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Water quality assessment of the Mopanshan Reservoir in the northeast China

Xiaodong Wang[a,†], Tingting Cao[b,†], Xindong Wei[a], Jinming Jiang[c], Chongwei Cui[b], Weijun Gao[c,d,*]

[a]*Jilin Jianzhu University, Changchun 130118, China, email: 369050446@qq.com (X.d. Wang), xindong33@hotmail.com (X.d. Wei)*
[b]*State Key Laboratory of Urban Water Resources Centre, School of Environment, Harbin Institute of Technology, Harbin 150090, China, email: cuichongwei1991@126.com (C.w. Cui)*
[c]*Qingdao University of Technology, Qingdao 266033, China, email: jjmwolf@outlook.com (J.m. Jiang)*
[d]*The University of Kitakyushu, Kitakyushu 808-0135, Japan, emails: gaoweijun@me.com (W.j. Gao)*

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ABSTRACT

The Mopanshan Reservoir, located in the northernmost of China, is the only drinking water source of Harbin city. The water quality assessment results indicated that the reservoir not only had a characteristic of low temperature, low turbidity, and high chroma but also possessed organic pollution and eutrophication. In the spring freshet period and summer, the Mopanshan Reservoir water exhibited a high concentration of chroma, COD_{Mn}, TN, and TP with a mean value of 20 PCU, 6.85, 2.25, and 0.068 mg/L, respectively. However, only TN of the reservoir exceeded the national standard in the frozen period (1.38 mg/L). The water quality of this reservoir exhibited distinctly seasonal variability. Water quality indicator (WQI) values in 2016, 2017, and 2018 were 0.75, 0.97, and 1.14, which was identified as "Good, Good, and Acceptable". The reservoir also had a trend of slight eutrophication by years through the amended Carlson trophic state index (TSIM) and the comprehensive trophic level index (TLI) analysis. Comparative analysis of effluent quality between the Mopanshan Reservoir and Songhuajiang River suggested that some measures were needed to strengthen the water supply safety for the urban area of Harbin City.

Keywords: Eutrophication; Mopanshan Reservoir; Water quality; Seasonal variability

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1. Introduction

The security of drinking water is closely bound up to human health and economic development [1,2]. It is necessary to evaluate the water quality of the drinking water sources. At present, there are three kinds of drinking water sources in China: river, lake, and groundwater. In terms of Harbin City, located in the northernmost part of China, only has a lake-type reservoir – Mopanshan Reservoir since the nitrobenzene pollution event in 2005 [3,4]. With the rapid development of the urban economy in recent years, the water supply mode of a single water source has seriously restricted the development of the later period. What's more, the water quality variation also plays an important role in ensuring water safety. Poor drinking water quality is harmful to human health [5,6]. Thus, it is necessary to monitor and evaluate the water quality variation of the Mopanshan Reservoir of late years, so that it can help to provide policy decisions concerning water supply security.

Up to now, numerous researches have focused on the assessment of drinking water sources [7,8]. For example, Zhang et al. [9] evaluated the land-use effects on water

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* Corresponding author.

† Co-authors

quality in a typical river basin (Daning River Basin) of the Three Gorges Reservoir Region through redundancy analysis. The spatial and seasonal variability of water quality from the Mopanshan Reservoir was also studied by Li et al. [10]. In addition, the Spatio-temporal changes in surface water quality and sediment phosphorus content of a large reservoir in Turkey were also evaluated by Varol through discriminant analysis, principal component analysis, factor analysis, and cluster analysis [11]. There are quantities of methods to evaluate the water quality, such as the fuzzy mathematical evaluation method, the single factor index evaluation method, and the Canadian Council of Ministers of the Environment (CCME) Water Quality Index (CCME-WQI) [12,13]. Among these water quality assessment methods, WQI is frequently applied, which can transform vast water quality data into a single one that presents the macroscopic water quality [14]. Hou et al. [15] reported the WQI values ranged from 17.8 to 77.8 of five reservoirs in the lower reaches of Yellow River, China, which indicated “good” to “very poor” water quality of reservoirs. Lobato et al. [16] found water sampling stations in fairly populated areas ranged from “Poor” to “acceptable” for the Amazon region, while water quality in the environmental preservation area and near the dam was categorized as “Acceptable”. The water quality of River Ganga in the Himalayan segment was evaluated by Seifi et al. [17] which obtained that the WQI indicated from “excellent” to “good” status.

Furthermore, eutrophication of the reservoir is also a significant index to display the pollution degree of the reservoir. Gámez et al. [18] found the connected reservoirs differed in Carlson’s Trophic Status Index during a drought in central Texas, USA. Guo et al. [19] reported that the Xinlicheng Reservoir was generally in a light-eutrophic state over 5 y, while the spring, summer, and autumn corresponded to mesotrophic, light-eutrophic, and light-eutrophic state, respectively. Moreover, the eutrophication assessment standards of trophic states for four lake regions in China were also established by Huo et al. [20] based on Chl-a concentration. The results indicated that the frequency distribution analysis based on chlorophyll-α combined with a trophic level index provided a useful metric for the assessment of the lake trophic status.

