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RESEARCH ARTICLE

Assessment of the trophic level and self-cleaning ability of water polluted by nutrients in the Zarafshan River, Uzbekistan

Shobegim SHOERGASHOVA [1,*], Erkin KARIMOV [2], Luqmon SAMIEV [3], Bakhtiyor KARIMOV [4]

[1] *National Research University, Ecology and Water Resources Management Department, Tashkent Institute of Irrigation and Agricultural Mechanization Engineers 100000, 39 Kori Niyazi st., Tashkent, Uzbekistan*
[2] *Tashkent State Agrarian University, Zootechnics and Veterinary Department, 111218, 2 University st., Tashkent province, Uzbekistan*
[3] *Research Institute of Environment and Nature Conservation Technologies, 100043, 7-A Bunyodkor ave., Tashkent, Uzbekistan*
[4] *Fergana Polytechnic Institute, 150100, 86 Fergana st., Fergana, Uzbekistan*

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ABSTRACT

The aim of this study was to assess the water quality of the Zarafshan River through a comprehensive evaluation of its trophic state, nutrient loads, self-cleaning ability, and the toxicity of nitrogen compounds for hydrobionts. This is the first study of its kind conducted on the Zarafshan River. The trophic state was determined by nutrient content, the self-cleaning ability was assessed using the nitrification index method, and the toxicity of nitrogen compounds was evaluated using the aggregation index. Eutrophication was observed at all studied river Gauging Stations (GS), primarily caused by high nitrate nitrogen concentrations. The self-cleaning ability of the water was classified as "high" in the lower reaches of the river and "medium" along its length. Major pollution sources were identified as agricultural influence from Siab collector (GS-3) and industrial wastewater from Navoiazot chemical factory (GS-8). It is recommended to intensify the monitoring of total phosphorus at GS-3 and mineral nitrogen at GS-8, alongside implementing measures to prevent anthropogenic pollution to mitigate nutrient contamination in the Zarafshan River.

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INTRODUCTION

The problem of water pollution in the world is becoming urgent. Scientific research on water quality and its management is being carried out in the world. In this direction, it is directly related to the achievement of several Sustainable Development Goals (SDGs) set by the United Nations to create a more just, sustainable and prosperous world. In particular, water quality plays a key role in achieving SDG 3: "Good health and well-being" and SDG 6: "Clean water and sanitation" [1]. At the same time, the continuation of the trend of degradation of water ecosystems and reduction of resources in terms of quantity and quality is considered as an urgent task to eliminate the risk of shortage of fresh and clean water for all water consumers. Surface waters are extremely susceptible to anthropogenic pollution caused by urbanization, industrialization, and intensive land use practices[2, 3]. Agriculture changes the natural soil cover and increases the flow of organic compounds, nutrients, toxic agrochemicals and other pollutants into aquatic ecosystems [4 -9]. The use of various mineral fertilizers in agriculture, the increasingly important role of various chemicals in everyday life, and the often insufficiently treated municipal and industrial wastewaters are discharged into rivers and sewers, are intensively pollute water resources. Currently, most of the mineral fertilizers used in the fields and the chemical poisons used to protect the plants lead to surface and underground water pollution. These impacts contribute significantly to the process of water eutrophication, which is a critical global concern [10]. The increase in agricultural land use, urban land use, and wastewater discharge has a very adverse effect on the trophic status of aquatic ecosystems and the quality of surface waters [8, 11, 12]. Eutrophication, driven by the enrichment of water bodies with nitrogen and phosphorus compounds, accelerates the growth of algae and aquatic plants, disrupting natural ecosystem processes. This phenomenon is a widely recognized indicator of aquatic ecosystem health, with water bodies classified into oligotrophic, mesotrophic, and eutrophic states based on their trophic status [13 – 16]. The eutrophication process of

