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SPATIAL DISTRIBUTION CHARACTERISTICS OF NITROGEN AND PHOSPHORUS NUTRIENTS IN HIGH-ALTITUDE INLAND RIVER CASCADE RESERVOIRS

The spatial distribution characteristics of nitrogen and phosphorus nutrients in cascade reservoirs in high-altitude regions are crucial for water quality management. Water samples were collected from 20 typical section points in the middle and upper reaches of the Heihe River. The research focused on the nutrient concentrations in the surface, middle, and bottom layers of the cascade reservoirs. Nutrient distribution characteristics in the reservoirs were analyzed using both longitudinal and vertical sampling. The results showed significant depth-dependent variations in nitrogen and phosphorus concentrations, influenced by hydrodynamic processes, sediment dynamics, and nutrient cycling. The overall trend for NO_2^--N, TP, and TN concentrations at the selected sampling points was consistent, with bottom-layer concentrations being significantly higher than those in the surface layer. NH_4^+-N concentration was highest in the middle layer and lowest in the bottom layer, while the COD_{Mn} was highest in the surface water and lowest in the middle layer. The primary factors affecting these spatial distribution characteristics include the types and quantities of microorganisms and biological communities at different water depths, water movement and convection, sedimentation rates of suspended particles and organic matter, as well as human activities.

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1. INTRODUCTION

Cascade reservoirs serving as water sources, flood control structures, and navigation aids, also impact the reservoir area and its surrounding ecosystems [1]. The nutrient cycles [2] and the spatiotemporal cumulative effects of nitrogen and phosphorus interactions in cascade reservoirs pose significant challenges to aquatic ecosystems and environmental changes [3]. These nutrients play crucial roles in many important processes within the reservoir ecosystem, affecting the overall ecological health [4]. Constructing cascade dams and reservoirs improves the efficiency of water resource utilization while altering the original hydrodynamic conditions of rivers [5]. Changes in hydrodynamic conditions and complex biogeochemical processes cause significant depth-dependent variations in the distribution of nitrogen and phosphorus nutrients in waters [6]. These changes also significantly alter the physicochemical properties of nutrient transport media, thereby affecting the geochemical cycling processes of nitrogen and phosphorus nutrients in cascade damming [7]. On a watershed scale, the development and construction of hydropower stations transform river surfaces from natural channels to static water lakes, altering the hydrological and hydraulic conditions of natural rivers, disrupting river continuity, and hindering material transfer and energy flow between upstream and downstream [8]. Additionally, climate, topography, and land use impacts result in spatial differences in river water quality [9]. For individual reservoirs, different water depths exhibit distinct water quality profiles, influencing water quality differences at various depths within the reservoir [10]. The accumulation of nitrogen and phosphorus nutrients and the intensification of water temperature stratification result in retained pollutants within the reservoir area, affecting water quality by reducing the self-purification capacity, increasing salinity, causing water temperature stratification, eutrophication, altering the redox state of the water, and impacting biodiversity [11]. Besides sediment inflow emissions, water quality may also be affected by agricultural activities in the catchment area, leading to prolonged retention time of nitrogen and phosphorus nutrients within the reservoir and exacerbating the degree of eutrophication [12]. Studying the stratification of nitrogen and phosphorus in cascade hydropower stations is crucial for understanding their impact on river water quality providing scientific evidence for formulating effective water resource management and protection measures.

In the academic community, the impact of cascade reservoir construction on aquatic ecosystems has been a widely studied topic. Research over the years has shown that the construction of reservoirs affects water quality and ecosystems in multiple ways. Fan et al. [13] found that these impacts include changes in river location, microbial community structure, and the levels of nitrogen and phosphorus, especially during the flood season. The strong correlation between nitrate nitrogen and total nitrogen indicates that reservoirs may alter water chemistry. In analyzing the trophic status of reservoirs, Christia et al. [14] used the trophic state index (TSI) to identify the eutrophic state of the Kaiafas saline lagoon, indicating that reservoirs can lead to the accumulation of nutrients, thereby affecting the ecological state of lake systems. In terms of studying reservoir-related issues, Skwierawski et al. [15] examined the transport of pollutants in rivers and noted that lakes, as the final storage points for pollutants, retain these substances. Additionally, the presence of large plants and bottom sediments in the river-lake system influences their distribution. This suggests that reservoirs impact waters not only chemically but also physically and biologically. In studying the Heihe River in the Hexi Corridor of China, Wang et al. [16] revealed the complex effects of reservoirs on watershed water quality. They found that the storage and blocking functions of cascade reservoirs in the downstream area indeed help improve water quality, possibly by reducing the direct discharge of pollutants. However, this improvement is not uniform, as water quality degradation remains severe in the midstream areas. Yang et al. [17] explored the long-term effects of upstream cascade reservoir construction and the rapid development of midstream cities on the ecological environment. They observed that with the development of these infrastructures, the nutrient content in sediments has gradually increased, leading to the deterioration of the ecological environment in the watershed. These studies highlight that the roles and impacts of reservoirs vary across different regions, suggesting that a comprehensive and balanced approach is needed in water resource management to address these environmental challenges. However, these studies primarily focus on river sediments, neglecting the spatial distribution and depth influence of nitrogen and phosphorus in the water column. Additionally, the mechanisms of nutrient transformation in cascade reservoirs and their impact on nitrogen and phosphorus in the reservoirs have also been neglected.

This study aims to specifically focus on the spatial distribution characteristics of nitrogen and phosphorus nutrients in the Heihe River basin and the impact of cascade reservoir construction on the stratification of these nutrients. The specific objectives of this study are as follows:

- Use variance analysis to investigate the variations in nutrient concentrations across different waters, thereby revealing the distribution patterns of these nutrients.
- To examine the impact of cascade hydropower stations on river water quality.
- To analyze the spatial distribution characteristics of these nutrients within the cascade reservoir area and explore their relationships with physical and chemical factors.

