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Original Research

The Temporal Variation and Flood Determined the Characteristics of the Water Quality Pattern in Danjiangkou Reservoir, China

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Abstract

As the water source of the Middle Route of China's South-to-North Water Transfer project, the change of water quality of Danjiangkou Reservoir has been attracting much attention. This study aimed to obtain the annual water quality pattern and influencing factors of Danjiangkou Reservoir by means of multivariate analysis and correlation analysis using monthly data surveyed in 2021. The results of PCA and RDA variation partition analysis showed that the water quality of Danjiangkou Reservoir was mainly affected by temporal factors, and the spatial effect was limited. The trajectory analysis results revealed that the unusual floods in the current years have specific impacts on water quality in Danjiangkou Reservoir at the temporal and spatial scales. The results of Pearson and Mantel correlation test indicated that the inflow and water level affected the spatial-temporal pattern of reservoir water quality mainly via the NO_3^- and PO_4^{3+}. With the global change i.e. extreme flood, this research would provide a basis for the decision-making of management empirically.

Keywords: Danjiangkou Reservoir, water quality, spatial-temporal pattern, flood

Introduction

Access to safe, clean, and affordable drinking water is a fundamental right that is essential for public health [1]. However, factors such as global population growth, food demand, industrialization, urbanization, and climate change are posing significant threats to the availability of freshwater resources worldwide [2]. Despite efforts to reduce pollution, improve wastewater treatment, and the restore rivers, lakes and reservoirs in China, archiving good quality for water reminds a challenge [3, 4]. Poor water quality exacerbates China's water scarcity and regional inequality [5], making it increasingly necessary to rely on reservoirs and lakes with better water quality and inter-regional water transfer projects to meet the demands for drinking water supply [6, 7].

The Middle-Route of the South-to-North Water Diversion Project of China (SNWDPC) is the world's largest inter-basin water diversion project and has

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effectively alleviated the severe water shortage in North China. As the water source of SNWDPC, the Danjiangkou Reservoir has provided more than 51.8 billion m^3 of water resources via 1276 km open canal and benefited over 85 million inhabitants in the water receiving area since 2014. It has become the primary domestic source of domestic water for 24 cities including the major municipalities of Beijing and Tianjin. Therefore, it is of crucial importance to protect the water quality and aquatic ecosystem health of the Danjiangkou Reservoir [8].

Multivariate statistical techniques, including cluster analysis (CA), principal component analysis (PCA), and discriminant analysis (DA), have become increasingly popular in recent years to evaluate surface water quality [9-13]. These techniques are also useful for assessing spatial or temporal variations that may be due to natural or anthropogenic factors and possibly linked to seasonality [14].

Previous studies on the Danjiangkou Reservoir mostly focused on normal or low water storage level conditions. However, during the research period of this study, the reservoir was operated at its historical highest water level for an extended period. Thus, it is of great significance to investigate the changes in the water quality and factors that influence them under such conditions. The objective of this paper is to use multivariate statistical techniques to assess temporal variations in the water quality of the Danjiangkou Reservoir and examine the impact of flooding on typical water quality parameters. The results could provide valuable insights for water quality agencies to effectively allocate their resources to combat severe water pollution.

Material and Methods

Study Area and Sampling Sites

The Danjiankou reservoir is the source of China's SNWDPC, located on the border of Henan and Hubei Province. In 2021, We collected surface water samples monthly at Sihekuwan (SHKW), Taijihu (TJH), Langhekou (LHK) and Baqian (BQ) along the main river from the end to the head of the dam (Fig. 1). Each month, we collected a total of 2 L raw water, 0.5 m under the surface, via the 5 L standard water sampler. 0.5 L water was filtered through a 1.2 µm-pore Whatman GF/C membrane filter, and the membrane was kept in a previously acid-washed 2 mL plastic tube for suspended Chlorophyll *a* (Chl *a*) concentration analysis; Another 0.5L water was acidified with sulfuric acid to pH = 2 for chemical oxygen demand (COD_{Mn}), total nitrogen (TN) and total phosphorus (TP) analysis; The last 1L water was transported to the laboratory and stored under 4ºC for total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP), ammonia nitrogen (NH_4^+), nitrate nitrogen (NO_3^-), nitrite nitrogen (NO_2^-), Phosphate (PO_4^{3+}) and silicate (SiO_4^{-4}) analyses. The standard techniques used for measuring these water quality parameters are following the "Environmental quality standards for surface water (GB 3838-2002)".