In this work, the main aims of the study are (1) to evaluate the raw water quality of the Mopanshan Reservoir; (2) to appraise the eutrophication of the reservoir through the eutrophic state index; (3) to evaluate the finished water quality of the reservoir through the traditional water purification process (coagulation–precipitation–filtering–disinfection). Moreover, the WQI method and eutrophication analysis were taken into account. By evaluating the water conditions of the northern cold region reservoir, it is hoped that the results can help to create management actions or decision-making policies to ensure drinking water safety.

2. Materials and methods

2.1. Study area

The Mopanshan Reservoir is located in the upper of the mainstream of the Lalin River, Wuchang City, Heilongjiang Province, which is about 180 km away from the urban area of Harbin City (Fig. 1). The longitude and latitude of the reservoir are 127°41′20″ E, 44°23′40″ N, respectively. The drainage area above the reservoir dam site is 1,151 km^2, with a total storage capacity of 5.23 billion m^3. The normal water storage of the reservoir is 318 m, which has a total water storage capacity of 3.56 billion m^3. And the reservoir has a dead water level of 304.5 m and a dead storage capacity of 0.91 billion m^3. Meanwhile, the annual average runoff amount of the reservoir is 5.61 billion m^3/a. The inflow mainly depends on three inflow streams and surface runoff in catchment areas, which is greatly affected by the natural precipitation. Among its outflows, the yield as the water source is 3.37 billion m^3/a, and the annual average environmental water supply is 0.13 billion m^3/a. The rest of the outflows are agricultural compensation water supply in irrigated areas, water-use for the environment, and irrigation water, which mainly concentrate on May to September every year. The Songhuajiang River Basin, located between 41°42′~51°38′ N and 119°52′~132°31′ E, is at the northernmost end of the seven major river basins in China. It has an interval catchment area of 18.64 ten thousand km^2. And the annual average runoff amount is 321.8 billion m^3.

2.2. Sampling and data

All water samples were obtained below 0.5 m from the surface water over 3 y (2016–2018). A 5 L acid-treated

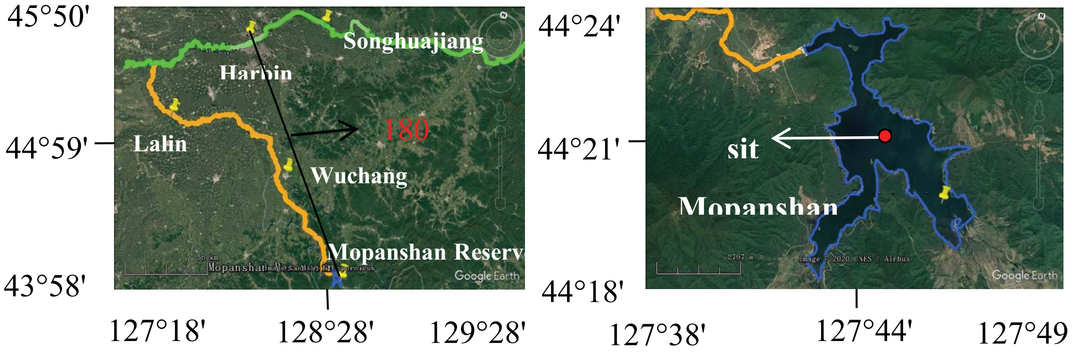

Fig. 1. Location map of Mopanshan Reservoir.

high-density polyethylene bottle was applied to collect water samples at a time interval. After the determination of field parameters (pH, temperature, turbidity, and dissolved oxygen (DO)), the samples were transported and stored for further analysis [21,22].

In order to assess the water quality of Mopanshan Reservoir, pH, temperature, chroma, turbidity, DO, 5 d biochemical oxygen demand $(\mathrm{BOD})_5$, the potassium permanganate index ($\mathrm{COD}_{\mathrm{Mn}}$), total phosphorus (TP), total nitrogen (TN), ammonium (NH_4^+–N), chemical oxygen demand ($\mathrm{COD}_{\mathrm{Cr}}$), routine ion, and typical disinfection by-products (DBPs) were available from the Ministry of Environmental Protection of the People's Republic of China and determined according to the Chinese National Standard Methods [23,24]. The detection methods of major indexes are as follows: $\mathrm{COD}_{\mathrm{Cr}}$ by GB/T 15456-2008, TP by GB11893-1989, TN by GB11894-1989, NH_4^+–N by HJ/T 195-2005, $\mathrm{COD}_{\mathrm{Mn}}$ by GB 11892-1989, typical DBPs by GB/T 17130-1997 [25–29].

2.3. Water quality indicator analysis

In this work, an improved WQI method, raised by Xu et al. [30], was applied regarding the water quality characteristics of reservoirs in China. This method is different from simple weighting and superposition, in which the worst index is highlighted to make the evaluation result more objective. The formula is listed in Eq. (1):

$$\mathrm{WQI} = \sqrt{\frac{1}{\mathrm{n}}\sum I_i \times I_i(\max)} \tag{1}$$

where WQI is the water quality indicator; I_i is the single factor index; $I_i(\max)$ is the maximum value among the single factor index; n is the total number of the studied parameter.

The corresponding scoring criteria are presented in Table S1. The higher the number, the worse the water quality.

2.4. Eutrophication analysis

2.4.1. Amended Carlson trophic state index

The amended Carlson trophic state index (TSIM) overcomes the one-sidedness of single factor evaluation of eutrophication, which includes transparency (SD), Chl-a, and phosphorus (TP). The relevant formulas are presented in Table S2. The relationship between the TSIM and eutrophication is listed in Table S3.