2. STUDY AREA AND METHODS

2.1. OVERVIEW OF THE STUDY AREA

The Heihe River, the largest inland water system in the Hexi Corridor, serves as the primary support for the corridor's oasis and as the lifeline for the northern desert. It is the second-largest inland river basin in the arid region of northwest China. The basin spans from 96°42′ to 102°04′ E and from 39°45′ to 42°40′ N, with a total length of approximately 928 km [18] and an annual average runoff of about 1.2 billion m³ [19]. Covering an area of 128 300 km², the river originates from the Tuolennanshan in the Qilian Mountains, with two tributaries – the Babao River and Yeniu Gully – which converge at Huangzang Temple in Qilian County, Qinghai Province. The river then flows into Gansu Province, passing through Yingluo Gorge into the Zhangye irrigation area and eventually merging into the Taolai River in Jinta County [20]. After passing through Zhengyi Gorge, the mainstream of the Heihe River finally flows into Juyanhai in Ejin Banner, Inner Mongolia.

The Heihe River basin exhibits significant climatic differences from east to west and north to south. The southern Qilian Mountain area experiences decreasing precipitation from east to west, an increasing snow line elevation, rugged terrain, and a cold, humid climate. In contrast, the central Hexi Corridor, characterized by flat terrain and abundant sunlight, is primarily used for agricultural irrigation. The downstream Alxa Plateau is a Gobi Desert region with open, flat terrain, a dry climate, sparse vegetation, and very little precipitation.

Table 1

Channel characteristics and hydrological features of the upper and middle Heihe River

River section	Length [km]	Channel gradient [%]	Runoff volume [10^8 m^3]	Average precipitation [mm]	Temperature [°C]
Yeniu Gully	175	8.5	7.5	424.3	–1.9
Babao River	75	9.3	14.6	422.4	2.0
Huangzangsi, Yingluo Gorge	95	9.1	44.7	300–600	<2.0
Yingluo Gorge, Zhengyi Gorge	85	2.0	10.5	140.0	2.8–7.6

The selected study area is located in the middle and upper reaches of the Heihe River (Table 1) [21]. The upper reaches range in elevation from 2600 m to 4300 m, with an annual average temperature between –5 °C and 4 °C and annual precipitation exceeding 350 mm, reaching up to 600 mm, or even 700 mm in some places. The glacier meltwater volume is approximately 4.0×10^3 m³, contributing to the cold and humid climate and supporting good vegetation cover, making it the main water source area of the Heihe River basin. In recent years, hydropower cascade development has taken place in this region, with a potential hydropower resource of 106×10^4 kW, of which 52.80×10^4 kW is developable. Based on the topographical features, eight cascade power stations have been constructed and put into operation in the upper reaches of the mainstream, including Huangzang Temple, Baoping River, Sandaowan, Erlongshan, Dagushan, Xiaogushan, Longshou II, and Longshou I, with a total annual power generation of 24.45×10^8 kW·h (Table 2). This data is sourced from the Gansu Provincial Hydrology and Water Resources Bureau, records from 1968 to 2018.

Table 2

Hydropower development in the upper reaches of the Heihe River

Power station	Installed capacity [10^4 kW]	Annual power generation [10^8 [kW·h]	Total reservoir capacity [10^8 m^3]	Elevation [m]	Construction time
Huangzang Temple	4.90	1.43	3.67	2590.00	Under construction
Baoping River	12.3	4.10	2.150	2528.90	2012-07
Sandaowan	11.2	4.00	0.053	2239.00	2009-05
Erlongshan	5.05	1.74	0.811	–	2007-09
Dagushan	6.50	2.01	1.410	2112.90	2009-07
Xiaogushan	10.2	3.91	0.014	1970.50	2006-07
Longshou II	15.7	5.28	0.862	1974.30	2004-08
Longshou I	5.20	1.98	0.132	1716.00	2002-04

2.2. SAMPLE COLLECTION AND ANALYSIS

To analyze the spatial distribution characteristics of nitrogen and phosphorus nutrients downstream of the cascade power stations in the upper reaches of the Heihe River, 20 sampling points were established along the sections from Sandaowan Hydropower Station (SDW), Dagushan Hydropower Station (DGS), Xiaogushan Hydropower Station (XGS), Longshou Second Hydropower Station (LS2) to Longshou First Hydropower Station (LS1), based on the topographical conditions and the status of hydropower development (Fig. 1). These points were named sequentially as S1–S5, T1–T5, Z1–Z5, H1–H5, where S1–S5 represent the SDW, DGS, XGS, LS2, LS1 surface layers, T1–T5 the middle layers, Z1–Z5 the bottom layers, and H1–H5 represent the river channels.

Water samples were collected at these 20 typical cross-sectional points in the Heihe River basin for testing. HR8300 portable data loggers and Hach portable multiparameter water quality testers were used to measure pH, resistivity (R), and dissolved oxygen (DO). Stratified water samplers were used to collect water samples, which were then preserved and transported to the laboratory at low temperatures for water quality analysis. Various water quality monitoring indicators were measured using methods such as alkaline potassium persulfate digestion UV spectrophotometry, ammonium molybdate spectrophotometry, diazotization coupling spectrophotometry, Nessler's reagent spectrophotometry, the potassium dichromate method, and the acidic potassium permanganate method. These indicators included total nitrogen (TN), total phosphorus (TP), nitrite nitrogen (NO_2^--N), ammonium nitrogen (NH_4^+-N), chemical oxygen demand (COD_{Cr}), and permanganate index (COD_{Mn}). To minimize systematic errors, each measurement was repeated three times, and the average was taken as the final data. The water quality monitoring methods are listed in Table 3. Water quality classification was based on the *Environmental Quality Standards for Surface Water* (GB 3838-2002) [22].