Water temperature (WT), pH, dissolved oxygen (DO), Electronic Conductivity (EC), total dissolved solid (TDS), and Turbidity (Turb) were measured using EXO3 (YSI Inc., Yellow Springs, Ohio, USA); Secchi depth (SD) was determined with a black and white Secchi disk (diameter = 20 cm). The above physico-chemical characteristics were determined for all the samples.

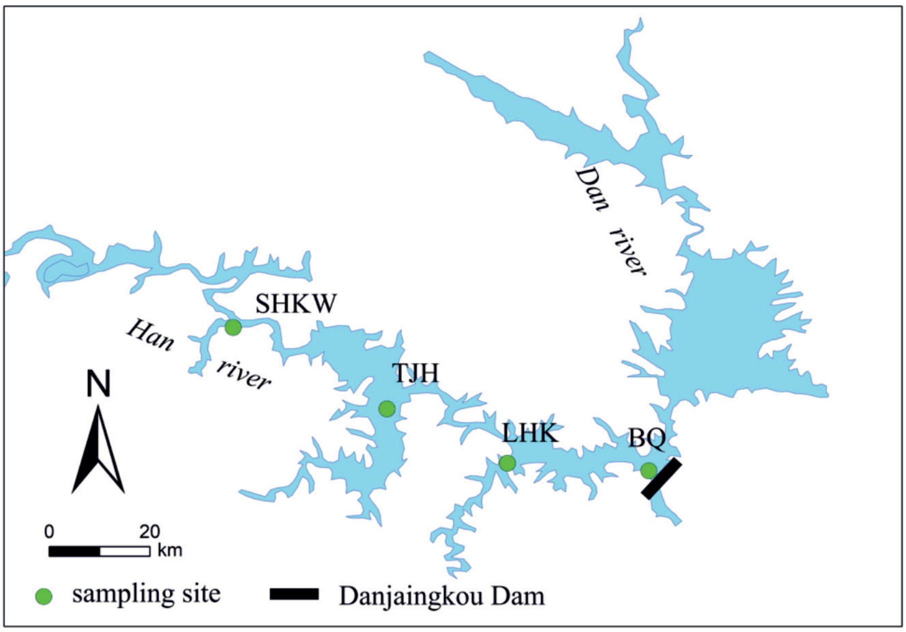

Fig. 1. Map of sampling sites. SHKW is for Sihekuwan, TJH is for Taijihu, LHK is for Langhekou and BQ is for Baqian.

The Data Statistical Analysis

The multivariate analysis methods of PCA and RDA/VPA were used to analyze the temporal and spatial pattern of the physico-chemical parameters in Danjiangkou Reservoir. The matrix of Euclidean distances was calculated and then Trajectory analysis was applied to analyzing the trend and degree of water quality changing at different sampling sites in a year. Pearson and Mantel analysis were used to analyze the relationship between various environmental factors and between hydrological conditions and environmental factors, respectively. All analysis methods were implemented in R language (Version 4.2.0), and PCA, RDA and VPA were conducted with package *factomineR* and *factoextra*. The Trajectory analysis was calculated using the package *ecotraj*, and Pearson and Mantel correlation were calculated using the package *linkET* [15].

Results

Hydrological Parameters

According to the Water Resources Monitoring Bulletin, the monthly water level was 161.3 m before July and increased to 168.82 m from August to December, reaching a historic high of 170 m in October and November. The average inflow of Danjiangkou reservoir was low from January to June at around 960.5 m^3/s and increased rapidly in July, reaching a peak of about 8470 m^3/ s in September. However, while the water level remained high, the average inflow decreased to about 1000 m^3/s in the last two months (Fig. 2).

Spatial and Temporal Variation of the Physico-Chemical Parameters

Table 1 lists the range and average values of physico-chemical parameters for each site. Since there was an increase in the inflow, the period from August to October was designated as the "Flood season" of 2021, while January to July was classified as the "Before flood season", and November to December as the "After flood season".