* Corresponding Author: sh.shoergashova@tiiame.uz (Shobegim Shoergashova)

streams, rivers, lakes, reservoirs, and coastal areas is one of the most critical consequences of anthropogenic activity [4]. During eutrophication, toxic cyanobacteria may bloom in water bodies, and green macroalgae grow in coastal areas [17, 18]. These processes disrupt natural ecosystem functions and significantly reduce the self-purification capacity of water bodies, creating long-term challenges for water quality management. The self-purification capacity of water bodies also holds global significance. In many studies, it has been reported that vegetation cover and physical-chemical environmental factors enhance natural self-cleaning processes. Most higher aquatic plants have algicidal properties that inhibit the development of blue-green algae that cause the blooming of water [19]. At the same time, competition for nutrients between higher and lower plants also plays a significant role. To better understand these dynamics, key indices like the nitrification index and the aggregation index are employed. The nitrification index represents the percentage ratio of nitrified nitrogen compounds (nitrite and nitrate) to the total nitrogen present in a water body. It is calculated to assess the efficiency of the nitrification process, which is essential for the transformation of ammonia into less toxic nitrogen forms. The nitrification index indirectly measures how well the ecosystem is cycling nutrients, an essential part of natural self-purification. Efficient nutrient transformation helps maintain ecological balance. The aggregation index, on the other hand, is used to measure the toxicity levels in water bodies. It reflects the combined effects of various pollutants on the aquatic ecosystem, particularly their influence on biological and chemical interactions. A high aggregation index typically indicates elevated levels of toxic substances, which can inhibit self-cleaning processes by disrupting microbial communities and nutrient cycling. In this respect, the ecological analysis of changes trophic level and self-cleaning ability of water polluted by nutrients are of great scientific and practical importance.

The study area focuses on the Uzbek part of the Zarafshan River in Central Asia. In Uzbekistan, along with the Amudarya and Syrdarya the Zarafshan River is one of the main water sources [20]. The Zarafshan River is used for various purposes: industry, municipal water use, and agriculture. The flow of the Zarafshan River is of great economic importance. Tajikistan is developing the hydropower resources of the rivers of the Zarafshan basin, the potential of which is more than 20 billion kWh, and for Uzbekistan it is a source of irrigation for 560 thousand hectares of fertile irrigated lands in the Samarkand, Navoi and partially Jizzakh, Kashkadarya and Bukhara regions [21].

As a result, it is polluted by the discharge and return waters of several sources that require thorough monitoring. A review of the literature on anthropogenic pollution in the Zarafshan River reveals investigations into spatio-temporal trends of nutrients, fluorine, heavy metal pollution, water mineralization changes from 2002 to 2010 [22, 23] and 2000-2016 [24]. Additionally, long-term water quality trends since the 1960s and assessment of spatio-temporal trends variations of water quality parameters in the Zarafshan River were examined [7, 25]. Assessment of water quality and the aquatic ecosystem's state based on communities of diatoms for the lower reaches of the Zarafshan River (2009-2015) were studied [26]. However, the analysis of the existing data on the pollution of the Zarafshan River have revealed the absence of studies on the trophic level and self-cleaning ability of water polluted by nutrients of the Zarafshan River. The novelty of this research lies in being the first comprehensive study to investigate these critical aspects, filling a significant gap in the understanding of the river's ecological processes.

The research aimed to determine the trophic level and the ability to self-purify the water of the Zarafshan River with nutrients. The following objectives were set: to assess the trophic status of waters based on the content of nutrients, to determine the self-cleaning ability of water, and to assess the toxicity of nitrogen compounds for hydrobionts.

MATERIALS AND METHODS

The Zarafshan River is a transboundary river, with its upstream located in Tajikistan and its middle and downstream sections passing through Uzbekistan. The Zarafshan River originates in the Alai mountains in Tajikistan as the Matcha River and later joins the Fondarya near Ayni. In the northwest of Uzbekistan, it creates a unique oasis, in the valley of which the city of Samarkand is located. It passes through the arid territories of Kattakurgan and Navoi, turns to the southwest of the country, carrying its waters through the cities of Bukhara and Karakul. It is approximately 520 km long with an average discharge of 131.6 m^3/s (2010-2022) [25, 27]. It is the lifeline for the culturally and economically important Uzbek oases of the Silk Road - Samarkand and Bukhara [22, 23, 28, 24]. The Zarafshan River is a representative of glacier-snow-fed rivers. An increase in water consumption is observed in April and generally increases every month until July, when it passes the flood period. The decline in runoff begins in August and continues until February-March when it reaches its minimum [29]. The study area was the Zarafshan River in Uzbekistan where many territories in the arid climate zone are focused mainly on agriculture, while industrial zones are located in adjacent desert zones [30]. The study area is presented on Figure 1.