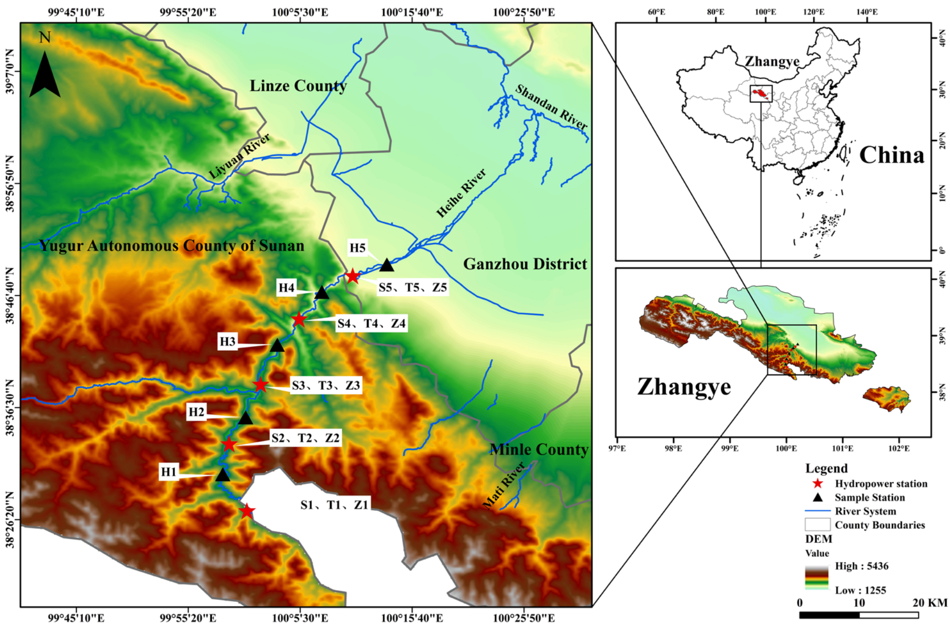


Fig. 1. Distribution of the study area and the sampling sites

Table 3

Water quality monitoring and analysis methods

Monitoring parameters	Method	Minimum detectable limit [mg/dm^3]	Reference national standard
TN	alkaline potassium persulfate digestion UV spectrophotometry	0.050	GB 1194-89
TP	ammonium molybdate spectrophotometry	0.010	GB 11893-89
NO_2^--N	diazotization coupled spectrophotometry	0.001	GB 7493-87
NH_4^+-N	Nessler's reagent spectrophotometry	0.025	GB 7479-87
COD_{Cr}	potassium dichromate method	10	GB11914-89
COD_{Mn}	acidic potassium permanganate method	0.5	GB11892-89

2.3. DATA ANALYSIS METHODS

Variance analysis was employed to analyze the differences in nitrogen and phosphorus content across different spatial categories in the Heihe River study area. Pearson correlation analysis was used to examine the main physicochemical factors influencing the distribution of nitrogen and phosphorus. The aforementioned analyses were conducted using the Microsoft Office 2020, SPSS Statistics 27.0, and Origin 2022 software. ArcGIS was used to create the map of the study area.