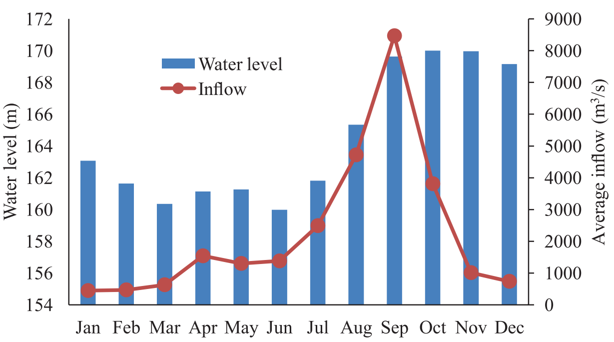

Fig. 2. Water level and average inflow of Jan to Dec, 2021 in Danjiangkou Reservoir.

Most of the nutrients of nitrogen, including TN, NO_3^-, NO_2^-, and NH_4^+, showed the highest average value at site SHKW, while the other three sites possessed an approximate value. In contrast, the nutrients of phosphorus, such as TDP, did not show significant difference among site SHKW, TJH, BQ (0.030-0.054 mg/L), but were higher than those of site LHK (0.017 mg/L). The spatial distribution of SiO_4^{-4} was similar to that of nitrogen nutrients (Table 1).

There was no significant difference in WT, DO, COD_{Mn} and pH among the four sites. On the other hand, EC and TDS showed similar patterns with nitrogen nutrients, and Turb showed similar patterns with phosphorus nutrients. The concentration of Chl *a* decreased along the main river of the reservoir, from 6.552 mg/L to 2.713 mg/L. Meanwhile, the SD showed an almost opposite trend with Chl *a*, increasing from 2.4 m to about 3.0 m (Table 1).

It's evident that the concentration of nutrients such as phosphorus, nitrogen, and silicon and COD_{Mn} increased during the flood season, and SD, DO and pH decreased. Among the three time periods, with Chl *a* and DO parameters displayed a significant difference, with Chl *a* increasing during the Flood season and decreasing during the After flood season, while the DO showed an opposite trend (Fig. 3).

Multivariate Analysis of Physico-Chemical Parameters

The PCA results indicate that samples from different months were clustered together in different quadrants, with October to January in the third quadrant; February and March in the fourth quadrant; samples from April to July in the first quadrant, and August to September in the second quadrant. Additionally, the results showed that the site SHKW was distinct from the other three sites, which had overlapping data points in the plots (Fig. 4a).

Overall, these findings suggested that the temporal changes in the physico-chemical parameters, such as seasonal variations and hydrological events, have a greater impact on the physico-chemical parameters of the reservoir compared to the spatial differences among sampling sites. The lack of spatial variation among sites THJH, LHK, and BQ may indicate that the environmental conditions in these areas are relatively homogeneous (Fig. 4b).

RDA variance partition analysis was performed for the environmental conditions based on the temporal variables of months and the spatial variables of sampling sites. The result further confirmed that the dominance of temporal variation in driving changes of physico-chemical parameters annual alteration (82.45%), and the spatial variation only explained 2.62%, whereas the rest 14.93% were remain unknown (Fig. 5).

Table 1. Spatial distribution of environmental parameters in Danjiangkou Reservior.