To assess the Zarafshan River's trophic status, the state water cadaster annual book "Annual data on the regime and resources of land surface waters" [27] were used. The following are 10 GSs (Gauging Stations) of the Uzhydromet monitoring network along the Zarafshan River: 1) Ravatkhodja Dam; 2) The city of Samarkand, 1.5 km above of the Akdarya water division; 3) 0.5 km below the mouth of Siab collector; 4) 3.7 km below the mouth of Taligulyan collector; 5) 0.8 km downstream of Kattakurgan city; 6) Karadarya near to the settlement of Khatirchi (Yangirabad), near to confluence of the Karadarya and Akdarya rivers; 7) The city of Navoi, 1 km above the wastewater discharge point at the Navoiazot factory; 8) The city of Navoi, 0.8 km below the wastewater discharge point at the Navoiazot factory; 9) Above the city of Bukhara; 10) Below the city of Bukhara. The used data were for 2010-2021 (annual averages). For 2020 and 2021, there were no data from the GS-9 and GS-10. All of the investigated GSs are located in Uzbekistan. Uzhydromet conducts monthly sampling and hydrochemical analysis of indicators from each GS. The sampling process followed the requirements outlined in ISO 5667-6:2014 [32]. Spectrophotometric methods were used to quantitatively assess nitrogen compounds and phosphorus [33]. A UV-Professional (UV755) spectrophotometer, with a wavelength range of 190-1100nm, manufactured by YOKE instrument (China) was used. Moreover, pH values were measured instrumentally with a PHscan-30 ph-metr. The guidelines of Galtsova and Dmitriev were used to assess the trophic state of the water of the Zarafshan River [34, 35] (Table 1).

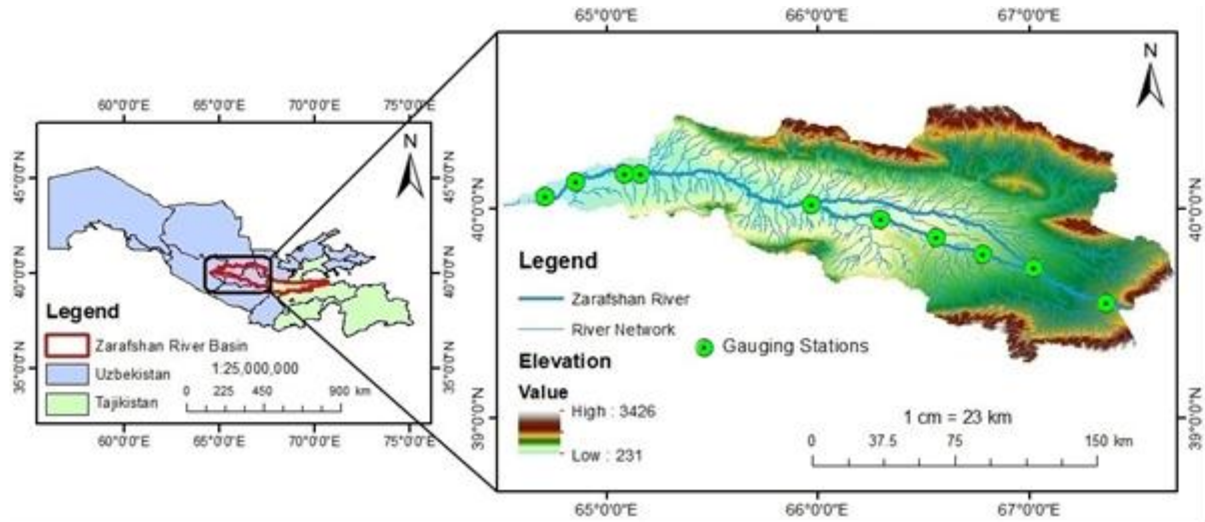

Figure 1. Study area

Table 1. Criteria of trophic waters by the content of nutrients [36, 37]