2.4.2. Comprehensive trophic level index

The comprehensive trophic level index (TLI) is another method to appraise the eutrophic state of the water body, which contains $\mathrm{COD}_{\mathrm{Mn}}$, SD, Chl-a, TN, and TP [31,32]. The involved formulas are shown in Table S4. The calculation of TLI is shown as in Eq. (2). A series of consecutive numbers from 0 to 100 are used to grade the eutrophic state of water bodies. The relationship between the TLI and eutrophication is presented in Table S5.

$$\mathrm{TLI}\,(\textstyle\sum) = \sum W_j \cdot \mathrm{TLI}\,(j) \tag{2}$$

where TLI ($\sum$) stands for the comprehensive trophic level index; W_j stands for the correlation weight of the eutrophic state index of the j parameter; and TLI (j) stands for the eutrophic state index of the j parameter.

With Chl-a as the reference parameter, the formula of the normalized correlation weight of the j parameter is shown in Eq. (3):

$$W_j = \frac{r_{ij}^2}{\sum m_{j=1}^{m} r_{ij}^2} \tag{3}$$

where r_{ij} stands for the correlation coefficient between the j parameter and Chl-a; and m is the number of evaluation parameters. The correlation between Chl-a of Chinese reservoirs and other parameters (r_{ij}, r_{ij}^2, and W_j) is shown in Table S6.

3. Results and discussion

3.1. Raw water quality of the Mopanshan Reservoir

3.1.1. Typical physical parameters

In this study, water quality variations about several typical physical parameters were explored (2016~2018) to evaluate the quality of the Mopanshan Reservoir. Results of chroma, turbidity, and water temperature obtained from the water samples are shown in Fig. 2. It was obvious that the water body presented a characteristic of low temperature and low turbidity during the freezing period. The mean water temperature ranged from 3°C to 8°C, showing no significant differences ($P_{\mathrm{ANOVA}} = 0.387 > 0.05$). During this period, the surface of the reservoir was completely frozen (1 m thick). The water under the ice layer exhibited a laminar flow or laminar-turbulent transition, which resulted in the material exchange mainly depending on the diffusion effect [33]. Moreover, the water body showed a correspondingly stable and low value of chroma, and turbidity for the sealed reservoir, decrease of inflow from the upstream catchment, and fewer suspended load. Among them, the mean turbidity and chroma were 1.7 NTU and 20 PCU, respectively. Furthermore, the variation of turbidity also exhibited no significant differences with $P_{\mathrm{ANOVA}} = 0.064 > 0.05$, while that of chroma was significantly higher in the spring freshet period with $P_{\mathrm{ANOVA}} = 0.000 < 0.05$.

The reservoir began to thaw after entering the spring freshet period, which caused the sediments from the ice surface to enter the reservoir and the inflow of the exogenous water body. During this period, the value of chroma, turbidity, and water temperature increased quickly. The water quality was impacted due to the low water level of this reservoir, the effect of the upstream inflow, input of organic pollutants, and suspended load. The chroma could reach a peak of 42 PCU in this period. The water quality changed greatly and presented poor stability, which was mainly owing to the water inflow in the freshet period and precipitation. However, the three water quality indexes showed dramatic changes in summer and autumn. The mean water temperature was at 12°C~17°C. The turbidity was close to 3 NTU. The chroma could reach up to 50 PCU. The water