	SHKW		TJH		LHK		BQ	
	Range	Average	Range	Average	Range	Average	Range	Average
TN (mg/L)	1.258~2.428	1.711	1.120~1.694	1.429	1.068~1.918	1.403	0.991~1.599	1.301
TP(mg/L)	0.004~0.125	0.034	0.006~0.154	0.032	0.007~0.059	0.027	0.005~0.139	0.040
NO_3^- (mg/L)	0.991~1.834	1.459	0.965~1.501	1.188	0.886~1.655	1.159	0.804~1.411	1.118
NO_2^- (mg/L)	0.001~0.048	0.014	0.0004~0.023	0.008	0.001~0.018	0.008	0.002~0.021	0.008
NH_4^+ (mg/L)	0.037~0.206	0.093	0.018~0.241	0.088	0.041~0.182	0.097	0.049~0.192	0.104
PO_4^{3+} (mg/L)	0.0005~0.031	0.010	0.0001~0.022	0.009	0.0002~0.032	0.011	0.0001~0.044	0.013
TDN (mg/L)	1.130~2.171	1.629	1.105~1.648	1.348	0.981~1.759	1.312	0.945~1.594	1.266
TDP (mg/L)	0.004~0.196	0.032	0.004~0.201	0.030	0.005~0.046	0.017	0.002~0.468	0.054
SiO_4^{-4} (mg/L)	3.815~11.184	8.225	3.559~10.902	7.224	3.046~10.66	7.669	2.273~10.420	7.491
WT (ºC)	8.938~29.807	18.338	10.705~29.544	19.114	11.183~30.222	19.403	11.181~29.356	18.933
DO (mg/L)	5.710~11.160	9.575	6.210~12.260	9.667	6.720~11.280	9.541	6.240~11.760	9.443
CODMn (mg/L)	1.381~4.950	2.615	1.161~3.383	2.209	1.220~8.222	2.944	1.18~8	2.853
EC (µS/m)	195.2~322.9	236.383	186.5~249.1	216.717	178.9~245.6	209.483	182.8~251.3	216.225
TDS (mg/L)	155~193	176.500	141~181	159.500	141~167	152.833	143~174	159.833
Turb (mg/L)	1.17~20.06	5.422	0.44~31.35	6.601	0.26~11.11	3.868	0.56~27	6.292
pH	7.74~8.9	8.401	7.96~8.87	8.417	7.9~8.88	8.385	7.89~8.83	8.372
SD (m)	0.5~4.8	2.4	0.5~6.1	2.9	0.8~7.9	3.1	0.5~6.4	2.9
Chl *a* (µg/L)	1.181~7.772	3.290	0.510~12.280	3.902	0.532~11.137	3.486	0.460~4.781	2.713

Affecting Factors of the Water Quality

Trajectory analysis was conducted to explore the monthly variation trend of different locations throughout the year. The results show that axis 1 of PCoA explained 62%, while axis 2 explained 16% of the variation, totaling to 78%. The trajectory analysis effectively captured the time-series regulation of water quality in the four survey sites of Danjiangkou Reservoir within 12 months. Initially, the sample points from TJH and LHK in the reservoir were mixed from January to July with little fluctuation. However, with a significant increase in water inflow in the reservoir (Fig. 2), sample points from August to September moved rapidly along the first axis, indicating that the physico-chemical parameters were greatly affected by the flood. Specifically, sample points from SHKW (black arrow in Fig. 6a) showed a longer step from August to September compared to other sites, while the sample points from BQ (green arrow in Fig. 6a) showed less impact from the flood.

To identify the contributing factors to the water quality succession in main area of the reservoir, PCA was conducted on variables from sites excluding SHKW (Fig. 6b). It can be observed that the WT, SiO_4^{-4}, pH were the top three contributing factors to the water quality succession, while the TP, TDP, Chl *a* showed less contribution.

The Pearson analysis revealed significant positive correlations of TP with COD_{Mn}, SiO_4^{-4}, PO_4^{3+} ($p<0.01$) and Turb ($p<0.05$), while significant negative correlations were found with DO, pH, SD ($p<0.01$) and NH_4^+ ($p<0.05$). Furthermore, the Mantel test was conducted to assess the correlation between individual environmental factor and monthly averages of inflow and water level (Fig. 7). The results showed that inflow was significantly correlated with the concentration of TDS, NO_3^- and COD_{Mn}, while the increase of water level was correlated with the concentration of PO_4^{3+}.

Discussion

Spatial-Temporal Patterns of Physico-Chemical Parameters in Danjiangkou Reservoir

Danjiangkou Reservoir is a long and narrow riverine reservoir, and the inflow of water mainly comes from the mainstream, Han River, which contributed up to 88%. Therefore, the spatial-temporal patterns of physico-chemical parameters in Han River represent the reservoir [16]. Comparison of different environmental parameters at each site and in each flood period, Before, During and After the Flood Season, suggested a distinct pattern in Danjiangkou reservoir, in which the temporal