Criteria mg/L	Type of trophicity		
	Oligotrophy	**Mesotrophy**	**Eutrophy**
$N_{ammonium}$	0,025-0,15	0,15-0,6	>0,60
$N_{nitrate}$	0,01-0,3	0,3-0,5	>0,5
$N_{nitrite}$	0,01-0,015	0,015-0,06	>0,06
Mineral N (N_{min})	0,05-0,35	0,35-0,95	>0,95
Total P (TP)	0,01-0,03	0,03-0,1	>0,1

Table 2. MAC of various forms of nitrogen in the water of reservoirs

Compound, mg/L	Types of water use and limiting indicators of harmfulness are toxicological (tox.) and sanitary-toxicological (san-tox.)	
	Household drinking and cultural water (MAC_w)	**Water used for fishery (MAC_f)**
$N\text{-}NH_4$/ NH_4+	2/2,6 (san-tox.)	0,39/0,5 (tox.)
$N\text{-}NO_2$/ NO_2^-	1/3,3 (san-tox.)	0,02/0,08 (tox.)
$N\text{-}NO_3$/ NO_3^-	10/45 (san-tox.)	8,89/40 (tox.)

The self-cleaning ability of water was assessed according to the nitrification index (I_{nitr}) using the formula [38, 39, 35]:

$$I_{nitr} = \frac{N_{NO_3}}{N_{min}} \cdot 100\%, \quad (1)$$

Where:

I_{nitr} – a nitrification index;

N_{min} = mineral nitrogen concentration ($N\text{-}NO_3$ + $N\text{-}NO_2$ + $N\text{-}NH_4$), mg/L;

N_{NO3} – nitrate nitrogen concentration, mg/L;

N_{NO2} – nitrite nitrogen concentration, mg/L;

N_{NH4} – ammonium nitrogen concentration, mg/L.

The toxicity assessment of nitrogen compounds for hydrobionts was conducted using an aggregation index (I_{aggr}), which is calculated by the ratio of concentrations of nitrogen forms to their Maximum Admissible Concentration (MAC) for fishery purposes [39, 40, 35]:

$$I_{aggr} = \sum \frac{C_i}{MAC_i}, \quad (2)$$

Where:

I_{aggr} – an aggregation index;

C_i – concentrations of various forms of nitrogen, mg/L;

MAC_i – maximum admissible concentrations in water bodies used for fishery (Table 2).

Table 2 shows the MAC for ammonium, nitrite, nitrate nitrogen, and their ions in the waterbodies. The MAC varies depending on the type of water use and the limiting indicator of hazard (toxicological, sanitary-toxicological). In this research, MACs for fishery use for nitrogen compounds were used.

RESULTS

The average long-term data of mineral nitrogen and phosphorus showed noticeable increases in the concentrations of these elements in GS-3 – for total phosphorus (0.16 mg/L) and in GS-8 – for mineral nitrogen (3.3 mg/L). However, in other cases, the content of total phosphorus and nitrogen along the length of the Zarafshan River practically did not change. Its values, excluding GS-3 and GS-8, ranged from 0.012-0.029 mg/L and 0.64-3 mg/L, respectively (Figure 2).

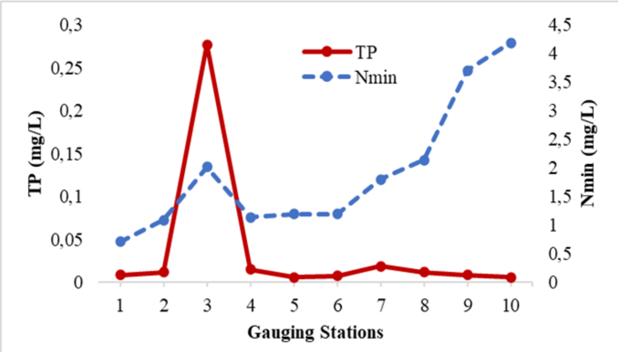

Figure 2. Average long-term dynamics of changes in mineral nitrogen and phosphorus concentrations in the Zarafshan River in 2010-2021