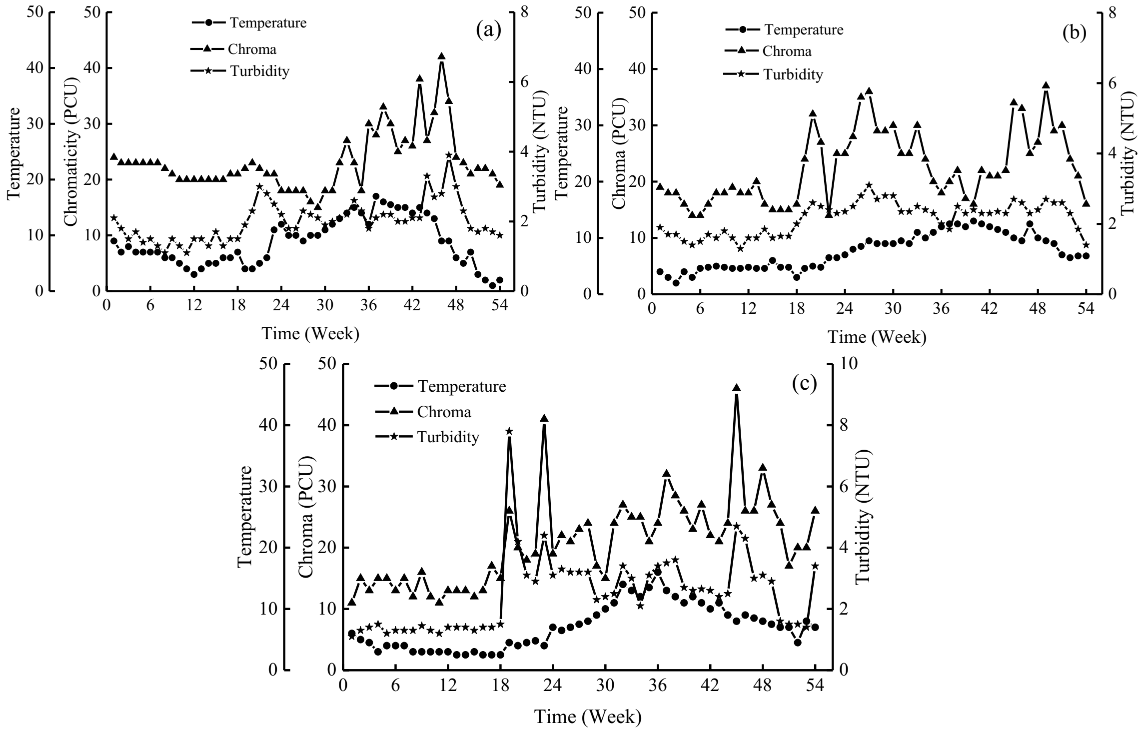

Fig. 2. Water quality variation of the Mopanshan Reservoir from 2016 to 2018: (a) 2016, (b) 2017, and (c) 2018.

body exhibited a characteristic of high chroma. This was mainly due to the heavy precipitation and surface water runoff [34]. In addition, the increased hydraulic gradient also played an important role in the variation of chroma and turbidity. Importantly, it caused the rapid water exchange in the reservoir and the release of the endogenous pollutants stored at the bottom. Furthermore, the change of chroma fluctuated greatly year by year, especially in the summer and autumn periods. This perhaps related to human activity and surrounding vegetation, which increased the content of humic acid and caused the high content of chroma.

3.1.2. Typical chemical parameters

The variation of COD_{Mn}, TN, and TP are significant chemical water quality indexes to reflect the degree of water pollution. The content variation of these indexes from 2016 to 2018 is shown in Fig. 3.

According to the "Environmental Quality Standards for Surface Water" (GB3838-2002) of China, the surface water quality can be divided into cases I~V. Among them, only the cases I~III are suitable for drinking water. The cases III standard of COD_{Mn}, TN, and TP are 6, 1, and 0.05 mg/L, respectively. Obtained from Fig. 3, the values of COD_{Mn}, TN, and TP also presented the characteristic of seasonal variation. In the spring freshet period and summer, the mean values of COD_{Mn}, TN, and TP were 6.85, 2.25, and 0.068 mg/L, which exceeded cases III. It was probably due to the increase of precipitation and the surface runoff, which carried numerous organic substances from soils into the reservoir. Meanwhile, the release of the organic substances in the bottom sludge was also one of the causes of the increase in concentration. Compared to the spring and summer periods, the values of the three indexes were sharply lower in the frozen period. The mean values of COD_{Mn}, TN, and TP were 4.47, 1.38, and 0.036 mg/L. That's because of the slight material exchange and hydraulic gradient for the frozen flow. Apart from the TN, the value of COD_{Mn} and TP both could reach the Cases III. This happened for the low water temperature restricting nitrogen removal by denitrification. Thus, TN was an important index to be controlled to ensure the water quality of the drinking water, especially the drinking surface water in cold northern regions.

Specifically, the value of TN was at a high level from April to September every year and reached a peak during June and July. Since the agricultural production period usually occurs from April to September, the value of TN increases with the nitrogen-containing fertilizers entering into the reservoir through surface runoff. The value of TP was lower than 0.05 mg/L in 2018, while it exceeded the cases III in April 2017 (0.093 mg/L). The value of TP reached the cases III in February 2017 as well as June 2018. The value of TP reached the peak in June (0.08 mg/L) every year due to the phosphorus fertilizer used in agricultural production, which entered the reservoir along with surface runoff. Thus, there existed a potential risk of water eutrophication in the Mopanshan Reservoir for the increasing of TN value year by year and non-negligible TP. Moreover, there showed a significant difference among the seasonal variation for COD_{Mn} ($P_{ANOVA} = 0.000 < 0.05$), TN ($P_{ANOVA} = 0.000 < 0.05$), and TP ($P_{ANOVA} = 0.000 < 0.05$), which indicated that the three indexes exhibited a remarkable seasonal variation.

