

Water quality assessment of Middle Route of South-North Water Diversion Project based on modified Nemerow index method

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ABSTRACT

It is of great significance to find a scientific way to assess the water quality of the Middle Route of the South-North Water Diversion Project. In this paper, the spatio-temporal changes of the 26 water quality indicators in eight key monitoring stations along the Middle Route since the project was put into use were analyzed, and the modified Nemerow index method was employed to assess the water quality of the route in its early stage of operation. The results show that the water quality remained good in the period of study. Important water quality indicators were identified, including temperature, permanganate index, dissolved oxygen, total phosphorus, total nitrogen, mercury content, and density of planktonic algae. It is advised that potential ecological risks related to algae and shellfish reproduction in the open canal deserve special attention.

Key words | Nemerow index, South-North Water Diversion Project, water quality assessment, water quality index

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HIGHLIGHTS

- The water quality of the MR-SNWTP since the operation was analyzed.
- The modified Nemerow index method was applied to the South-North Water Diversion Project.
- The performance of the single factor method and the modified Nemerow index method was compared.
- The water quality indicators that deserve special attention were pointed out.
- The suggestion of strengthening monitoring of potential risks posed by algae was put forward.

INTRODUCTION

The South-North Water Diversion Project of China is a grand strategic infrastructure project designed to alleviate the water shortage in northern China, optimize allocation of water resources, guarantee sustainable socio-economic development, and build a well-off society in an all-round way (Wei *et al.* 2010; Tang *et al.* 2014). Since the beginning of the construction of the Middle Route of the South-

North Water Diversion Project (MR-SNWDP), its water quality has been an issue of top concern around the nation, and the water quality standards are high and difficult to meet (Zhao *et al.* 2019). Meanwhile, as the society moves forward and urbanization advances, the water quality of the diversion project draws increasing attention. Especially in recent years, there are frequent reports about seasonal algae outbreaks and siltation in the canal (Lin *et al.* 2017; Zhu *et al.* 2019), which not only poses threat to the water quality and water supply safety of the project, but undermines sustainable development of the water-receiving areas.

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Water quality assessment is a process of selecting proper water quality indicators, water quality standards and calculation methods according to the assessment objective to assess the objective state of water quality by means of numerical values and images and thereby demonstrate the degree of water pollution (Veetil & Mishra 2016; Wu *et al.* 2017). In 1970, R. M. Brown *et al.* put forward the Water Quality Index (WQI) and N.L Nemerow put forward the Nemerow index method to assess the surface water pollution in the New York state (Angelakis *et al.* 1999; Liu *et al.* 2018; Long *et al.* 2019); recent years have seen the application of the fuzzy set theory, grey system theory and mathematical statistics theory to water quality assessment (Shi *et al.* 2017; Wang *et al.* 2017), but the widely discussed topics in water quality assessment research are mainly on the following three aspects: (1) studies on the concentration of selected water quality indicators are based on chemical or biological detection techniques; (2) water quality risk analysis is taken into account in water quality assessment; (3) studies on water quality assessment models. There is currently little research on open-canal water diversion projects under the artificial-natural complex conditions. To fill the research gap, this study intends to: (1) analyze and assess the water quality change characteristics of the main canal of the Phase I project of the MR-SNWD (hereinafter

referred to as the ‘main canal’) since the canal was put into use; (2) employ the modified Nemerow index method to perform a comprehensive assessment according to the water quality characteristics of the main canal and the realities of the project; (3) select and analyze key water quality indicators and offer scientific suggestions for project management in combination with the characteristics of the main canal of the Middle Route.

MATERIALS AND METHODS

Overview of the study area

The South-North Water Diversion Project is by far the largest and most important inter-basin water diversion project in China, consisting of the East Route, the Middle Route, and the West Route (Figure 1). The Middle Route project (32.67–39.98° N; 111.71–116.27° E) is a manually-dug open canal with a total length of 1,432 km that starts from the Danjiangkou Reservoir of Hubei, spans the Yangtze River, Huaihe River, Yellow River and Haihe River from south to north, and crosses Henan, Hebei, Tianjin and Beijing, diverting water to the four aforementioned provinces and municipalities directly under the central