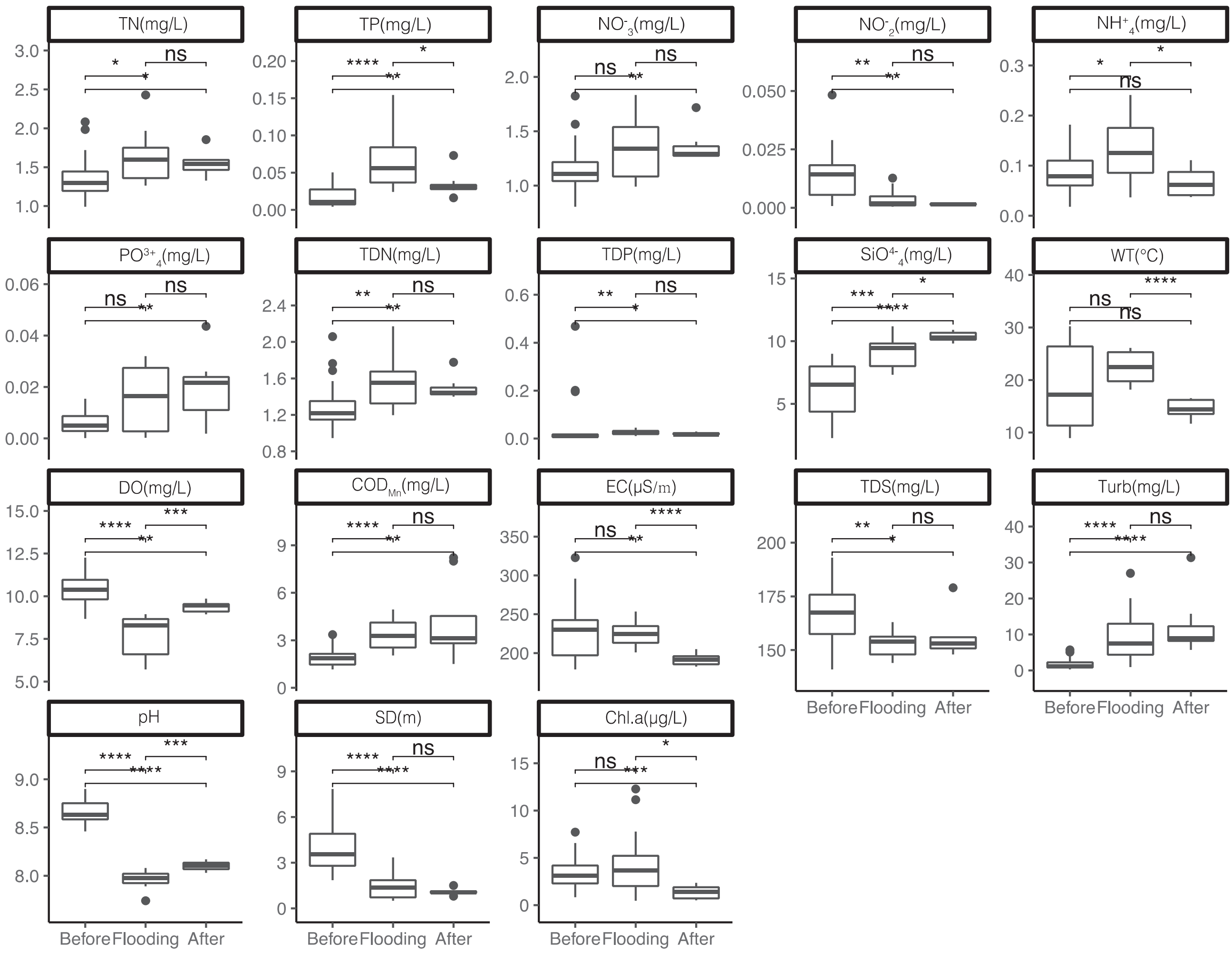

Fig. 3. The environmental parameters of different period in Danjiangkou Reservoir. Group "Before" indicates Jan to July, group "Flooding" indicates Aug to Oct, and "After" indicates Nov to Dec; "ns", "*", "**", "***" and "****" indicates the p value of the "t-test" was >0.05, ≤0.05, ≤ 0.01, ≤ 0.001, and ≤ 0.0001.