The concentration of ammonium nitrogen along the GSs from the maximum value of 0.59 mg/L (GS-3) decreased by 12 times downstream of the river (GS-9 and GS-10). The concentration of nitrite nitrogen, on the contrary, increased by 11 times, and the concentration of nitrate nitrogen - by seven times. The concentration of total phosphorus was the highest in GS-3 and amounted to 0.277 mg/L. GS-3 has an overall increased content of the studied nutrients compared to the rest of the GSs. Moreover, according to calculations of the ratio of N_{min} and TP, it was found that in GS-3, N:P was the smallest compared to the rest of the GSs. The values of the ratios N_{min} and TP had a wide range and varied from 7.3 to 698.3. The water of the Zarafshan River was identified as slightly alkaline according to the hydrogen pH index. GSs 7-10 show a decreasing pH trend towards a neutral environment (Table 3).

During the determination of the trophicity type of the Zarafshan River, it was found that according to the content of total phosphorus, the water in all GSs was oligotrophic, except for GS-3, where the water was eutrophied. According to the nitrogen compounds (N_{min}) content in the water, the river belonged to the eutrophied type of trophic in all GSs, except for GS-1, where the water was mesotrophic. According to the ammonium nitrogen content in the water, the river belonged to the oligotrophic type in all GSs, except for GS-2 and GS-3, where the water was mesotrophic. Based on the nitrite nitrogen content in the water, the river was determined to be oligotrophic in all GSs, except for GS-3, GS-8, and GS-10, where mesotrophy occurs. According to the nitrate nitrogen content in the water, the river was determined to be eutrophied by all the studied GSs (Figure 3).

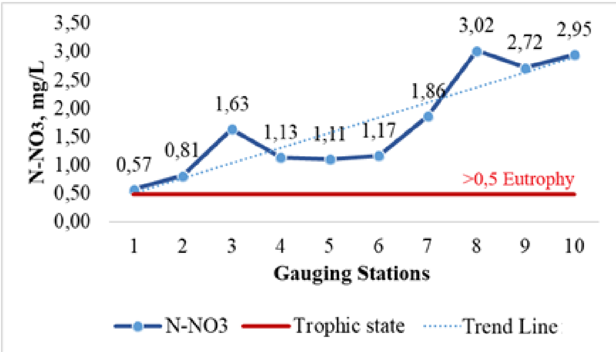

Figure 3. Long-term trophic state of the river by nitrate nitrogen content in the water

Table 3. Average annual concentrations of nutrients and pH in the Zarafshan River (2019 y.)

GS No.	Concentrations, mg/L (trophic status)					The ratio of N_{min} to TP	pH min – max - average
	N_{NH4}	N_{NO2}	N_{NO3}	N_{min}	TP		
1	0,11 (oligotrophy)	0,005 (oligotrophy)	0,59 (eutrophy)	0,71 (mesotrophy)	0,009 (oligotrophy)	78,8	7,81 – 8,21 8
2	0,18 (mesotrophy)	0,01 (oligotrophy)	0,90 (eutrophy)	1,09 (eutrophy)	0,012 (oligotrophy)	90,8	7,81 – 8,21 8
3	0,59 (mesotrophy)	0,051 (mesotrophy)	1,38 (eutrophy)	2,02 (eutrophy)	0,277 (eutrophy)	7,3	7,21 – 8,21 8
4	0,13 (oligotrophy)	0,008 (oligotrophy)	1,00 (eutrophy)	1,14 (eutrophy)	0,015 (oligotrophy)	76	7,62 – 8,21 8
5	0,12 (oligotrophy)	0,008 (oligotrophy)	1,07 (eutrophy)	1,2 (eutrophy)	0,006 (oligotrophy)	200	7,37 – 8,21 8
6	0,12 (oligotrophy)	0,008 (oligotrophy)	0,95 (eutrophy)	1,2 (eutrophy)	0,008 (oligotrophy)	150	7,81 – 8,21 8,1
7	0,09 (oligotrophy)	0,011 (oligotrophy)	1,71 (eutrophy)	1,8 (eutrophy)	0,019 (oligotrophy)	94,7	6,8 – 8,01 7,7
8	0,11 (oligotrophy)	0,056 (mesotrophy)	1,97 (eutrophy)	2,14 (eutrophy)	0,012 (oligotrophy)	178,3	6,9 – 8,17 7,6
9	0,05 (oligotrophy)	0,015 (mesotrophy)	3,66 (eutrophy)	3,7 (eutrophy)	0,009 (oligotrophy)	411,1	6,75 – 8,35 7,6
10	0,05 (oligotrophy)	0,039 (mesotrophy)	4,10 (eutrophy)	4,19 (eutrophy)	0,006 (oligotrophy)	698,3	6,95 – 8,15 7,6