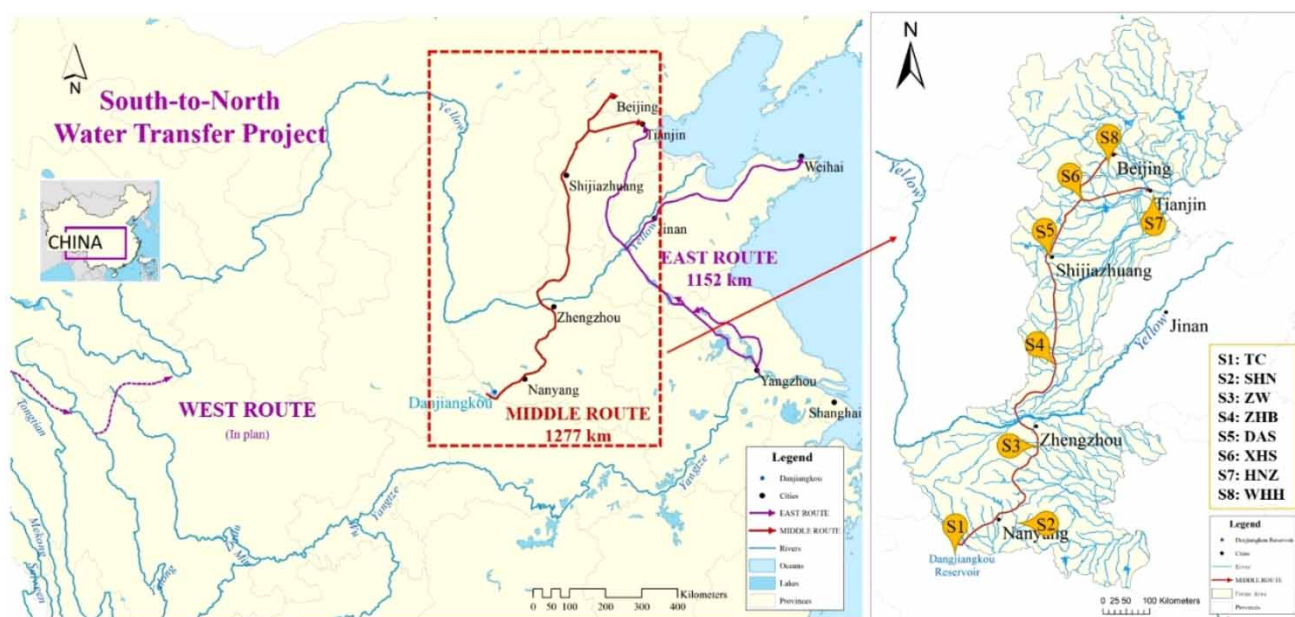


Figure 1 | Schematic diagram of the study area and the locations of the water quality monitoring stations.

government. Since the canal started to divert water on December 12th, 2014, the Middle Route has benefited about 60 million residents along the route.

Data source and sample test methods

The original water quality data used in this study are from the Construction and Administration Bureau of South-to-North Water Diversion Middle Route Project (the MR Administration Bureau) and official permission has been obtained for the analysis and processing of these data. Data from eight monitoring stations (Figure 1) were used in this study, and 26 water quality indicators were used, of

Data processing

The indicators were not comparable due to the different dimensions and magnitudes of the original data, and normalization was thus required to exclude the influences of different dimensions and magnitudes (Long et al. 2019). In particular, the larger the index value of a positive indicator, the better; while the smaller the index value of a reverse indicator, the better. Here, the 'Range 0~1' method was used to process the data (Yang et al. 2020): suppose the indicators of the system to be $X_{ij} = (x_{ij})$ ($i = 1, 2, \dots, n$; $j = 1, 2, \dots, m$). Normalization processing is performed on X_{ij} , and the normalization formula is as follows:

$$x'_i = \begin{cases} (x_i - x_{\min}) / (x_{\max} - x_{\min}), & x_i \text{ is a positive indicator; the greater } x_i \text{ is, the better} \\ (x_{\max} - x_i) / (x_{\max} - x_{\min}), & x_i \text{ is a negative indicator; the smaller } x_i \text{ is, the better} \end{cases}$$

which 24 are the routine test items stipulated in the Environmental Quality Standards for Surface Water of the People's Republic of China, and the remaining two are the monitoring items added by the MR Administration Bureau to its actual water quality management; the threshold standards were determined according to the regular items in the *Environmental Quality Standards for Surface Water* (GB3838-2002) and the standards specified in the *Water Quality Guide*. The sampling methods and the methods for chemical analysis of samples were based on the *Standards and Methods for Water and Wastewater Inspection* (Appendix A).

Establishment of assessment methods

Building the assessment indicator system

The water quality assessment indicator system of the main canal of MR-SNWDP was built based on data of normal operation of the long-distance water diversion project and statistics from the MR Administration Bureau. The characteristics and risks of the MR-SNWDP were comprehensively considered, and new indicators including bio-toxicity and ecological indicators were added to the system, as shown in Table 1.

where x_{\min} and x_{\max} are the minimum and the maximum values of the indicator x_i .

RESULTS AND DISCUSSION

Water quality characteristic analysis

General indicators

The indicators of the assessment system were analyzed first, and then a further characteristic analysis was performed on indicators with obvious changes, including the pH value, water temperature (T), permanganate index (PI), five-day biochemical oxygen demand (BOD₅) and dissolved oxygen (DO). Among nutritional salts, total phosphorus (TP), total nitrogen (TN) and ammonia nitrogen (NH₃-N) were selected as the key indicators for in-depth analysis.