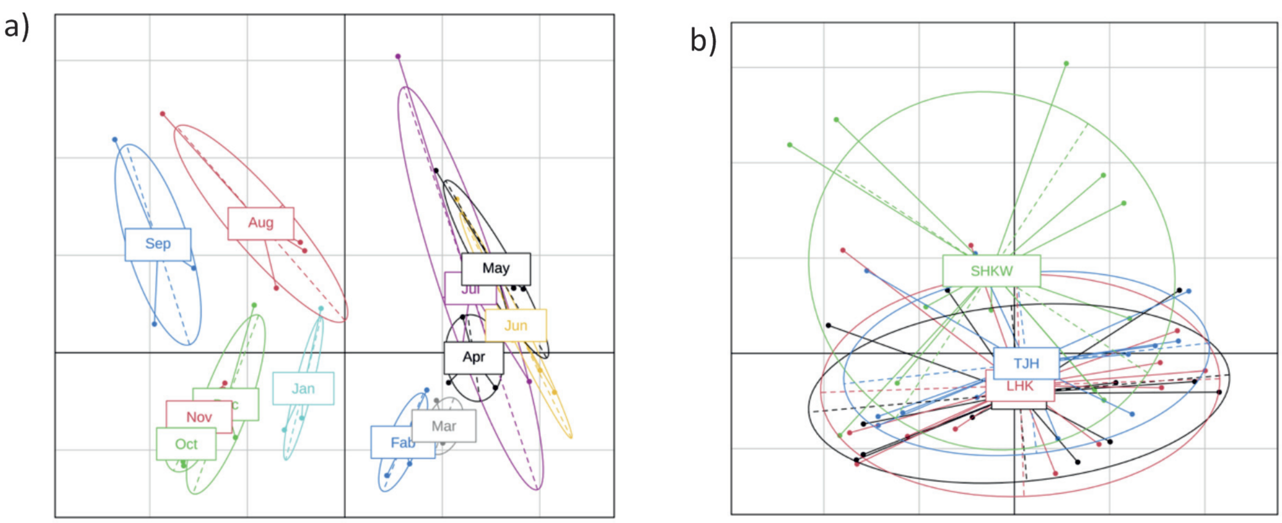

Fig. 4. The PCA results of the environmental parameters in Danjiangkou Reservoir.

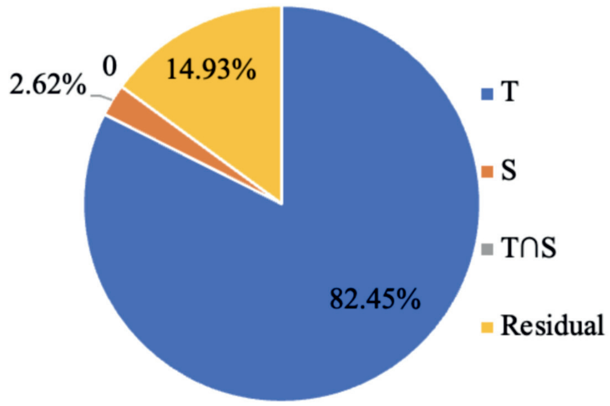

Fig. 5. The contribution of temporal and spatial variation on the physico-chemical parameters annual alteration (T: temporal; S: spatial; T∩S: both temporal and spatial explained; Residual: Unexplained).

variation explained most of the total variation rather than the spatial variation.

The upstream received large amount of rainfall, which caused the formation of floodwater mixed with pollutants that run into the Reservoir. This had a profound impact on the water quality at both temporal and spatial scales [17]. As a result, the transparency (SD) of the SHKW sample site was the lowest, and gradually increased to about 3 m at BQ sample site, due to the slowing down of water velocity. The turbid water caused a decrease in SD and an increase in EC, TDS, and nitrogen concentration at the SHKW site, while the other three sites archived less effect because of their great distance. It can be confirmed that the less spatial difference in Danjiangkou Reservoir were contributed from flood, rather than the local environment.

Phosphorus and nitrogen are drivers of eutrophication in aquatic lakes and reservoirs systems [18], and both nutrients are influenced by flood and water level regime [19-20]. The distribution of nitrogen and silicon decreased from the end to the head of the reservoir, while the spatial difference of phosphorus was not significant. This may be due to the self-cleaning processes such as dilution and sedimentation in the reservoir water [21]. In addition, the decreased inflow after the Flood season, coupled with the effect of temperature reduction, led to a decrease in phosphorus concentration to the level observed before Flood Season. Since temperature and key nutrient element are wildly known to be the main contributors of algae growth [22-23], the level of Chl *a*, which represents the growth of freshwater algae, decreased in Danjiangkou Reservoir.