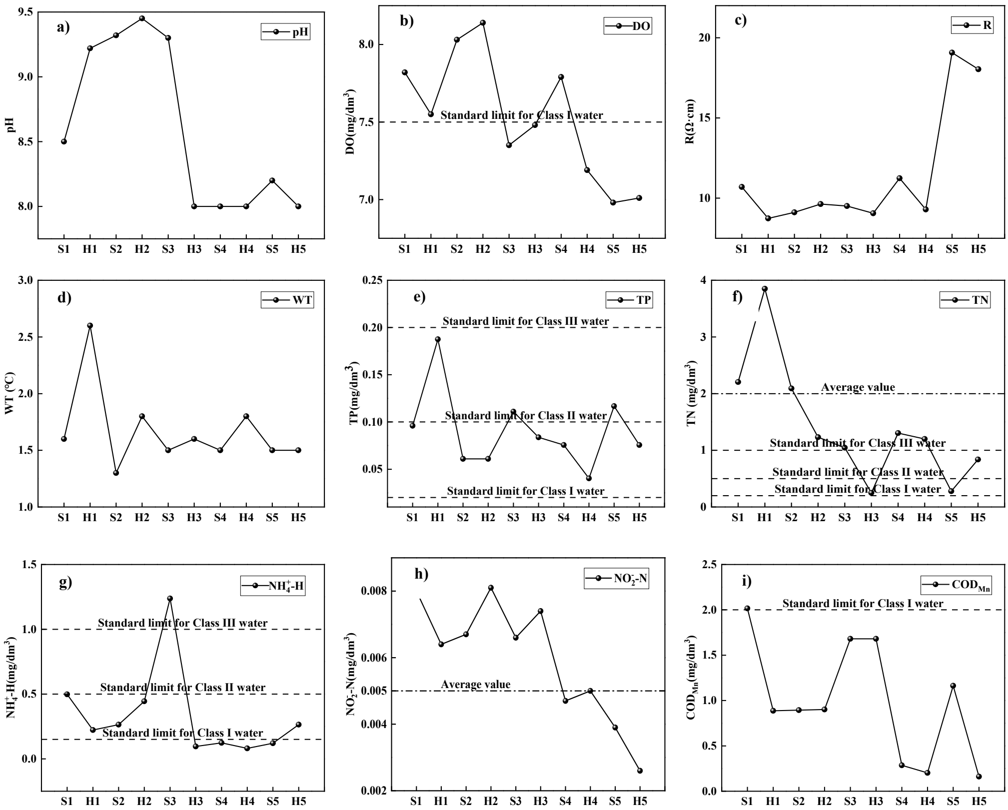
3. RESULTS AND ANALYSIS

3.1. LONGITUDINAL DISTRIBUTION CHARACTERISTICS OF PHYSICOCHEMICAL FACTORS IN THE HEIHE RIVER AND CASCADE RESERVOIRS

The investigation results indicate that from the longitudinal distribution perspective, i.e., from the reservoir area to the river channel (S1–S5, H1–H5), the overall trend shows a decrease in dissolved oxygen (DO) content (Fig. 2b), likely due to an increase in organic matter or a reduction in oxygen supply in the water. Nitrite nitrogen (NO_2^--N) concentration also shows a decreasing trend (Fig. 2h). In the surface water, the average concentration of nitrite nitrogen is 0.005 mg/dm^3, with the highest value of 0.0081 mg/dm^3 at H2 and the lowest value of 0.0026 mg/dm^3 at H5. Other indicators show no significant trends. pH (Fig. 2a) remained relatively stable, exhibiting slight alkalinity, while resistivity (Fig. 2c) reached its maximum at S5 (19.07 Ω·cm). Total nitrogen (TN) content showed no significant overall trend but slightly increased at H1 (Fig. 2f). The average concentration of TN in the surface water is about 2.0 mg/dm^3, ranging from 1.0 mg/dm^3 to 3.9 mg/dm^3, possibly influenced by external inputs into the waters. Total phosphorus (TP) concentration in the surface water does not vary much and remains at a relatively low level, with an average concentration of 0.09 mg/dm^3 and a range of 0.040 mg/dm^3 to 0.0186 mg/dm^3 (Fig. 2e). NH_4^+-N content shows little variation across different locations, with a slight increase at S3 (1.238 mg/dm^3) (Fig. 2g). Chemical oxygen demand (COD_{Cr}) (Fig. 2j) and permanganate index (COD_{Mn}) (Fig. 2i) show some degree of variation across the region. COD_{Cr} concentration in the surface water shows minimal variation, with an average concentration of about 13.1 mg/dm^3, indicating a relatively stable distribution (Fig. 2j).

The physicochemical factors of the waters exhibit significant spatial variation trends. Moving along the river flow direction, these factors generally show a decreasing trend. pH levels are the highest overall at DGS (S2, T2, Z2), then gradually decrease, reaching the lowest values at LS1 (S5, T5, Z5) (Fig. 3a), pH levels first incease and then decrease. While dissolved oxygen (DO) (Fig. 3b) and resistivity remain relatively stable along the way, though R fluctuates at LS2 (Fig. 3c). DO and R have relatively small fluctuations, with R peaking at LS2 (S4, T4, Z4) and DO reaching its minimum at LS1 (T5, Z5).

Total phosphorus (TP) in the middle water layer varies more significantly than in the surface water, reaching its maximum at T2 (0.267 mg/dm^3) (Fig. 4d). The permanganate index (COD_{Mn}) shows a decreasing trend along the course. In the bottom water layer, COD_{Mn} initially increases and then decreases, with TN showing a relatively large overall fluctuation range. The maximum values for both COD_{Mn} and TN appear at Z2 (Figs. 4a, 4e). In the surface water of the cascade reservoir area, except for total nitrogen (TN) reaching its minimum value at S4 and ammonium nitrogen (NH_4^+-N) reaching its maximum value at S3, other indicators show S1 > S3, indicating significant differences in the physicochemical factors of water at different locations.



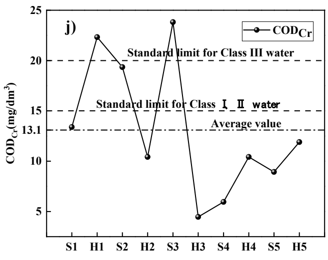


Fig. 2. Spatiotemporal distribution characteristics of nitrogen, phosphorus, and oxygen concentrations in the Heihe River: a) pH, b) dissolved oxygen (DO), c) resistivity (R), d) water temperature (WT), e) total phosphorus (TP), f) total nitrogen (TN), g) ammonium nitrogen (NH_4^+-N), h) nitrite nitrogen (NO_2^--N), i) permanganate index (COD_{Mn}), j) chemical oxygen demand (CODCr)

Studies indicate significant differences in the vertical distribution of water layers in cascade reservoirs. Comparison of different water layers shows that surface water characteristics mainly vary in NH_4^+-N and TN, while middle layer water mainly varies in TP. The bottom layer water shows larger fluctuations in COD_{Mn} and TN. Surface layer water shows greater variation compared to bottom layer water, while the middle layer water remains relatively stable along the river. TP and NO_2^--N fluctuate relatively steadily throughout the waters, whereas NH_4^+-N and COD_{Mn} fluctuate similarly at different water depths in various reservoirs.

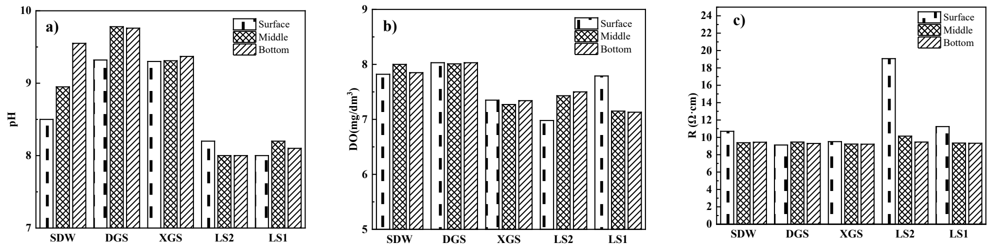


Fig. 3. Spatial distribution characteristics of physicochemical factors in water of cascade reservoirs: a) pH, b) dissolved oxygen (DO), c) resistivity (*R*)