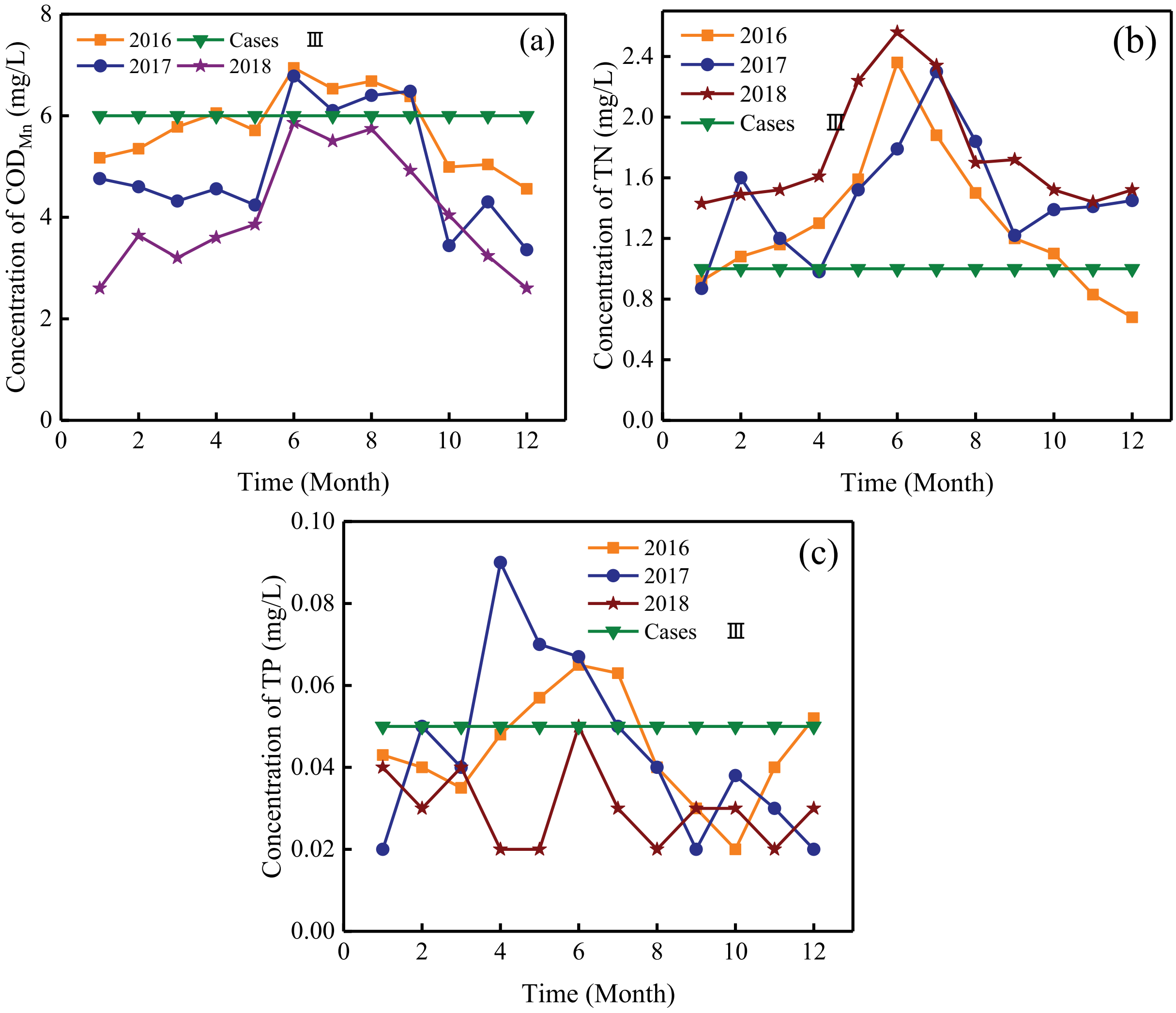

Fig. 3. Variation of COD_{Mn}, TN, and TP in the Mopanshan Reservoir between 2016 and 2018: (a) COD_{Mn}, (b) TN, and (c) TP.

Overall, the water quality of the Mopanshan Reservoir exhibited high-value chroma, organic pollution, and the excess of TN, TP in spring and summer, while showed the excess of TN in the frozen period.

3.1.3. Assessment of the WQI

The water quality parameters in the Mopanshan Reservoir exhibited a characteristic of seasonal variation. To thoroughly evaluate the water quality of the reservoir, WQI in the freshet period and frozen period was evaluated. In this work, this method was mainly involved 15 parameters: pH, DO, COD_{Mn}, COD_{Cr}, BOD_5, TN, TP, fluoride, sulfate, chloride, nitrate, iron, manganese, chroma, and turbidity. The WQI values of the reservoir in the freshet period and frozen period from 2016 to 2018 are displayed in Fig. 4.

The WQI values in the freshet period from 2016 to 2018 were 1.73, 1.63, and 1.82, which was rated as "Bad". This was mainly due to the precipitation, surface runoff, release from substrate sludge, and the rising of the water temperature, resulting in the strong exchange of substance and numerous

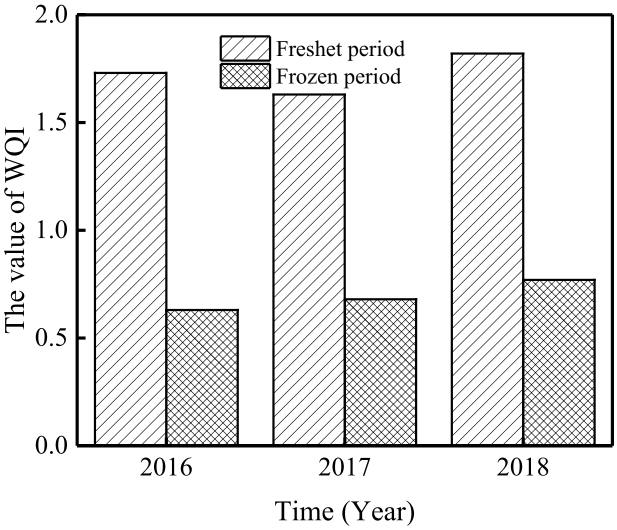

Fig. 4. WQI values of the reservoir in the freshet period and frozen period from 2016 to 2018.

pollutants entering the reservoir. However, the WQI values in the frozen period from 2016 to 2018 were 0.63, 0.68, and 0.77, which was rated as "Good". This was mainly owing to the low temperature, which caused the reservoir to freeze, and zero input of exogenous source. Furthermore, the calculated WQI values in 2016, 2017, and 2018 were 0.75, 0.97, and 1.14, which was identified as "Good, Good and Acceptable". It indicated the water quality of the reservoir tended to deteriorate in recent years.