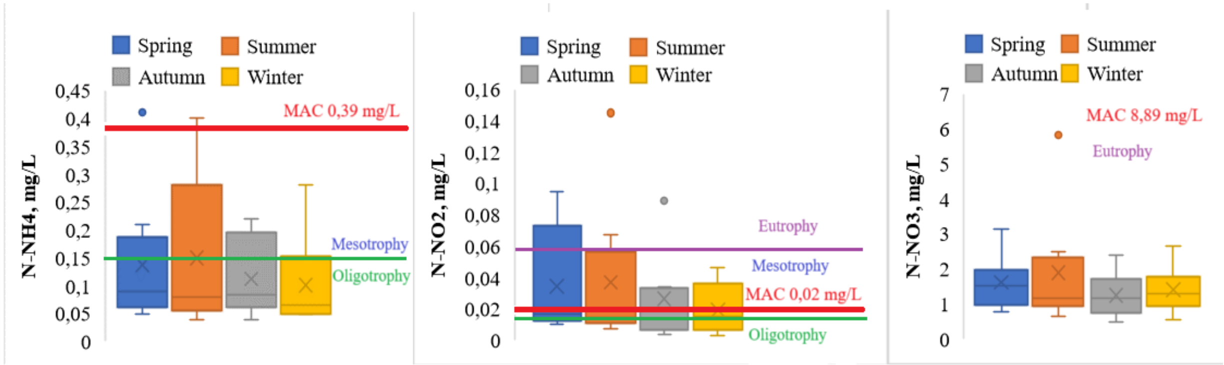

Figure 4. Long-term seasonal variations of trophic status in the river by nitrogen content

Seasonal variations of ammonium nitrogen concentrations peaked in summer above the mesotrophic threshold but below the MAC of 0.39 mg/L. Moreover, nitrite nitrogen concentrations were highest in summer, frequently exceeding the MAC to 1,2-7,25 times and in spring exceeding the MAC to 1,05-4,75 times. In both seasons, trophic status mostly was in a mesotrophic and eutrophic state. Nitrate nitrogen exhibited elevated levels in summer and spring, often surpassing the eutrophic threshold, indicating significant nutrient enrichment and a risk of eutrophication (Figure 4).

The nitrification index ranged from 68.3% to 98.9%. GSs 1, 2, 4, 5, and 6 indicated average self-cleaning ability, with values of 83,1%, 82,6%, 87,7%, 89,1% and 79,1% respectively. A high self-cleaning ability was observed in GSs 7, 8, 9, and 10. In the lower reaches of the river, in GSs 7-10, the nitrification index exceeds 92% (92%-98.9%). According to the results of our research, the lowest self-cleaning ability was observed in GS-3 - 68.3%. Calculations of the nitrification index revealed a tendency to improve the ability to self-purify in the river's lower reaches (Table 4).

Table 4. The self-cleaning ability of the Zarafshan River

GS No.	Nitrification index, %	The self-cleaning ability
1	83,1	Medium
2	82,6	Medium
3	68,3	Low
4	87,7	Medium
5	89,1	Medium
6	79,1	Medium
7	95	High
8	92	High
9	98,9	High
10	97,8	High

According to our calculations, the aggregation index of the Zarafshan River waters in 2019 was determined, with values ranging from 0.60 to 4.22. The highest aggregation index was found in GS-3, which was 4.22. There were also sharp increases in this indicator in GS-8 (3.30) and GS-10 (2.54) (Figure 5). In addition to calculating the aggregation index in 2019, an aggregation index was determined based on long-term average data (2010-2021). In this case, there was also an increase in the index in GS-3 (4.24) and GS-8 (4.67). The values of the aggregation index varied in the range of 0.57-4.67 (Figure 6).