Based on the given statement, it appears that there was no decrease in the concentration of nitrogen in the reservoir area during the “After flood” season. This could be due to the high water level operating in the reservoir during that year, which resulted in some coastal areas being soaked in water for an extended period. As a result, there was a continuous leaching of nitrogen in the form of NO_3^-, which helped to maintain the nitrogen concentration at the level of the flood season.

It is worth noting that high levels of nitrogen in water can lead to eutrophication, which can cause harm to aquatic ecosystems. Therefore, it is essential to monitor the levels of nitrogen in water bodies and take appropriate measures to prevent excessive leaching of nitrogen into the water.

Based on the given statement, it appears that the annual succession of Danjiangkou Reservoir is mainly explained by temporal variation, similar to the previous study conducted at Tangpu Reservoir [24]. However, the difference is that Danjiangkou Reservoir was affected by floods both temporally and spatially in a certain year, which could have an impact on the reservoir’s ecological succession.

Temporal variation refers to changes that occur over time, such as seasonal changes, while spatial variation refers to changes that occur across space,

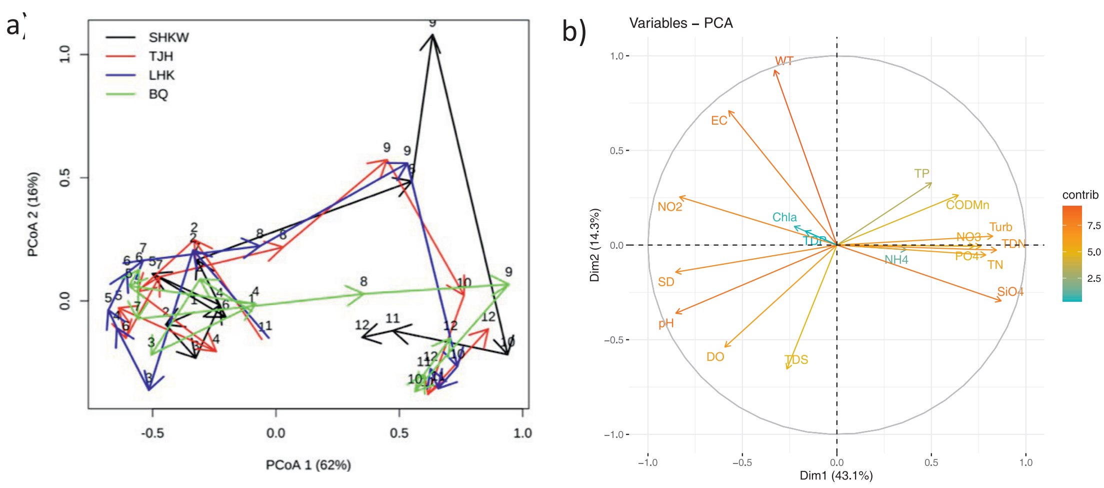

Fig. 6. The effecting factors based on trajectory analysis and PCA .

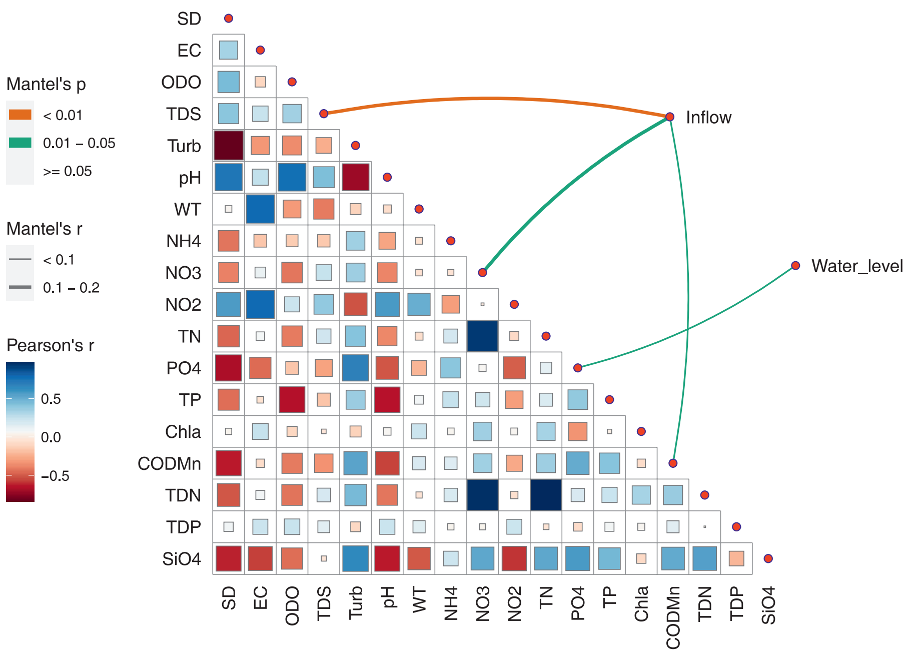

Fig. 7. The Pearson correlation between environmental parameters and Mental test between each hydrological parameter with environmental parameter.