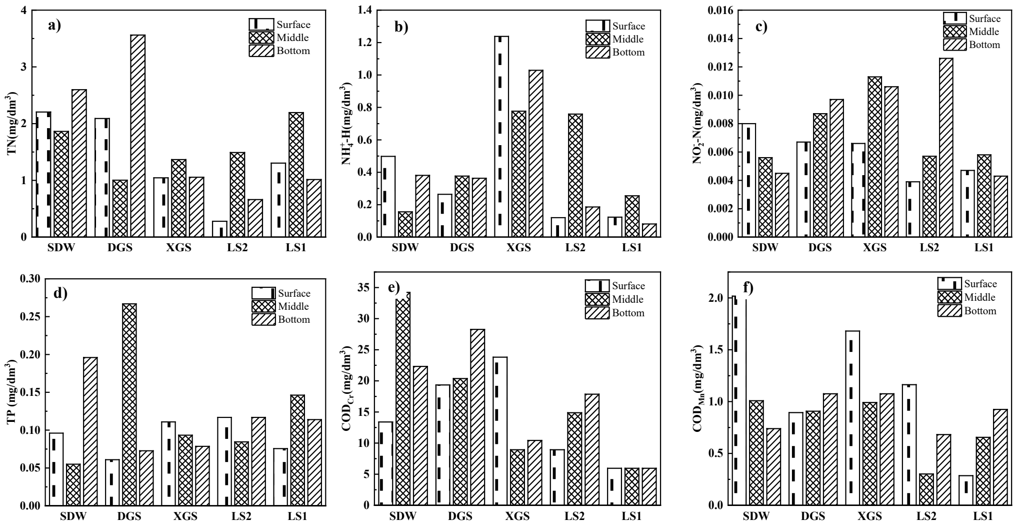


Fig. 4. Spatial distribution characteristics of nitrogen and phosphorus nutrient concentrations in water: a) total nitrogen (TN) of cascade reservoirs , b) ammonium nitrogen (NH_4^+-N), c) nitrite nitrogen (NO_2^--N), d) total phosphorus (TP), e) chemical oxygen demand (COD_{Cr}), f) permanganate index (COD_{Mn})

3.2. VERTICAL DISTRIBUTION CHARACTERISTICS OF PHYSICOCHEMICAL FACTORS IN CASCADE RESERVOIRS

Investigations reveal that pH is slightly alkaline (Fig. 5a), with an overall average DO concentration of 7.55 mg/dm^3, showing lower concentrations in the bottom (7.57 mg/dm^3) and middle (7.48 mg/dm^3) layers compared to the surface layer (7.59 mg/dm^3, Fig. 5b). According to the basic item standard limit table in the *Environmental Quality Standards for Surface Water*, the water quality generally meets class III standards.

The resistivity shows a clear stratification phenomenon in the vertical profile, with the highest *R* in the surface layer (11.33 Ω·cm), followed by the middle layer (9.51 Ω·cm), and the lowest in the bottom layer (9.35 Ω·cm, Fig. 5c).

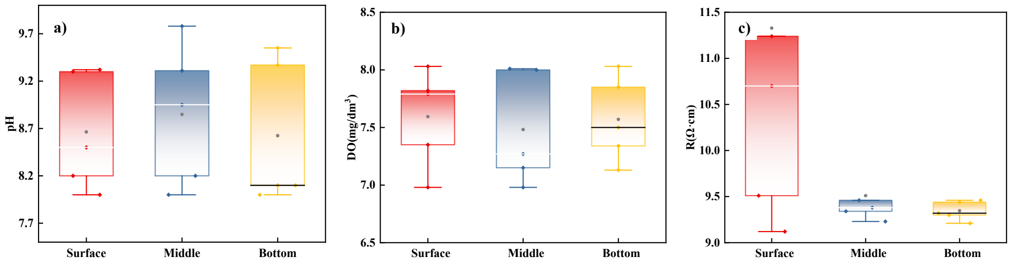


Fig. 5. Spatial distributions of physicochemical factors in cascade reservoirs: a) pH, b) dissolved oxygen (DO), c) resistivity (R)

Slight variations in the distribution of NO_2^--N and NH_4^+-N in the river water were observed. NH_4^+-N concentration exhibits a vertical distribution with the highest average concentration in the middle layer (0.4647 mg/dm^3), followed by the surface layer (0.4486 mg/dm^3), and the lowest concentration in the bottom layer (0.408 mg/dm^3) (Fig. 6b). NO_2^--N concentration increases gradually from the surface to the bottom layer, with average concentrations of 0.00598 mg/dm^3 in the surface layer, 0.00742 mg/dm^3 in the middle layer, and 0.00834 mg/dm^3 in the bottom layer (Fig. 6c).