The annual average pH scale was between 8.1 and 8.4, indicating the water quality in the main canal of the MR-SNWDP remained alkaline throughout the monitoring and assessment period (Figure 2(a)). Water temperature (T) showed a trend of overall decline from south to north, in conformity with the temperature change pattern of China,

Table 1 | Water quality assessment indicator system for the main canal of the MR-SNWDP

Target layer	Primary criterion layer	Secondary criterion layer	Factor layer	Indicator attribute	
Water quality assessment of the main canal of the MR-SNWDP	Conventional indicators	General indicators	Water temperature	Variable-amplitude indicator	
			pH value	Range indicator	
Dissolved oxygen			Positive indicator		
Permanganate index			Reverse indicator		
Chemical oxygen demand (COD)			Reverse indicator		
Five-day biochemical oxygen demand (BOD ₅)			Reverse indicator		
Ammonia nitrogen (NH ₃ -N)			Reverse indicator		
TP (measured in P)			Reverse indicator		
TN (measured in N in lakes and reservoirs)			Reverse indicator		
Toxicity indicators			Toxicity indicators	Copper	Reverse indicator
				Zinc	Reverse indicator
				Fluoride (measured in F ⁻)	Reverse indicator
				Selenium	Reverse indicator
				Arsenic	Reverse indicator
	Mercury	Reverse indicator			
	Cadmium	Reverse indicator			
	Chromium (hexavalent)	Reverse indicator			
	Lead	Reverse indicator			
	Cyanide	Reverse indicator			
Unconventional indicators	Biotoxicity Ecological indicators	Volatile phenol	Reverse indicator		
		Petroleum	Reverse indicator		
		Anionic surfactant	Reverse indicator		
		Sulfide	Reverse indicator		
			Fecal coliform (ind./L)	Reverse indicator	
			Comprehensive biotoxicity	Reverse indicator	
			Density of planktonic algae (DPa × 10 ⁴ ind./L)	Reverse indicator	

as shown in Figure 2(b). The maximum and minimum values were recorded at 32 °C and 0.5 °C, respectively, and the average temperature was 16–18 °C, without significant spatial differences. The PI value displayed a gradual increase from south to north along the canal, as shown in Figure 2(c). According to the limit of 2.0 mg/L for national standard (GB3838-2002) Level I water, only 50% of the sections met the standard, and it thus can be seen that the significant change trend of PI requires close attention. The BOD₅ of all the sections met the standard of GB Level I water and was less than 3.0 mg/L, as shown in Figure 2(d). COD and BOD₅ are indicators for the degree of pollution of organic matter to water. This showed the concentration of organic matter in the water along the canal was in a significant downward trend, and the possible cause is that the organic matter was

utilized and assimilated by the animals and plants in the water (Cheng et al. 2019) or that the organic matter settled on a small scale with the utilization of sediment microorganisms and the like in the water (Shao et al. 2014). To sum up, the changes in the two indicators, PI and BOD₅, deserve special attention.

Dissolved oxygen (DO) is a positive indicator, and the average value at each station were all higher than 7.5 mg/L and met the requirements of GB Level I water, as shown in Figure 3(a). The changes in TP are presented in Figure 3(b), and the concentration was around 0.01 mg/L during the monitoring and assessment period, meeting the standard of Level I water. TN exhibited no obvious spatial differences and temporal changes from south to north, as shown in Figure 3(c). The annual average concentration