3.2. Eutrophication assessment of the Mopanshan Reservoir

The evaluation of the eutrophic state index is usually used to study the eutrophication trend of water quality in the reservoir. It mainly involves five eutrophication indicators: TN, TP, COD_{Mn}, SD, and Chl-a. According to the above water quality analysis of the Mopanshan Reservoir, TN and TP exceeded the cases III standard. It implied the reservoir existed the risk of eutrophication. In this work, TSIM and TLI were applied to evaluate the eutrophication of the Mopanshan Reservoir. The value of the eutrophication indicators of the reservoir from 2016 to 2018 is listed in Table 1. It was obvious that the value of COD_{Mn} decreased year by year, while the value of TN increased year by year. The value of Chl-a was also increasing by years, which caused the transparency of the reservoir to reduce every year.

The TSIM was calculated based on the formulas in Table S2. The results are presented in Table 2. In general, the higher the Carson index at the same nourishment state, the more severe the eutrophication is. The TSIM of the Mopanshan Reservoir from 2016 to 2018 was 61.49, 66.79, and 68.15, respectively. The TSIM value increased by the year. The reservoir showed a state of eutropher. Compared to the Carson index, the TLI takes TN and COD_{Mn} into account, which can comprehensively appraise the eutrophication of the reservoir. The results about the TLI are listed in Table 3. The higher the TLI value at the same nourishment state, the worse the eutrophication is. It could be seen that the TLI of the Mopanshan Reservoir from 2016 to 2018 were 52.32, 56.21, and 56.55, respectively. The TLI value also increased by years, while the reservoir showed a state of light eutropher. In a word, the Mopanshan Reservoir exhibited a characteristic of eutrophication in recent years, no matter what the evaluation method was. The eutrophication not only can produce the algal toxin but also can induce the generation of trichloromethane, which reduces the safety of drinking water [35]. Thus, it is significant to relieve the eutrophication of the reservoir.

As a whole, the existence of some seasonal-exceeding parameters and trend of eutrophication increased the difficulty in water treatment and safety risk of drinking water, although the water quality of the Mopanshan Reservoir was still suitable for drinking water in recent years. Thus, it is necessary to dispose of the water in the reservoir to improve the water quality of the drinking water source.

Table 1
Value of the eutrophication indicators of the Mopanshan Reservoir from 2016 to 2018

Year	Eutrophication indicator				
	TP (mg/L)	TN (mg/L)	COD_{Mn} (mg/L)	Chl-a (μg/L)	SD (m)
2016	0.028	1.22	5.53	16.34	0.5
2017	0.05	1.87	4.26	25.63	0.4
2018	0.034	2.34	3.28	37.41	0.3

Table 2
Amended Carlson trophic state index of the reservoir

Year	Eutrophication indicator			Carlson index-TSIM	Eutrophic state
	TSIM (TP)	TSIM (Chl-a)	TSIM (SD)		
2016	52.92	55.09	76.45	61.49	Eutropher
2017	60.20	60.00	80.17	66.79	Eutropher
2018	55.35	64.13	84.97	68.15	Eutropher

Table 3
Comprehensive trophic level index of the reservoir

Year	Eutrophication indicator					Comprehensive trophic level index-TLI	Eutrophic state
	TLI (TP)	TLI (TN)	TLI (COD_{Mn})	TLI (Chl-a)	TLI (SD)		
2016	36.29	57.90	46.60	55.34	64.63	52.32	Light eutropher
2017	45.71	65.13	39.66	60.23	68.96	56.21	Light eutropher
2018	39.45	68.93	32.70	64.33	74.54	56.55	Light eutropher

3.3. Analysis of finished water quality in the Mopanshan Reservoir

According to the above raw water quality analysis of the Mopanshan Reservoir, the reservoir not only had a characteristic of low temperature, low turbidity, and high chroma but also possessed organic pollution and eutrophication. It seriously threatened the safety of drinking water. At present, the prevalent water purification process is still "coagulation-precipitation-filtering-disinfection". In this study, the water quality of the treated reservoir from 2016 to 2018 was analyzed as follows.

The major water quality indexes of the finished water are presented in Table 4. Based on the "Standards for drinking water quality" (GB5749-2006), the majority of detectable indexes all could reach or be inferior to the national standard except for COD_{Mn} in the freshet period and NH_4^+–N in the frozen period, which averagely exceeded 1.16 and 1.21 folds than the standard value. The conventional treatment was ineffective to eliminate the COD_{Mn} in the freshet period and NH_4^+–N in the frozen period.

Just as the above analysis, the reservoir had a trend of eutrophication, which was easy to lead to the disinfection by-products (DBPs) exceeding the standard after the use of liquid chlorine disinfection [36,37]. Hence, a detailed statistical analysis of DBPs was performed. The results are shown in Table 5. According to the qualitative analysis of organic substances in the effluent, there were 10 types of DBPs detected, including trichloromethane, chloral hydrate, trichloroacetic acid, dichloroacetic acid, bromodichloromethane solution, dichloromethane, tribromethane, dibromochloromethane, cyanochloride, and 2,4,6-trichlorophenol. Only five of them could be detected, while the concentration of the other ones was below the limit of detection. All of these DBPs met the drinking water standard except for chloral hydrate, which averagely exceeded 1.87 folds than the standard value. The DBPs content of the reservoir could not reach the drinking water standard through the conventional water purification process. Thus, it is urgent to adopt measures to ensure drinking water safety.

