly impact water quality and aquatic ecosystems. In comparison, average nitrate and phosphate levels along the Texas River were reported to be between 9-12 mg/L and 1-2 mg/L, respectively.[53] Furthermore, total nitrate and phosphate concentrations in samples from the Qazal Ozon River have been reported to be below 15 mg/L.[54] These findings suggest that the Karun River experiences higher levels of nitrate and phosphate pollution compared to other reported studies. This elevated nutrient load is largely attributed to agricultural runoff and the discharge of industrial wastewater. The results also indicate that the average annual concentration of DO in the Karun River

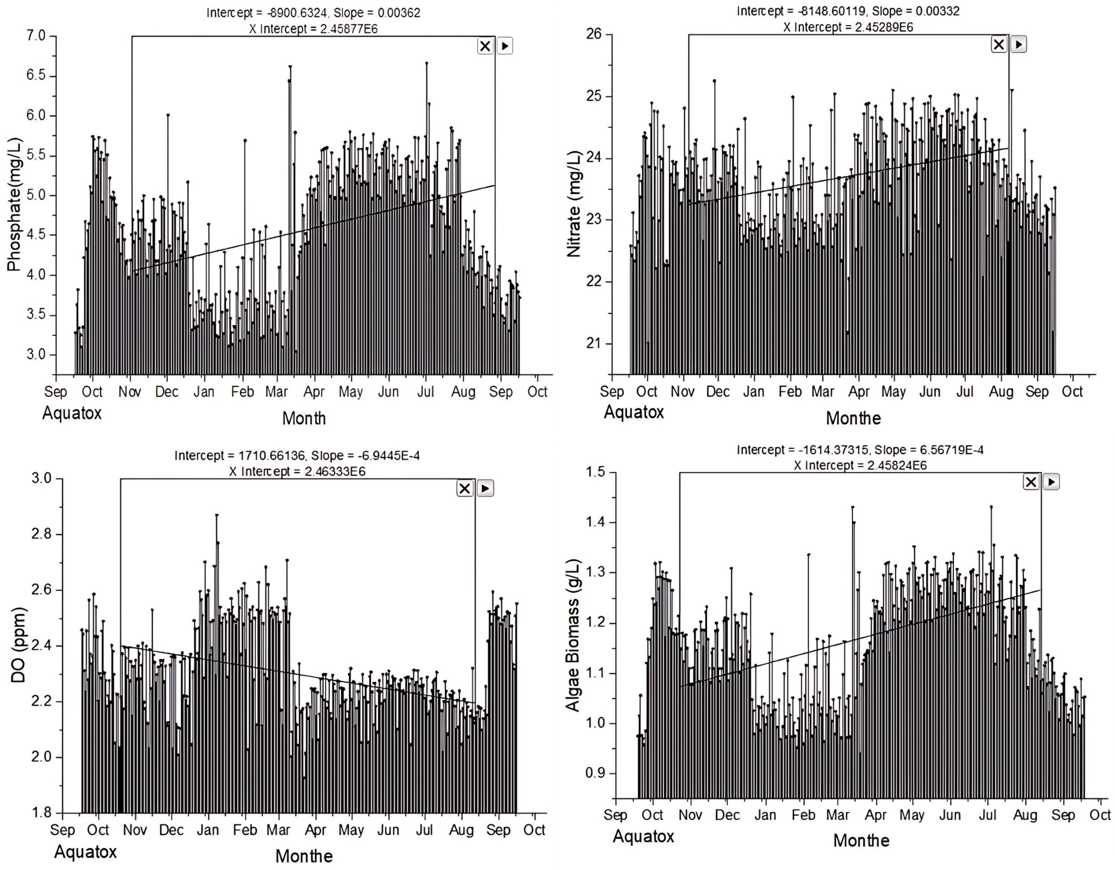

Figure 3. Estimation of Annual Amounts of Phosphate (3A), Nitrate (3B), Dissolved Oxygen (3C), and Algal Biomass (3D) by the AQUATOX Model in the Water of the Karun River

is approximately 2.31 mg/L, while algal biomass averages around 1.16 g/L. Analysis of simulation curves shows that DO levels peak during the months of January, February, and March. This seasonal increase may be due to lower water temperatures and reduced metabolic activity of algae and other aquatic organisms during winter, which enhances oxygen solubility. Moreover, higher rainfall during these months likely increases river flow, which can improve organic matter decomposition and contribute to greater oxygen availability[55]