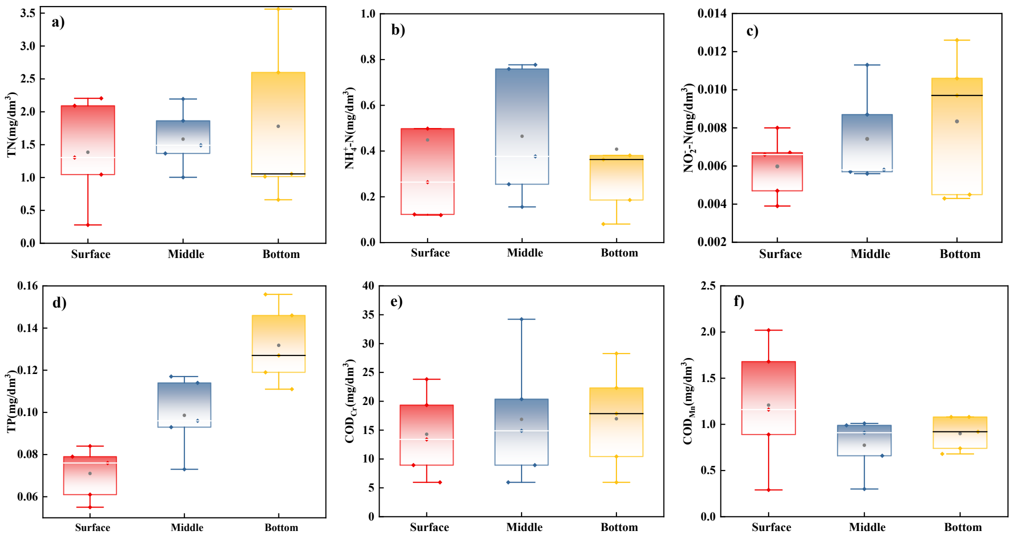


Fig. 6. Distribution of nitrogen and phosphorus concentrations in water of different sampling points of the Heihe River basin: a) total nitrogen (TN), b) ammonium nitrogen (NH_4^+-N), c) nitrite nitrogen (NO_2^--N), d) total phosphorus (TP), e) chemical oxygen demand (COD_{Cr}), f) permanganate index (COD_{Mn})

TN concentration is highest in the bottom layer (1.778 mg/dm^3), followed by that in the middle layer (1.584 mg/dm^3), and relatively lower in the surface layer (1.385 mg/dm^3,

Fig. 6a). TP concentration ranges from 0.055 to 0.156 mg/dm^3, with the highest average concentration in the bottom layer (0.132 mg/dm^3), followed by the middle layer (0.099 mg/dm^3), and the lowest in the surface layer (0.071 mg/dm^3, Fig. 6d). TP and TN concentrations show slight differences in their distribution, with a consistent trend of higher concentrations in the bottom layer than in the surface layer [23]. TP and TN concentrations generally meet class III water quality standards, with some sampling points reaching class IV standards due to the influence of agricultural activities and urban and industrial discharges [24]. Bottom water has the highest COD_{Cr} (16.96 mg/dm^3), followed by the middle layer (16.87 mg/dm^3), with the Surface layer being relatively lower (14.28 mg/dm^3, Fig. 6e).

COD_{Mn} measurements indicate the highest values in the surface water (1.208 mg/dm^3), followed by that in the bottom layer (0.900 mg/dm^3), and the lowest in the middle layer (0.774 mg/dm^3, Fig. 6f). COD_{Mn} concentrations fall within class I water quality standards.

4. DISCUSSION

4.1. ANALYSIS OF LONGITUDINAL CHANGES IN PHYSICOCHEMICAL FACTORS IN THE HEIHE RIVER BASIN

Survey results indicate that the longitudinal distribution trend (i.e., from the reservoir to the river S1–S5, H1–H5) is the result of the interaction between natural and anthropogenic factors. Despite minimal changes in pH the dissolved oxygen (DO) content decreases significantly. This is mainly due to an increase in organic matter contents in the waters or a reduction in oxygen supply. In particular, organic matter tends to accumulate in the downstream sections, where the degradation of plant and animal remains, along with the input of organic matter from upstream, can lead to oxygen depletion, thereby affecting DO content [25]. In the upstream regions, turbulent water flow ensures adequate contact with air, resulting in higher DO content. This indicates that downstream areas are more vulnerable to organic pollution, requiring focused water quality management and pollution control.

The concentrations of TN, NH_4^+-N and NO_2^--N show a gradual decline along the Heihe River basin. This is primarily attributed to biological degradation and nitrification, which convert these compounds into nitrate nitrogen. Additionally, the impact of reservoir construction reduces the accumulation trend of nutrients in waters along the course, aligning with the “interception-attenuation” expectations of several scholars regarding nutrient trapping by cascade damming. In contrast, the total phosphorus content shows a gradual increase, influenced by soil erosion in coastal areas and the absorption, decomposition, and release of phosphorus by aquatic plants, raising phosphorus levels in the water. Total nitrogen content, on the other hand, does not exhibit a significant overall trend, though it slightly increases at H1, likely due to increased nitrogen compound emissions from industrial and agricultural activities, as well as soil erosion. COD_{Cr} and COD_{Mn} show some degree of variation across the region, influenced by biological degradation, organic matter input, and photosynthesis, but without a clear trend.

4.2. ANALYSIS OF LONGITUDINAL DISTRIBUTION CHARACTERISTICS OF PHYSICOCHEMICAL FACTORS IN CASCADE RESERVOIRS

Correlation analysis (Table 4) reveals significant correlations between dissolved oxygen and multiple parameters. DO is significantly positively correlated with chemical oxygen demand, ammonia nitrogen, nitrite nitrogen, total nitrogen, and pH. This reflects that the DO level in the water is usually affected by organic load, nitrogen input, and pH. High DO is typically associated with low organic pollution and adequate nitrogen control. There was a strong positive correlation between DO and COD_{Cr}, with a correlation coefficient of 0.716. The correlation coefficient between DO and pH is 0.497, indicating a certain synchronicity between the increase in pH and DO content. This is because the DO concentration in water is usually influenced by pH. DO also shows a positive correlation with NO_2^--N. The correlation between DO and total phosphorus is relatively weak, with a correlation coefficient of –0.354. DO shows also a negative correlation with the resistivity (r = –0.161).