3.4. Analysis of finished water quality in the Songhuajiang River

Due to the poor treatment effect of the traditional process for the Mopanshan Reservoir water, it is imperative to solve this problem to ensure the drinking water safety of

Table 4
Major water quality indexes of finished water in the Mopanshan Reservoir

Index	Threshold value	2016		2017		2018	
		Freshet period	Frozen period	Freshet period	Frozen period	Freshet period	Frozen period
pH	6.5–8.5	7.02	6.92	6.80	7.00	7.00	7.02
Chloride (mg/L)	250	6.73	6.35	8.20	7.724	9.17	8.84
Sulfate (mg/L)	250	8.54	8.12	10.33	7.657	9.16	8.17
Total hardness (mg/L)	450	30	38	34	38	36	40
NH_4^+–N (mg/L)	0.5	0.165	0.54	0.245	0.6	0.15	0.68
Fluoride (mg/L)	1.0	0.05	0.02	0.08	0.017	0.02	0.01
COD_{Mn} (mg/L)	3	3.13	2.74	3.62	2.06	3.70	2.27
Chroma (PCU)	15	8.40	6.20	5.2	9.20	8.20	7.4
Turbidity (NTU)	1	0.29	0.68	0.74	0.81	0.21	0.33

Table 5
Monitoring value of disinfection by-products of finished water in the Mopanshan Reservoir

Index	Threshold value (mg/L)	2016		2017		2018	
		Freshet period	Frozen period	Freshet period	Frozen period	Freshet period	Frozen period
Trichloromethane	1	0.0253	0.0244	0.0207	0.0073	0.0052	0.0032
Chloral hydrate	0.01	0.021	0.015	0.015	0.016	0.027	0.018
Trichloroacetic acid	0.1	0.019	0.018	0.012	0.010	0.013	0.01
Dichloroacetic acid	0.05	0.011	0.006	0.004	<0.001	0.015	<0.001
Bromodichloromethane solution	0.06	0.0023	0.003	0.001	<0.001	<0.001	<0.001
Dichloromethane	0.02	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Tribromethane	0.1	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Dibromochloromethane	0.1	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Cyanogen chloride	0.07	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
2,4,6-Trichlorophenol	0.2	<0.02	<0.02	<0.02	<0.001	<0.001	<0.001

Harbin City. Changing the water source and upgrading the drinking water treatment process are two effective methods. However, the Mopanshan Reservoir, which is the single supplying source, possesses two disadvantages for the development of economics. The first one is the inherent eutrophication, which can produce algal toxins and DBPs. The other one is the long water transfer distance between the reservoir and the urban area of Harbin City (180 km), which results in two gravity pipelines are used for water transport. In case of the pipeline explosion, it will directly affect the production and domestic water supply of Harbin residents and enterprises, and bring about an adverse impact on society. Although the Songhuajiang River has been withdrawn as a water source of Harbin City for the nitrobenzene pollution event in 2005, the water quality can reach up to the Cases III standard after more than 10 y remediation and treatment. Several researchers maintain the Songhuajiang River is suitable for the drinking water source at the moment [38,39]. Thus, reconsidering the Songhuajiang River as the drinking water source perhaps is an alternative for Harbin City. The monitoring values of the major water quality indexes after the conventional treatment in 2017 are listed in Table 6.

It could be seen that all water quality indexes met the drinking water standard except for the NH_4^+–N in the frozen period, which exceeded 3.78 folds than the standard value. However, the excessive NH_4^+–N could be solved by adopting advanced treatment processes, such as O_3/activated carbon process, biological contact aeration process, biological filter biological fluidized bed, and membrane filtration [40]. When the concentration of NH_4^+–N in raw water was 1.65 mg/L, the value in the effluent after the process was 0.33 mg/L, which distinctly reached the drinking water standard.

The monitoring result of the DBPs after the treatment of raw water in the Harbin segment from the Songhuajiang River in 2017 is listed in Table 7. It could be seen that there were 10 types of DBPs in the Songhuajiang River. Only four of them could be detected, while the concentration of the other ones was below the limit of detection. Surprisingly, the detected DBPs all met the drinking water standard. Although there existed excessive NH_4^+–N in the frozen period for the Songhuajiang River, the effluent could reduce the content of DBPs and guarantee the safety of drinking water.