From April to August, there is a significant decline in DO levels. This decrease is primarily because of rising temperatures and increased metabolic activity of algae. During this period, as light and temperature rise, algae begin to grow rapidly, leading to higher oxygen consumption for their respiratory processes. This phenomenon results in a reduction of DO levels in the water.[56] The results from the AQUATOX model reveal a complex interaction between DO and algal biomass in the Karun River. While increasing temperatures and light levels promote algal growth and lead to a decrease in DO, cooler conditions, and higher rainfall contribute to maintaining oxygen levels. These seasonal fluctuations not only have significant implications for water quality but can also impact aquatic ecosystems and the health of aquatic life. The average algal biomass measured was 1.16 g/L, with values exceeding 1 g/L indicating a relatively high level of pollution in aquatic ecosystems.[57,58] Following the presentation of the nutrient fate analysis based on the current scenario, the AQUATOX model also provided insights into nutrient fate under two hypothetical scenarios: Scenario S1, which involves a 15% reduction in nutrient levels in the water, and Scenario S2, which entails a 15% increase in nutrient levels in the Karun River. The use of these scenarios allows for a sensitivity analysis of the ecological system of the Karun River in response to changes in nutrient concentrations. Both reductions and increases in nutrient levels can play a role in biochemical and biological processes, enhancing our understanding of the complexity of ecosystem responses to fluctuations in nutrient availability.[59] The proposed scenarios hold significant value from a management perspective. Variations in pollution loads or nutrient inputs in rivers are often driven by human activities such as agriculture, industrial operations, and wastewater discharge. Therefore, modeling and simulating these scenarios offer a practical approach to informed decision-making for the sustainable management of water and environmental resources. By analyzing these scenarios, it becomes possible to evaluate their effects on nutrient distribution and fate within the aquatic ecosystem, biological responses (such as algal growth, biodiversity, and water quality), and the progression of these dynamics over time. The simulation results for algal biomass and total nutrient concentrations under scenarios S1 and S2 in the Karun River have been indicated in Figure 4.

The results obtained from these two scenarios illustrated the direct and linear impacts of nutrient changes on the total nutrient concentrations in the river water. In the first scenario, the average total nutrient concentration decreased to 23.9 mg/L. This reduction in nutrients may be attributed to a decline in natural or anthropogenic inputs to the river, leading to a deficiency of essential elements required for algal growth.[60] Consequently, the average algal biomass also dropped to 0.71 g/L. This situation indicates that the decrease in nutrients has directly negatively affected algal growth, resulting in reduced biomass production. Algae, as photosynthetic organisms, require nutrients such as nitrogen and phosphorus, and any reduction in these elements can significantly impact their growth and reproduction.[61]

In the second scenario, assuming a 15% increase in nutrient levels, the average total nutrient concentration rose to 32.42 mg/L. This increase may stem from higher nutrient inputs from various sources, such as domestic wastewater, agricultural runoff, or precipitation, which enriches the river water. The results indicate that in this scenario, the average algal biomass increased to 1.6 g/L. This rise in algal biomass is a direct result of the enhanced availability of nutrients, allowing algae to grow and reproduce more effectively.