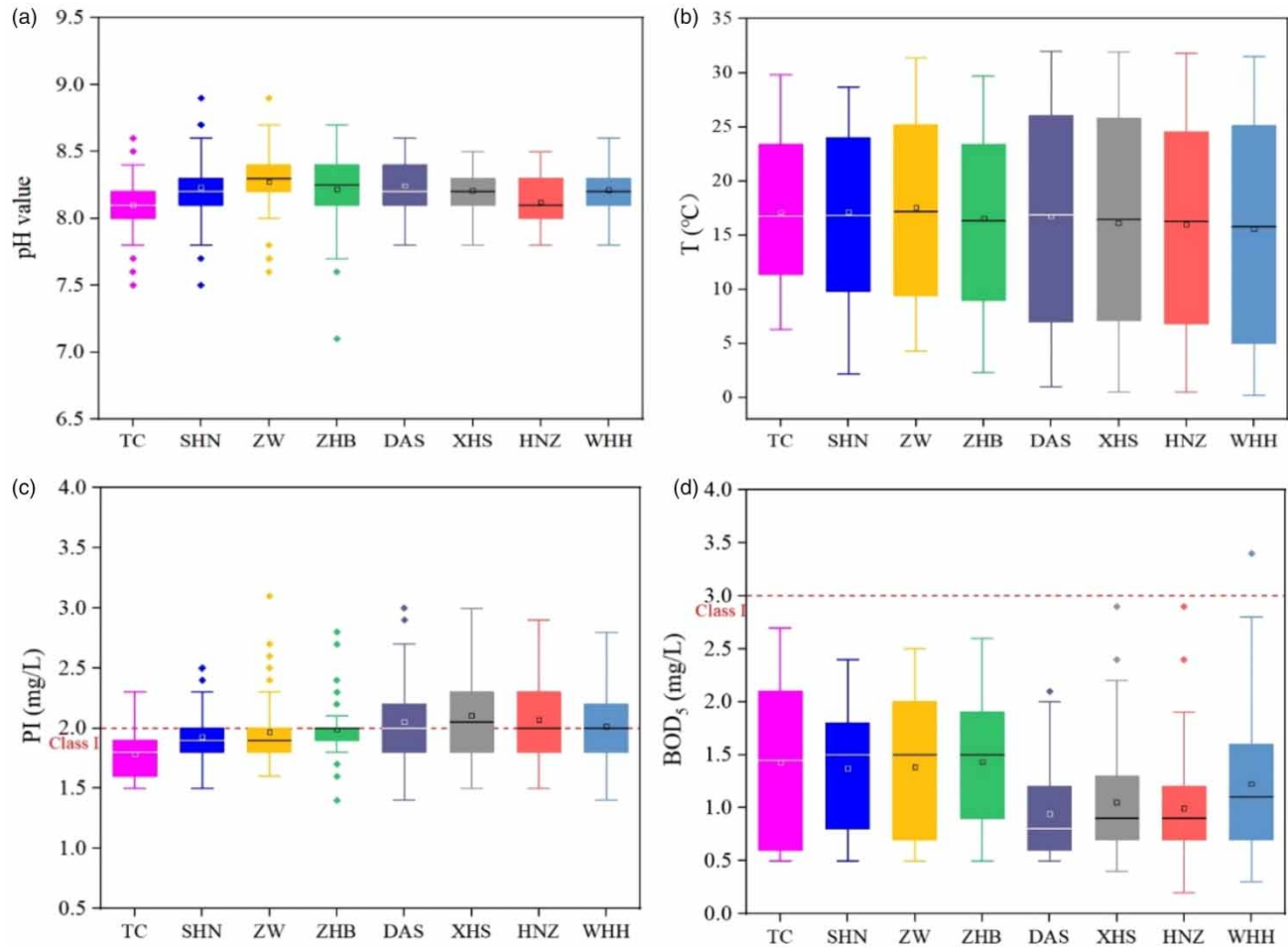


Figure 2 | Average concentration and standard deviation of (a) pH, (b) T, (c) PI and (d) BOD₅ in eight water quality monitoring sections of the MR-SNWDP from 2015 to 2018.

was around 1.0 mg/L, and the concentration at some sections was 50% higher than this concentration standard, which might be related to the high background value of total nitrogen in water source (Tan *et al.* 2015). Ammonia nitrogen did not show obvious changes from south to north, as shown in Figure 3(d). However, the ammonia nitrogen value exceeded the Level I water standard of 0.15 mg/L in a few stations in the latter stage, so it should be monitored as an important water quality indicator.

Toxicity indicators

Heavy metal ions and other toxic substances are important indicators affecting water quality. After comprehensive

analysis of all toxicity indicators, mercury and arsenic were selected for in-depth analysis. The limit value of mercury in Level I water was lower than 0.00005 mg/L, and the values from all the sections met the requirement of Level I water, as shown in Figure 4(a); the values at several time points were lower than the detection limit of 0.0001 mg/L, but it requires long-term attention due to its high toxicity. The concentration of arsenic was all lower than the standard limit of Level I water, as shown in Figure 4(b). Arsenic showed a random trend and this might be related to the weathering and settlement of the rock mass or the soil composition in the vicinity (Liu *et al.* 2016). It is advisable to focus on the changes of these two indicators in future work and perform cumulative monitoring and assessment.