Table 6
Major water quality indexes of finished water in the Songhuajiang River

Index	Threshold value	Monitoring value (mg/L)	
		Freshet period	Frozen period
pH	6.5–8.5	7.05	7.03
Chloride (mg/L)	250	14.79	14.17
Sulfate (mg/L)	250	18.72	27.96
Total hardness (mg/L)	450	69.33	88.67
NH_4^+–N (mg/L)	0.5	0.05	1.89
Fluoride (mg/L)	1.0	0.25	0.26
COD_{Mn} (mg/L)	3	2.77	2.65
Chroma (PCU)	15	13.62	8.40
Turbidity (NTU)	1	0.79	0.43

Table 7
Monitoring value of disinfection by-products of finished water in the Songhuajiang River

Index	Threshold value (mg/L)	Monitoring value (mg/L)	
		Freshet period	Frozen period
Trichloromethane	1	0.0027	0.0072
Chloral hydrate	0.01	0.003	0.005
Trichloroacetic acid	0.1	0.002	0.011
Dichloroacetic acid	0.05	0.005	0.020
Bromodichloromethane solution	0.06	<0.001	<0.001
Dichloromethane	0.02	<0.0001	<0.0001
Tribromethane	0.1	<0.001	<0.001
Dibromochloromethane	0.1	<0.001	<0.001
Cyanogen chloride	0.07	<0.01	<0.01
2,4,6-Trichlorophenol	0.2	<0.001	<0.001

In view of the favorable treatment of the Songhuajiang River water via the traditional water purification process, it is possible to reemploy the Songhuajiang River as the drinking water source. Importantly, the dual-source combined water supply of the Mopanshan Reservoir and Songhuajiang River perhaps can strengthen the water supply safety for the urban area of Harbin City and relieve the disadvantage of a single water source.

4. Conclusion

This paper evaluated the raw water quality of the Mopanshan Reservoir through typical index variation, the WQI method, and eutrophication analysis. In addition, the comparative analysis of effluent quality between the Mopanshan Reservoir and Songhuajiang River was also taken into account. Three conclusions can be summarized as follows:

- The raw water quality of the Mopanshan Reservoir had a characteristic of low temperature, low turbidity, and excessive TN in the frozen period. It was mainly due to the cold climate and poor denitrification. Meanwhile, in the spring freshet period and summer, the reservoir possessed a characteristic of high chroma, COD_{Mn}, TN, and TP. It was mainly owing to the precipitation, surface water runoff, agricultural activity, and the material released from the substrate sludge.
- WQI values in 2016, 2017, and 2018 were 0.75, 0.97, and 1.14, which were rated as "Good, Good, and Acceptable". Moreover, results concluded that the Mopanshan Reservoir had a trend of slight eutrophication by years through the TSIM and TLI analysis.
- After the traditional water purification process, the finished water quality of the Mopanshan Reservoir was

basically up to the requirements of "Standards for drinking water quality" (GB5749–2006), except for COD_{Mn} in the freshet period, NH_4^+–N in the frozen period, and chloral hydrate. However, the finished water quality of the Songhuajiang River could meet the national drinking water standard, apart from NH_4^+–N in the frozen period, which could be removed by upgrading the traditional process.

In view of the poor water quality and long-distance water diversion of the Mopanshan Reservoir, the Songhuajiang River may be an alternative choice to be reemployed as the drinking water source. Importantly, we suggest that the dual-source combined water supply of the Mopanshan Reservoir and Songhuajiang River perhaps can strengthen the water supply safety for the urban area of Harbin City and relieve the disadvantage of a single water source.

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Supplementary information

Table S1
Scoring criteria of the WQI

Value of WQI	Classification
WQI < 0.5	Excellent
0.5 < WQI < 1	Good
1 < WQI < 1.5	Acceptable
1.5 < WQI < 2	Bad
WQI > 2	Poor

Table S2
Formulas of the amended Carlson trophic state index

Index	Formula
TSIM (Chl-a)	TSIM (Chl-a) = 10 (2.46 + lnChl-a/ln2.5)
TSIM (SD)	TSIM (SD) = 10 [2.46 + (3.69 – 1.53 lnSD)/ln2.5]
TSIM (TP)	TSIM (TP) = 10 [2.46 + (6.71 + 1.151 lnTP)/ln2.5]
TSIM	TSIM = [TSIM(Chl-a) + TSIM(SD) + TSIM(TP)]/3

where the unit of Chl-a is μg/L, the unit of SD is m, and the unit of TP is mg/L.

Table S3
Relationship between the TSIM and eutrophication

Value of TSIM	Eutrophic state
<30	Oligotrophic
30~50	Mesotropher
50~100	Eutropher

Table S4
Formulas of the comprehensive trophic level index

Index	Formula
TLI (Chl-a)	TLI (Chl-a) = 10 (2.5 + 1.086 lnChl-a)
TLI (SD)	TLI (SD) = 10 (5.118 – 1.94 lnSD)
TLI (TP)	TLI (TP) = 10 (9.436 + 1.624 lnTP)
TLI (TN)	TLI (TN) = 10 (5.453 + 1.694 lnTN)
TLI (COD_{Mn})	TLI (COD_{Mn}) = 10 (0.109 + 2.661 lnCOD_{Mn})

Table S5
Relationship between the TLI and eutrophication

Value of TLI	Eutrophic state
TLI (∑) < 30	Oligotrophic
30 ≤ TLI (∑) ≤ 50	Mesotropher
TLI (∑) > 50	Eutropher
50 < TLI (∑) ≤ 60	Light eutropher
60 < TLI (∑) ≤ 70	Middle eutropher
TLI (∑) > 70	Hyper eutropher

Table S6
Correlation between Chl-a of Chinese reservoirs and other parameters (r_{ij}, r_{ij}^2, and W_j)

Parameter	Chl-a	TP	TN	SD	COD_{Mn}
r_{ij}	1	0.84	0.82	–0.83	0.83
r_{ij}^2	1	0.7056	0.6724	0.6889	0.6889
W_j	0.2663	0.1879	0.1790	0.1834	0.1834