A positive and linear relationship between nutrient concentrations and algal biomass was found. In other words, higher nutrient levels in the water correlate with

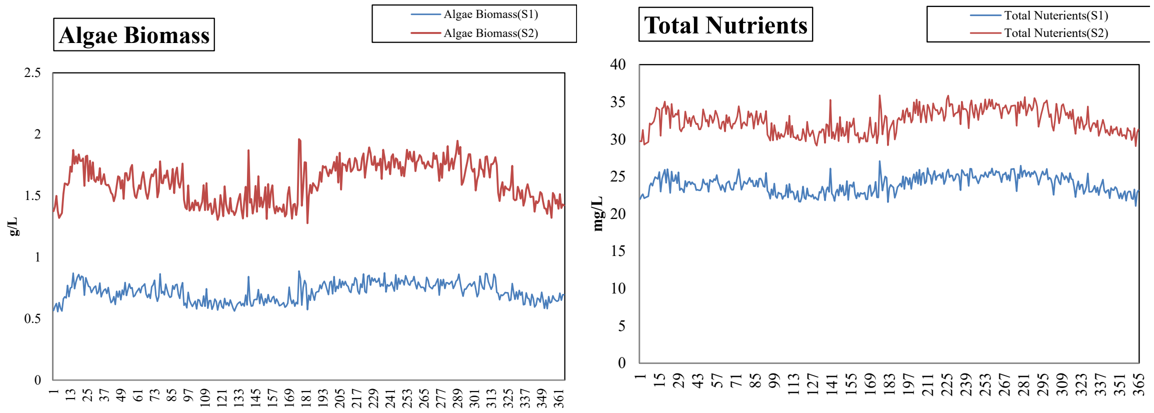

Figure 4. Results of Simulation of Algal Biomass (A) and Total Nutrients (B) by AQUATOX Model in Two Scenarios S1 and S2 in Karun River

increased algal growth. This underscores the importance of controlling and managing nutrient inputs to rivers, as excessive nutrient enrichment can lead to eutrophication-a phenomenon that poses serious environmental consequences, including deteriorated water quality, hypoxic conditions, and damage to aquatic ecosystems. The simulation results for biological indices based on the AQUATOX model, including Shannon's index (5A), Simpson's index (5B), Camargo index (5C), and Brillouin index (5D), have been presented in Figure 5.

The results obtained from simulations conducted using the AQUATOX model to assess the environmental fate of nutrients in the Karun River demonstrated noticeable impacts of nutrient concentration changes on the biodiversity of this aquatic ecosystem. In the first scenario, where a 15% reduction in total nutrients (nitrate and phosphate) was considered, the average biodiversity indices were notably higher than in the second scenario. The average Shannon index in the first scenario was 1.48, compared to 1.01 in the second scenario. This finding indicates a greater diversity of species under conditions of reduced nutrient concentrations. The decrease in nutrients may lead to a reduction in the growth of algae and plant species that typically thrive in nutrient-rich conditions, thereby creating more space for other species, which in turn enhances biodiversity.[62]

Similarly, the Simpson index showed values of 0.46 in the first scenario and 0.79 in the second. The increase in species diversity observed in the first scenario suggests that lower nutrient levels are associated with a higher likelihood of rare and specialized species existing, which can contribute to ecosystem stability. In other words, conditions become more favorable for the survival and evolution of various species. Regarding the Camargo index, the values obtained were 0.515 for the first scenario and 0.22 for the second, indicating that as nutrient levels decrease, the ecosystem moves toward greater balance and stability. This situation may arise from reduced competition among species, allowing more species to survive and thrive.

The Brillouin index also yielded similar results, showing values of 1.8 in the first scenario and 1.08 in the second. This index further emphasizes the higher species diversity under reduced nutrient conditions, highlighting that biodiversity is influenced by nutrient concentrations.

The findings of this study underscore that changes in nutrient concentrations can profoundly affect the biodiversity of aquatic ecosystems. A reduction in nitrate and phosphate concentrations not only enhances biodiversity but may also contribute to better ecosystem stability. Conversely, an increase in nutrient levels can lead to excessive algal growth and a decline in species diversity, posing a threat to ecosystem health.