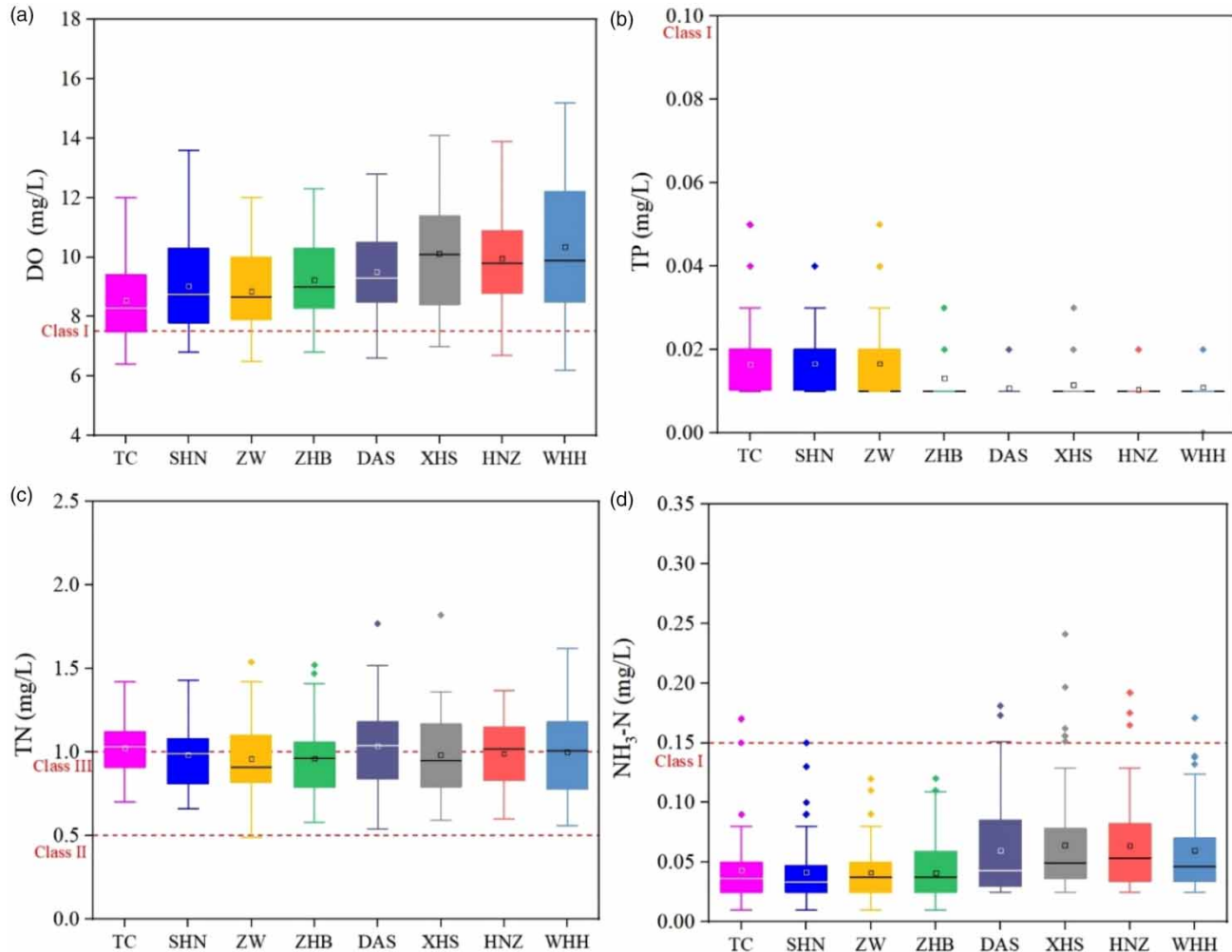


Figure 3 | Average concentration and standard deviation of (a) DO, (b) TP, (c) TN and (d) NH₃-N in eight water quality monitoring sections of the MR-SNWD from 2015 to 2018.

Ecological factor indicators

The ecological factors for assessment include comprehensive biotoxicity, fecal *Escherichia coli* and density of planktonic algae. The percentage concentration of luminescent bacteria was used to monitor the comprehensive biotoxicity, and there was no case where the concentration of luminescent bacteria was higher than 30%, but the comprehensive biotoxicity remains a very important indicator. The overall average concentration of fecal *E. coli* in all monitoring stations was lower than 200 ind./L, meeting the requirements for Level I in GB, as shown in Figure 4(c). The concentration tended to increase gradually from south to north along the canal, and this increasing trend is

particularly prominent in the northern part of the water-receiving area. Algae is another important ecological indicator. The annual average data in Figure 4(d) revealed that the density of planktonic algae (DPA) gradually increased from south to north, but not an increase in the strict sense. This trend may be related to the impact of management measures such as manual salvage of algae.