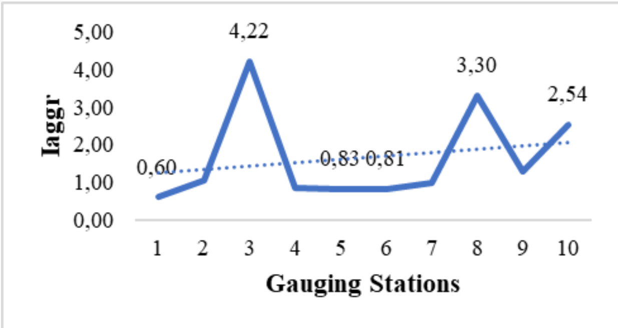

Figure 5. Aggregation index of Zarafshan River in 2019

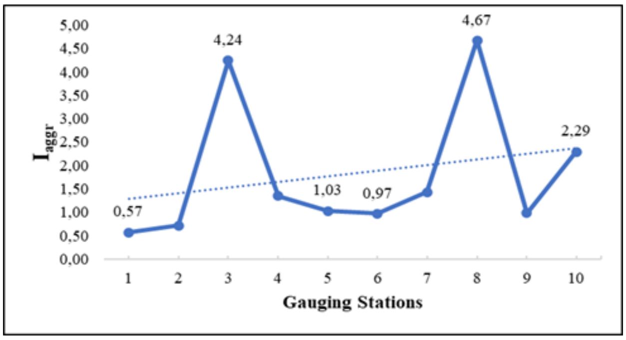

Figure 6. Long-term aggregation index of Zarafshan River for the period of 2010-2021

The dynamics of the change in the aggregation index calculated based on long-term average data reflects the exact pattern of the variability of the aggregation index, which was calculated using data for only one year (Figure 5, 6).

DISCUSSION

To assess the water quality of the Zarafshan River, three approaches were used: evaluating the trophic content of the Zarafshan River water using criteria for nitrogenous compounds and total phosphorus, determining self-cleaning ability by the nitrification index, and calculating the aggregation index while assessing the toxicity of nitrogen compounds for hydrobionts.

According to our results, it can be assumed that GS-3 is intensively polluted by the influence of agriculture because it receives discharge of return waters of the Siab collector. This leads to an increase in nutrient levels, particularly nitrogen and phosphorus, in the river. The use of fertilizers further increases nutrients in the river. In contrast, in GS-8, mineral nitrogen increased under the influence of industrial effluents from the Navoiazot chemical factory which produces mineral fertilizers, chemical reagents, and other low-tonnage chemical products.

Our findings align with those of other researchers, confirming that the load of nitrogen (N) and phosphorus (P) is noticeably increasing in water bodies due to intensive agricultural activity and industry [41]. The ratio of concentrations of nutrients in the environment influences the taxonomic and dimensional structure of the phytoplankton community. The value of the N:P ratio is considered a significant factor for the structure of algocenosis. The lowest ratio of N_{min} and TP was observed in GS-3, indicating nitrogen limitation, which may favor the growth of nitrogen-fixing cyanobacteria (blue-green algae), potentially leading to harmful algal blooms. [42]. In contrast, most of the other ratios were relatively high, suggesting phosphorus limitation. In these cases, phosphorus is likely the limiting nutrient for algal growth, potentially controlling the risk of eutrophication. This condition can also be associated with the accumulation of organic matter due to the decay of blue-green algae and runoff from agricultural land [43].

In most cases, the overall assessment of the type of trophicity by nutrients indicates eutrophy in GS-3. It may be due to the influence of agriculture from Siab collector. The return waters from agriculture entered the river, resulting in the highest mineral nitrogen and phosphorus concentration in this GS, leading to eutrophication and algal blooming. The trophic status of the tributary responds exceptionally well to changes in anthropogenic activity at the small-scale boundaries of the catchment area and also accelerates the development of the trophic status of the river [4, 44].

Our findings showed that nitrogen compounds concentrations were elevated during summer and spring seasons. Seasonal changes significantly influence nitrogen content and trophic status due to varying agricultural activity. During the irrigation season, increased agricultural runoff raises nitrogen concentrations, accelerating eutrophication. Conversely, in non-irrigation periods, nitrogen input decreases, reducing nutrient loads in the river [45, 46].