Conclusion

The results of this study underline the critical role of nutrients in shaping aquatic ecosystems and their direct impact on biodiversity in the Karun River. Using the AQUATOX model, the environmental fate of nutrients, particularly nitrate and phosphate, was examined, revealing that elevated concentrations significantly degrade water quality and reduce species diversity. In the scenario with a 15% reduction in nutrient inputs, the model showed a notable increase in biodiversity, reflected by improvements in the Shannon, Simpson, and Camargo indices, indicating enhanced ecological balance and

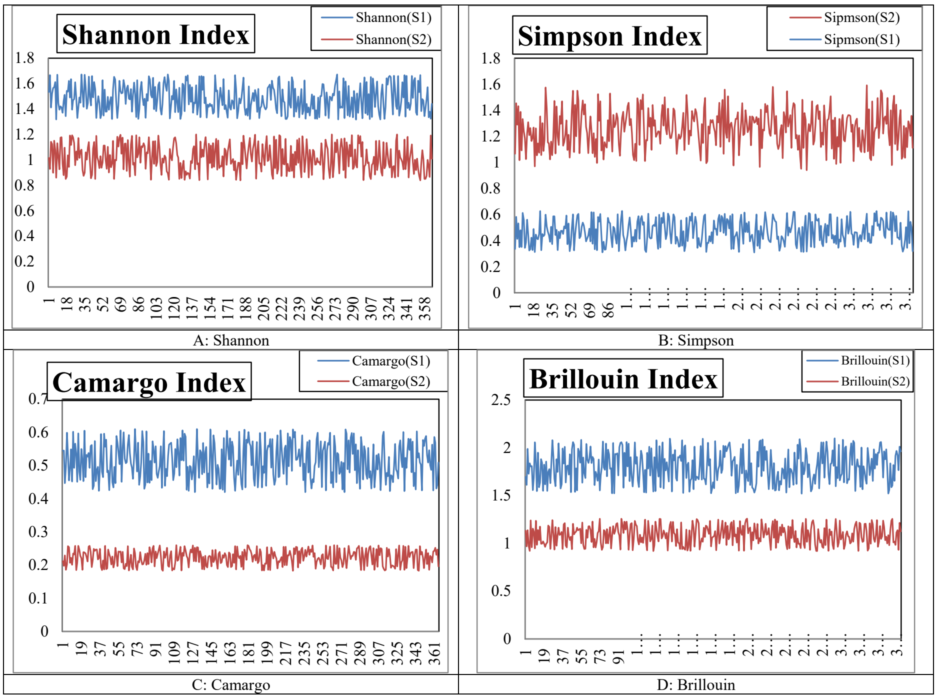

Figure 5. Simulation Results of Biological Indicators Based on the AQUATOX Model in the Karun River: Index of Shannon (5A), Simpson (5B), Camargo (5C) and Brillouin (5D)

stability. Conversely, nutrient-rich conditions promoted species dominance, diminishing overall biodiversity and ecological health. These findings highlight the importance of nutrient management as a key strategy for protecting aquatic ecosystems. Moreover, physicochemical and biological data revealed poor water quality in areas affected by industrial and agricultural discharges, emphasizing the need for targeted interventions. To support effective management, future research should focus on implementing a comprehensive monitoring program that tracks both nutrient levels and biological indicators over time. Identifying specific pollution sources—whether from agriculture or industry—will enable the development of localized solutions to reduce nutrient loading. Ultimately, the study calls for continuous monitoring, robust pollution control, and integrated water resource management to safeguard and restore the ecological integrity of the Karun River.

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Authors' Contribution

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Data curation: Mohsen Davoudi.
Investigation: Mohsen Davoudi.
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Validation: Azita Koushafar, Fatemeh Karimi Organi, Hosein Fathian, Hadide Maboudi.
Visualization: Hosein Fathian.
Writing–original draft: Mohsen Davoudi.
Writing–review & editing: Mohsen Davoudi.

Competing Interests

The authors declared no conflict of interest.

Ethical Approval

There were no ethical considerations to be considered in this research.

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