Comprehensive water quality assessment based on the modified Nemerow index method

With the modified Nemerow index method, comprehensive water quality assessment was carried out based on the standard limit of Level II water quality in the *Environmental*

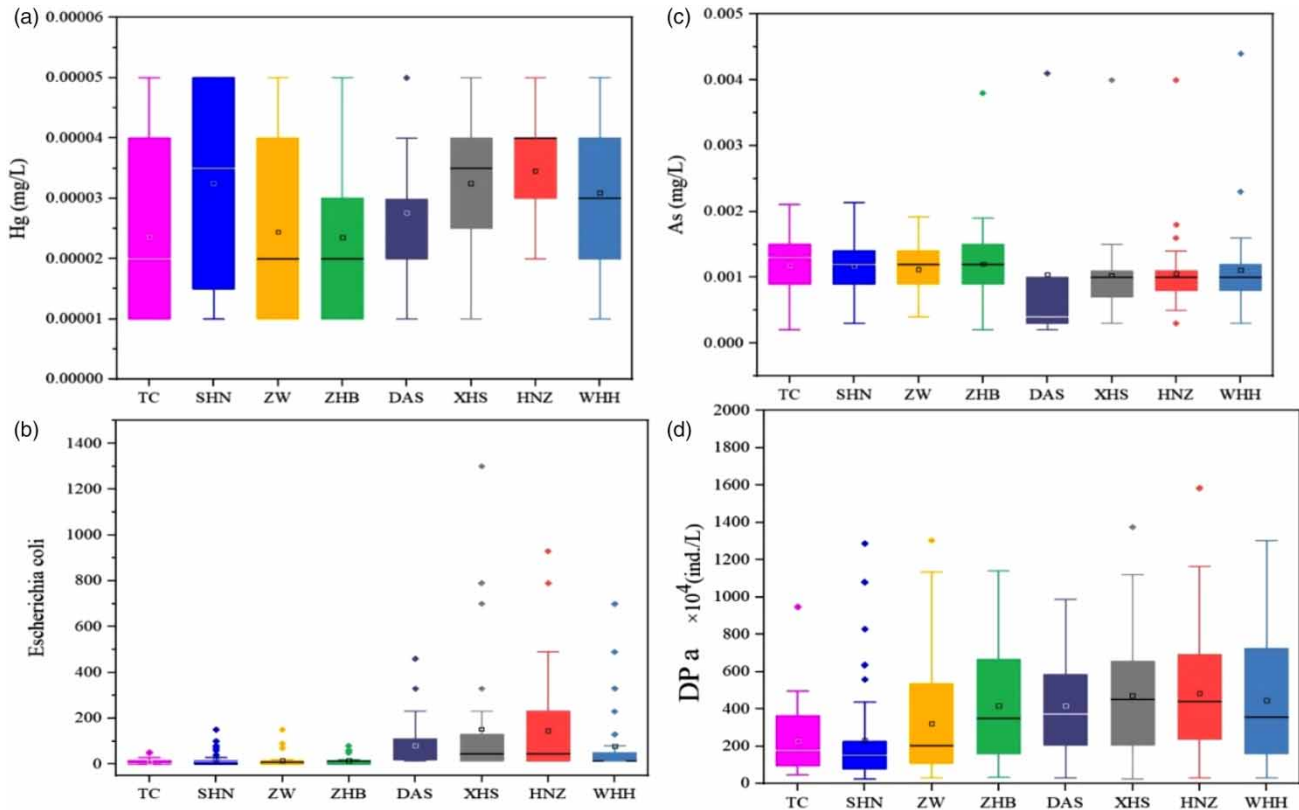


Figure 4 | Average concentration and standard deviation of (a) Hg; (b) As; (c) *Escherichia coli*; and (d) DP-a in 8 water quality monitoring sections of the MR-SNWDP from 2015 to 2018.

Quality Standards for Surface Water (GB3838-2002) and 26 indicators, including 24 selected water quality assessment indicators and two added indicators (comprehensive biotoxicity and density of planktonic algae). The water quality was divided into five categories (A1, A2, A3, B1 and B2) as per the GB standards, and through value assignment and weighted calculation, the water quality standard limits for different categories of water quality were obtained. These values of water quality standard limits (for rivers) were then used to calculate the modified Nemerow index corresponding to various water quality levels, as shown in Table 2. When the calculation result of the modified Nemerow index is less than 1, the water quality is considered as A1; that is, the best water quality; when the

calculation result of the modified Nemerow index is between 1 and 2, the water quality is categorized into A2, which means the water is 'safe and sensitive', and so on.

The overall assessment results of the water quality of the main canal in 2018 were shown in Figure 5. The overall *P*-value was between 0.5 and 2.0, suggesting a safe and good water quality. Different sections presented certain changes and differences in different seasons, and the Nemerow index scores of TC, SHN, DAS and WHH experienced obvious seasonal changes and underwent a typical increase in spring and autumn. The water quality was ranked by season according to the scores: winter < summer < spring < autumn. There are two possible causes: first, the impact of climate, light and temperature; second, the multidimensional

Table 2 | The modified Nemerow index and classification of water quality categories

Water quality category	A1 Very good	A2 Safe and sensitive	A3 Safe but fragile	B1 Poor	B2 Badly
Nemerow index <i>P</i>	$P \leq 1.0$	$1.0 < P \leq 2.0$	$2.0 < P \leq 3.0$	$3.0 < P \leq 4.0$	$4.0 < P \leq 5.0$