such as changes in different areas of a reservoir. The impact of floods on the reservoir's ecology could have both temporal and spatial components, affecting the reservoir's ecological succession in various ways.

The Affecting Factors of the Water Quality Pattern in Danjiangkou Reservoir

Danjiangkou Reservoir is the important water source of the south-north water diversion in China, and its water quality and the factors that affect it have received widespread attention [25-27]. In many reservoirs across China, phosphorus is considered the primary determinant of water quality [12, 28-30]. Studies have shown that the total phosphorus concentration in China's reservoirs ranges from 0.02 to 0.21 mg/L, with a decreasing trend [31]. For example, Li et al. [32] found that the average annual TP and TN in the Three Gorges Reservoir were about 0.15 mg/L and 1.5 mg/L, respectively. Phosphorus was found to be the limiting factor for phytoplankton growth (represented by Chl *a*) in all seasons. Cao et al. [25] noticed a significant relation between water quality and parameters such as DO, Turb, Cl^- and NO- 3, but not with TN or TP. This finding indicates that the reservoir dispatching, fertilizer utilization, and rock weathering have an impact on the water quality. Li et al. [33] focused on the changes in different ion concentrations in water from 2004 to 2014, revealing the long-term effects of rock weathering and human activities on the water quality in Danjiangkou Reservoir.

Although the total phosphorus concentration in Danjiangkou Reservoir is at the lowest level among deep water reservoirs in China, the risk of eutrophication and algae bloom cannot be ignored [34]. Similar to previous studies [20], phosphorus from upstream tributary watersheds remained relatively high and stable in the head area of reservoir, which increase the high risk of eutrophication. In the present study, Chl *a* was significantly positively correlated with nitrogen (including TN, TDN, and NO_3^-), but negatively correlated with orthophosphate (PO_4^{3+}), which may be influenced by the unusual flood in this year. Research has shown that utilization of agricultural land and seasonal precipitation jointly promoted the dry deposition of NH_4^+ in dissolved inorganic nitrogen (DIN) in Danjiangkou Reservoir, thereby increasing the risk of water pollution [27]. However, Chen et al. [26] assessed the risk of eutrophication in Danjiangkou Reservoir through a 3D model based on hydrodynamic conditions (EFDC) and found that even when TN increased by 50%, it did not pose an obvious threat to the bloom risk in the Reservoir.

The spatial-temporal patterns in the Danjiangkou reservoir could be attributed to its spatial structure and seasonal hydrological conditions. As a riverine reservoir system, spatial heterogeneity was concealed by temporal heterogeneity [24]. The water quality pattern was mainly determined by temperature and other seasonal parameters. With the influence of global warming [35], nutrients were dissolved in rainwater and formed as turbid water flowed into the river from the end to the head of the reservoir. This reminds us that the precipitation and runoff are major causes of eutrophication risk in Danjiangkou Reservoir. Therefore, further long-term monitoring and research are needed to address the spatial-temporal variation of water quality in Danjiangkou Reservoir.

Conclusions

The main conclusions may be summarized as follows.

i. The unusual flood in this year affected the pattern of water physical and chemical parameters both at spatial and temporal scales.

ii. Phosphorus loading from precipitation and runoff still was the risk of eutrophication even though the low concentration.

iii. Seasonal variation and unusual flood shaped the water quality parameters in 2021.

In conclusion, routine monitoring in temporal change is more important than in spatial variation in riverine reservoirs e.g. Danjiangkou reservoir with a limited budget. Furthermore, variation in reservoir hydrological regimes caused by events such as floods or heavy rainfall also have a dramatic impact on its water quality.

Acknowledgments

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Conflict of Interest

The authors declare no conflict of interest.

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