The study results indicate a weak self-cleaning ability of the water from nitrite nitrogen and a good self-cleaning ability of water from ammonium nitrogen in the river's lower reaches. The lowest self-cleaning ability was observed in GS-3, likely due to the high nutrient load originating from agricultural return waters. Excessive nutrient input, especially from fertilizers, disrupts natural processes, overwhelming the river's capacity to purify itself effectively. In contrast, the ability to self-purify improved towards the lower reaches of the river, which can be attributed to the increased density of algae species that play a significant role in nutrient uptake and biological filtration. However, the self-cleaning processes are periodically disrupted by recurrent anthropogenic factors, such as agricultural runoff, industrial discharges, and untreated wastewater entering the river system [47]. These external pressures not only increase nutrient concentrations but also reduce dissolved oxygen levels, further impairing natural purification processes. Additionally, seasonal variations in water flow, temperature, and biological activity can influence self-purification rates, often intensifying the disruption during periods of peak agricultural activity or low water discharge. Long-term exposure to elevated nitrogen and phosphorus levels may alter the composition of algal communities, reducing their efficiency in nutrient assimilation and self-cleaning. This highlights the need for stricter management of pollutant inputs and enhanced monitoring efforts to maintain the river's self-purification potential.

The highest aggregation index of the waters of the Zarafshan River was observed in GS-3 and GS-8; therefore, the high toxicity of the water for hydrobionts may reach dangerous levels in these GSs [35]. According to the average long-term data, it is possible to distinguish GS-3 and GS-8, in which the river was loaded with nutrients, since there is an increase in total phosphorus and mineral nitrogen concentration, respectively. Despite the fact that GS-8 showed a high toxicity level for hydrobionts, it had a high self-cleaning ability and a high ratio of N_{min} to TP. This suggests that agricultural activities influencing GS-3 have a greater overall impact on nutrient pollution compared to industrial activities, as GS-3 was revealed to be the most sensitive section of the river based on the assessed parameters.

For future studies, it will be advisable to calculate the trophic state index applying logarithmic transformation using the values of chlorophyll-a concentrations, Secchi disk depth, total phosphorus, and nitrogen concentrations [16, 48, 49]. Additionally, creating a GIS map of land use, fertilizer usage, and potential nutrient load pathways into the river will provide valuable insights [14, 50, 51].

CONCLUSION

As a result of the conducted research, it was discovered that the main drivers of nutrient pollution are agricultural and industrial activities. Furthermore, the section of the river 0.5 km below the mouth of Siab collector (GS-3) is considered as the most vulnerable throughout the river since the worst water quality indicators were identified here:

- The highest level of eutrophication of water in terms of the content of total phosphorus, mineral forms of nitrogen, and nitrate nitrogen;
- Lowest self-cleaning capacity;
- Formation of blue-green algae due to the low ratio of mineral nitrogen to total phosphorus;
- Elevated toxicity of water for hydrobionts.

It is established that the Zarafshan River is characterized by a medium self-cleaning ability along its length. In all GSs, the river is eutrophied according to the pollution level with nitrate nitrogen. It was identified that within the area of the Samarkand province (GS-3), the river had a significant phosphorus load for more than 10 years. After the Navoiazot factory (GS-8) was discharged, it was also highly polluted with mineral nitrogen. The load of nutrients occurs under the influence of agriculture and industry by discharging poorly treated wastewater into the Zarafshan River. Therefore, it is important to improve the technology for treating polluted industrial wastewater, enforce stricter effluent standards at the Navoiazot chemical factory, to control the use of fertilizers in agriculture and enhance public awareness campaigns to reduce nutrient pollution in the river.

This study provides a comprehensive assessment of the Zarafshan River's trophic status and self-cleaning ability, highlighting the urgent need for effective nutrient pollution management and improved monitoring efforts. By evaluating the river's trophic level and self-purification potential, the study identifies critical gaps in its capacity to recover from nutrient pollution. The methods and insights presented can be applied to other river systems facing similar challenges.

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DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

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