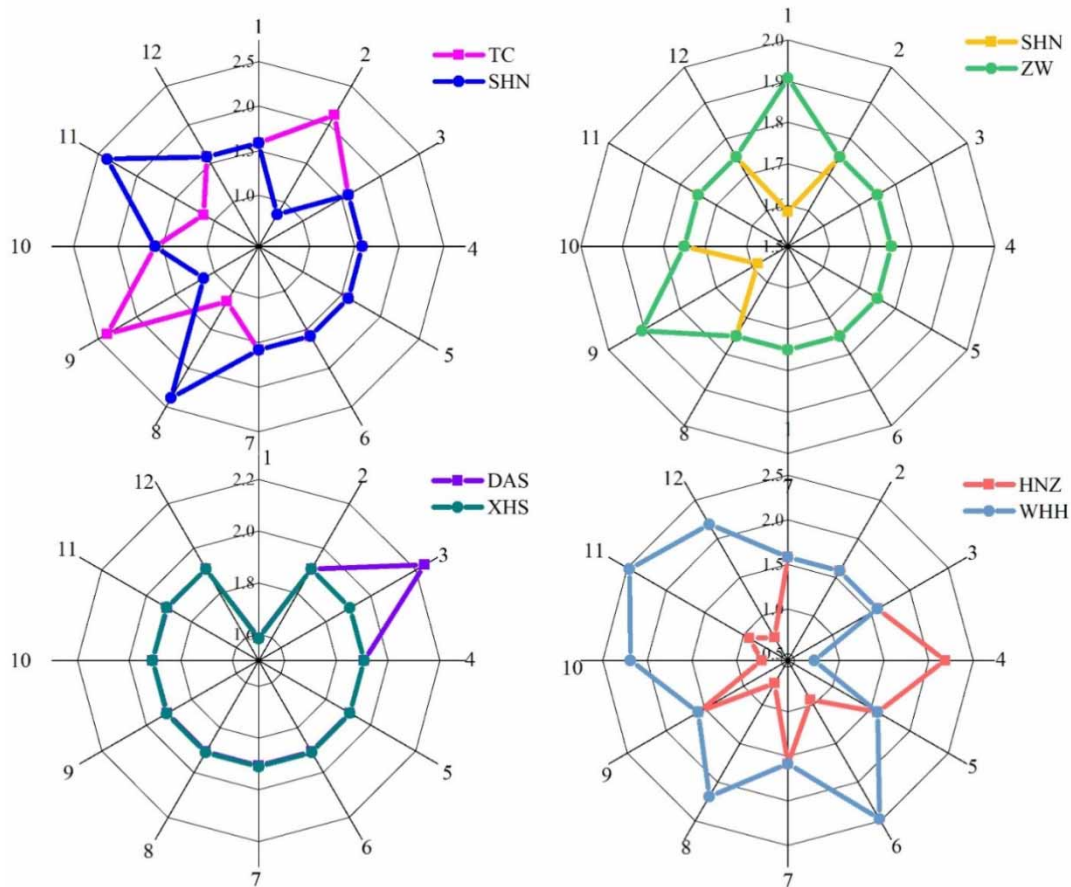


Figure 5 | Results of applying the modified Nemerow index method to assess the 8 monitoring stations of the main canal of the MR-SNWDP from January to December 2018.

comprehensive effect of water quality factors. In terms of natural environmental conditions, water quality indicators such as water temperature, dissolved oxygen, permanganate index, ammonia nitrogen and density of planktonic algae had great influences on the comprehensive calculation result of the water quality index (Nong *et al.* 2020); then in terms of project operation and management, uncertain factors such as the control over risk sources and mechanical operation might also affect the water quality (Kuo *et al.* 2019). As a small-scale ecological system, the open canal creates a suitable growing environment for aquatic plants in spring and autumn when the light and temperature are comfortable. Nonetheless, the ecological system is still unstable at the beginning of the project operation, and there might be an explosive growth of aquatic animals and plants without a natural enemy or artificial intervention. Using the modified Nemerow index method to analyze and assess the water

quality of the main canal can, under the condition that the overall water quality is good, help discover the hidden dangers and pollution risks, in order for the management department to carry out emergency prevention and control or disposal accordingly (Nong *et al.* 2020).

Impact of weight on the assessment results

In routine operation, the MR Administration Bureau used the single-factor assessment method based on the national standards for surface water assessment to select the worst water quality level as the basis for assessment (Figure 6(a)), but this method might fail to reach an accurate assessment of the overall water quality. The assessment result obtained by this method showed that the water quality of the monitoring stations was at a poor level, meeting the GB standards for Class IV or Class V water, as shown in Figure 6(a).