Table 4

Pearson correlation analysis

Parameter	pH	DO	*R*	NO_2^--N	TP	TN	NH_4^+-N	COD_{Cr}	COD_{Mn}
pH	–								
DO	0.497	–							
R	–0.503	–0.161	–						
NO_2^--N	0.326	0.263	–0.415	–					
TP	0.013	–0.354	0.312	–0.114	–				
TN	0.321	0.497	–0.309	0.032	–0.338	–			
NH_4^+-N	0.445	0.098	–0.172	0.525*	–0.023	0.239	–		
COD_{Cr}	0.547[a]	0.716[b]	–0.108	0.210	–0.209	0.285	0.307	–	
COD_{Mn}	0.395	–0.071	–0.013	0.134	–0.113	–0.038	0.282	0.284	–

[a]Significant correlation at the 0.05 level (two-tailed).
[b]Significant correlation at the 0.01 level (two-tailed).

COD_{Cr} shows significant positive correlations with NH_4^+-N, DO and pH. This indicates that increased COD_{Cr} in the water may be related to organic wastewater discharge, sources of ammonia nitrogen, and water acidity or alkalinity. The decomposition of organic pollutants usually requires oxygen and may produce nitrogen compounds and ammonia nitrogen. Therefore, higher COD_{Cr} may be associated with higher concentrations of DO, nitrogen, and ammonia nitrogen. COD_{Cr} and pH show a positive correlation (r = 0.547), as the decomposition of organic pollutants usually requires oxygen, and a higher pH may promote the decomposition of these organic substances, leading to increased COD_{Cr}. The negative correlation between COD_{Cr}, TP, and R may reflect the impact of different pollutant loads on nutrient distribution in water.

NO_2^--N shows positive correlations with NH_4^+-N, DO, and pH, and a negative correlation with TP. This indicates that NO_2^--N concentration in water may be influenced by ammonia nitrogen conversion, nitrification, and DO levels, while the negative correlation with TP may reflect the dynamic competition and distribution among different nutrients. NO_2^--N and NH_4^+-N show a positive correlation, with a correlation coefficient of 0.525.

NH_4^+-N shows significant positive correlations with NO_2^--N. This indicates that increased NH_4^+-N concentration in water may be related to organic pollution, nitrification, and environmental conditions. NH_4^+-N has a strong positive correlation with the permanganate index (COD_{Mn}), with a correlation coefficient of 0.282, indicating that increased NH_4^+-N concentration is associated with enhanced oxidation properties in the water, showing a common trend under certain conditions. This is because the presence and decomposition of NH_4^+-N in water can affect the oxidation of organic matter, leading to an increase in COD_{Mn}. However, the correlation coefficient between NH_4^+-N and pH is 0.445, possibly due to other factors affecting NH_4^+-N concentration. TP shows a negative correlation with TN (r = –0.338), which may originate from the decomposition process of organic matter in sediments, affecting phosphorus and nitrogen concentrations in water. Additionally, TP shows a weak negative correlation with COD_{Mn}, with a correlation coefficient of –0.113, indicating that increased TP content in water leads to decreased COD_{Mn}, and vice versa. This is because the presence of phosphorus promotes the decomposition of certain organic substances, reducing the demand for COD_{Mn}. This negative correlation is related to the degree of eutrophication in water, as TP is a primary nutrient causing eutrophication, while COD_{Mn} is a common water quality indicator used to assess the oxidation and pollution level of water. COD_{Mn} shows weak but positive correlations with other indicators, mainly reflecting the oxidizable organic content in water, whose degradation process may influence the concentration of other indicators.

4.3. ANALYSIS OF VERTICAL DISTRIBUTION CHARACTERISTICS OF PHYSICOCHEMICAL FACTORS IN CASCADE RESERVOIRS

According to the basic item standard limit table in the *Environmental Quality Standards for Surface Water*, the overall water quality meets class III standards. Monitoring data of Heihe showed that the average dissolved oxygen (DO) concentration in the bottom, middle, and surface layers were 7.57, 7.48, and 7.59 mg/dm^3, respectively, reflecting the difference in oxygen distribution in the water. Surface DO concentration is mainly due to photosynthesis and good gas exchange, surface waters by abundant sunlight, water phytoplankton and aquatic plants generate oxygen through photosynthesis, increased DO concentration, surface contact with the atmosphere, oxygen can quickly dissolve in water through gas exchange, further enhance the oxygen content, in addition, the surface water temperature helps to enhance biological activities, can promote the generation of oxygen and dissolution.

The moderate underlying DO concentration is affected by the sediment, but the water fluidity and mixing situation keep the oxygen concentration stable, and the underlying biological community structure may be relatively stable, and the oxygen consumption of biological activities is relatively balanced with the supplementation. The lowest DO concentration in the middle level may be due to the lack of light, low water mobility in the middle level, and the lack of mixing of water, which makes the oxygen replenishment rate slower. The middle layers contain more organic matter from sources such as suspended solids and decomposition products of bottom sediments. The microbial decomposition of this organic matter consumes oxygen, reducing DO concentrations. Water dynamics, including wind and turbulence, lead to mixing and quicker DO depletion, resulting in relatively lower concentrations.

The average pH values in the surface, middle, and bottom layers were 8.66, 8.85 and 8.62, respectively, showing the difference in pH of different aqueous layers. The low surface pH value (8.66) may be due to the decomposition of oxygen and organic matter produced by photosynthesis, which enhances the generation of alkalinity in water. The highest pH in the middle level (8.85), is probably because the water in this layer is less affected by external interference, the biological activities are relatively balanced, and the oxygen release of organic matter decomposition and photosynthesis reaches a stable state, resulting in relatively high alkalinity. The low bottom pH (8.62) may be due to the decomposition of organic substances in the sediment consumes part of the alkaline material, and the poor fluidity of the bottom water, which reduces the self-regulation ability of the water.

Clear stratification in resistivity is observed vertically, with the highest R in the surface layer, followed by the middle and bottom layers. Clear resistivity stratification was observed in the vertical direction, with the surface layer being the highest and the middle layer being the lowest. This stratification phenomenon may be related to the physicochemical characteristics of the water and its environmental factors. The electrical resistivity of the surface layer is higher, usually because the surface water is relatively less polluted and less dissolved salt and suspended particles, thus improving the resistivity. In addition, the high surface water temperature increases the electrical conductivity of the water. The resistivity of the intermediate layer is moderate, which may be due to the lack of light leading to the decomposition of organic matter and active microorganisms, and the formation of more dissolved organic matter and suspended particles, thus reducing the resistivity. The lowest resistivity in the bottom layer is probably due to the high content of mineral and organic substances in the sediment, which increases the conductivity of the water, and the poor fluidity of the bottom water, leading to the accumulation of pollutants and ions, further reducing the resistivity.

COD_{Mn} shows higher concentrations in the surface layer compared to the middle and bottom layers. The COD_{Mn} concentration in the surface layer of the Heihe cascade reservoir area is 1.208 mg/dm^3, which is significantly higher than that in the middle layer (0.774 mg/dm^3) and the bottom layer (0.900 mg /dm^3). The main reasons for this phenomenon may be related to the biological activity of the surface water, the enrichment of nutrients, and the accumulation of pollutants. The surface waters are often exposed to sunlight, and the phytoplankton and aquatic life grow more active, producing more organic substances, resulting in the increase of COD_{Mn} concentration. In addition, the surface water comes into contact with the atmosphere and is vulnerable to pollution by the surrounding environment, leading to the rise of COD_{Mn} concentration. In contrast, the middle and bottom waters are relatively stable, with less mixed water bodies, relatively low biological activity, and relatively low decomposition rate and concentration of organic matter, resulting in significantly lower COD_{Mn} values than the surface layers.

In the Heihe cascade reservoir area, the concentration of chemical oxygen demand showed some changes in different water layers, and the surface layer was 14.284 mg/dm^3, while the middle and bottom layers were 16.87 and 16.964 mg/dm^3, respectively, indicating that the COD_{Cr} concentration in the surface layer was lower than that of other layers. This phenomenon may be closely related to photosynthesis and biodegradation in surface waters. Due to sufficient light, the surface growth of phytoplankton and aquatic plants is more active, which can consume some organic matter through photosynthesis and reduce the concentration of COD_{Cr}. The surface water is relatively easy to exchange gas with the external environment, which may promote the degradation of some organic matter. Relatively speaking, the middle and bottom water mix is poor, the biodegradation ability is weak, and the accumulation of organic matter and pollutants leads to the increase of COD_{Cr} concentration. Therefore, the low concentration of COD_{Cr} in the surface layer reflects the ecological health status and self-purification ability of the water, while the higher concentration in the middle and bottom layers indicates the potential accumulation of organic matter and the risk of environmental pollution.

Regarding nitrogen forms, the concentrations of NH_4^+-N and NO_2^--N exhibit clear stratification patterns. NH_4^+-N is highest in the middle layer (0.4647 mg/dm^3), likely due to the accumulation of organic nitrogen from both the surface and bottom layers. In contrast, NO_2^--N concentrations are lowest in the surface layer (0.00598 mg/dm^3) due to active assimilation by phytoplankton and rapid oxidation. The higher concentrations in the middle and bottom layers (0.00742 and 0.00834 mg/dm^3, respectively) are attributed to anoxic conditions, enhanced microbial denitrification, and limited vertical mixing.

Total nitrogen and total phosphorus concentrations are significantly higher in the bottom layer compared to the surface and middle layers. The bottom layer's TN concentration reaches 1.778 mg/dm^3, primarily due to nitrogen release from sediments and the lack of sufficient oxygen for complete nitrification. Similarly, TP concentrations (0.132 mg/dm^3) are elevated in the bottom layer due to phosphorus release from sedimentary organic matter and microbial degradation. The surface and middle layers are more affected by external nutrient inputs and biological uptake, resulting in lower concentrations.

The vertical distribution characteristics of nitrogen and phosphorus indicate that sedimentary release, microbial activity, and hydrodynamic conditions play a critical role in nutrient stratification. The bottom layer, with its reduced oxygen levels and stable conditions, serves as a reservoir for nutrients, whereas the surface layer is primarily influenced by photosynthetic activity and external nutrient inputs.

5. CONCLUSIONS

The authors systematically analyzed the spatial and temporal distribution characteristics of nitrogen and phosphorus nutrients in the high-altitude inland river cascade reservoirs of the Heihe River basin. The findings demonstrate that the longitudinal and vertical distribution of nitrogen and phosphorus is influenced by multiple factors, including hydrodynamic processes, and the distribution characteristics of microorganisms and biological communities.

- *Longitudinal distribution characteristics*. The longitudinal changes from reservoirs to river channels show a decreasing trend in dissolved oxygen (DO) and nitrite nitrogen (NO_2^--N) concentrations, primarily due to an increase in organic matter or a reduction in oxygen supply. This indicates significant differences in water quality characteristics across various regions, particularly in terms of changes in dissolved oxygen and nitrogen, which are crucial for water quality assessment and ecosystem health.
- *Vertical distribution characteristics*. The vertical profile of the water reveals a distinct stratification phenomenon. Nitrogen and phosphorus concentrations are significantly higher in the bottom layer than in the surface layer, mainly due to the degradation of organic matter and the release of nutrients from sediments. In regions with weak hydrodynamic conditions, the self-purification capacity of the bottom layer is limited, leading to the accumulation of nitrogen and phosphorus in these layers.
- *Impact of cascade reservoirs*. The construction of cascade reservoirs impacts river water quality through complex regulatory pathways, including multi-stage physical interception, nutrient fixation, and resuspension. While multi-stage dams contribute to water purification and downstream water quality improvement, the re-release of nitrogen and phosphorus from bottom sediments in the lower water layers poses a risk of secondary pollution that requires continuous monitoring.

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