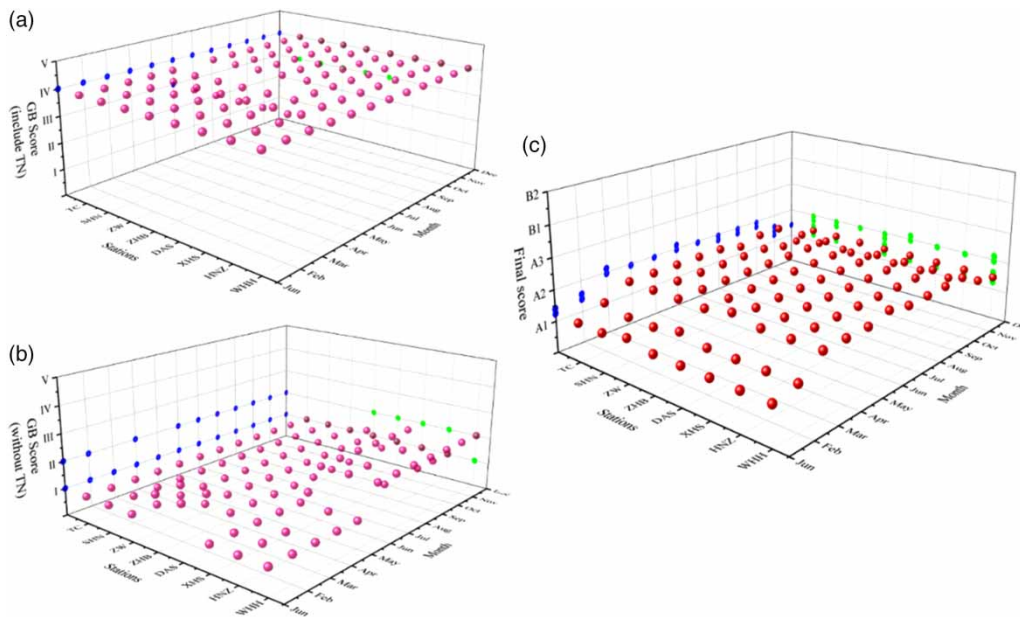


Figure 6 | Results of the comparison of the traditional single-factor method with (a) or without (b) TN index and the results with the Nemerow index method (c) with the 26 indicators from Table 1.

This result, however, was subject to the impact of the high value of TN. With the impact of TN excluded, the water quality improved considerably and met the GB standards for Level I and Level II water, as shown in Figure 6(b). The assessment result obtained by the modified Nemerow method was shown in Figure 6(c), where A1, A2, and A3 represent ‘very good’, ‘safe and sensitive’, and ‘safe but fragile’ water quality, respectively; B1 and B2 represent ‘poor’ and ‘bad’ water quality, respectively. Comparison of these three figures shows that the assessment result obtained by the modified Nemerow method indicates the poor water quality measured in the stations from March to October, which more accurately reflects the overall water quality and ecological conditions in these stations than the single-factor method and excluded the impact of the abnormally high indicator of TN concentration. Moreover, the proposed method can reflect the dynamic changes of the water quality along the open canal of the Middle Route. Different from natural water delivery systems, the open canal is an artificial system that has been in service for merely five years, so its long-term ecological impact should be given attention. The comparison verified the modified Nemerow method and confirmed its validity to guide real-world engineering practice.

CONCLUSION

In this paper, the water quality of the main canal of the MR-SNWDP from its start of service to March 2019 was analyzed based on 26 water quality indicators in eight key stations along the canal. The modified Nemerow index method was employed to provide comprehensive water quality assessment, and the major conclusions are as follows.

- (1) During the study period, the water quality of the MR-SNWDP has stayed at ‘Level II’ or ‘Level I’ water quality level; that is, a ‘good’ or ‘excellent’ level, of the GB Water Quality Standards (with the impact of TN concentration excluded); physicochemical and heavy metal indicators all met the GB standards of Level II water quality; water safety was assured during the monitoring and assessment period.
- (2) Compared with the single-factor assessment method, the modified Nemerow index method delivers a more objective assessment result and better reflects the changes of water quality in spring and autumn; it also demonstrates the contribution of indicators like the heavy metal content and nutrient salt content to the overall water

quality, thereby providing a more comprehensive view of the impacts of different factors on the water quality than the single-factor method. Despite the different results these two methods reached, both showed that the water quality of the Middle Route remained at a good or excellent level since it has been put into service.

- (3) Major water quality indicators that deserve special attention were defined, including temperature, permanganate index, total phosphorus, total nitrogen, mercury, arsenic and density of planktonic algae. Moreover, it is advisable that administrations pay more attention to environmental indicators like the temperature and TN/TP that might cause abnormal reproduction of algae and shellfish.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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