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Research on Water Quality Assessment Using the Water Quality Index for the Eastern Route of the South-to-North Water Diversion Project

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Abstract: The South-to-North Water Diversion Project's Eastern Route (SNWDPC-ER) has drawn a lot of attention as one of China's most significant water diversion projects. This study calculated the water quality index (WQI) to analyze the spatial and temporal characteristics of water quality in the study area as well as the effects of water diversion, and developed the minimum water quality index (WQI_{min}) model based on stepwise multiple linear regression, using data from 56 monitoring stations along the delivery canal of the SNWDPC-ER (the SNWDPC-delivery ER's canal) from 2014 to 2018. Here are the findings: (1) The water quality state was rated as "good" and the annual average value of WQI climbed year over year along with improvements in water quality. (2) There was a clear difference in water quality across time and space, with autumn having better water quality than other seasons and the south having better water quality than the north. (3) Water quality is impacted by water diversion; throughout the era of diversion, water quality was steadier. (4) The weighted WQI_{min} model, which is a quick and inexpensive way to assess water quality, can be used to evaluate the water quality in the SNWDPC-delivery ER's canal. The model's parameters are DO, NH_3-N, BOD_5, and TN.

Keywords: water quality index (WQI); the South-to-North water diversion project; water quality assessment

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1. Introduction

Due to socio-economic development, it has become difficult to meet the water demand of economically developed areas by intra-basin water diversion alone. Long-distance inter-basin water transfers have become a major means of redistributing water resources and alleviating the needs of water-scarce regions [1–4]. While long-distance water transfer brings many benefits, it also has a long-term impact on the ecological environment of the transfer area, the receiving area, and the rivers and lakes along the route [5,6]. Therefore, it is essential to evaluate the water quality of rivers on the route of long-distance water transfer projects.

The methods of water quality evaluation mainly include the single factor evaluation method, water quality index method, fuzzy evaluation method, and so on. Among them, the water quality index method is a method that has been widely applied in recent years. The water quality index (WQI) method converts selected water quality parameters to the same scale and produces a dimensionless number that reflects the water quality of a river or lake by calculation [7,8]. The WQI, which was first proposed by Horton, R.K. [9], breaks through the limitations of traditional water quality evaluation by simply comparing water quality parameters. Among various water quality assessment methods, WQI is suitable for long-term comprehensive water quality assessment of rivers, which can provide complete information about the health status of water bodies and play an important role in evaluating the management effectiveness of rivers after long-term treatment [9–11]. Depending on the method, parameter weight determination, and purpose of the evaluation, the WQI can be subdivided into a variety of methods, such as the minimum WQI method (WQI_{min}) [11–16]. WQI_{min} is constructed based on a small number of key water quality parameters, and because it can simplify the evaluation process, improve the efficiency of water quality assessment, and reduce monitoring costs, many scholars have conducted in-depth research on this and applied it to water quality assessment [11]. For example, Pesce, S.F. et al. [17] used the unweighted WQI_{min} to evaluate the water quality of the Suquía River. Nong, X. et al. [18] used the stepwise multiple linear regression method to screen the key water quality parameters for the WQI_{min} and used the weighted WQI_{min} to evaluate the water quality of the Middle-Route (MR) of the South-to-North Water Diversion Project of China.

The Eastern Route of the South-to-North Water Diversion Project of China (SNWDPC-ER) is a typical example of a long-distance water transfer project, which diverts water from the Yangtze River near Yangzhou City, Jiangsu Province, China, and passes through several lakes along the route to reach Tianjin and Shandong Province, among others, to effectively solve the water shortage problem in northern China. Between the start of operations in November 2013 and 2021, 5.298 billion cubic meters of water have been transferred to Shandong Province [19].

Recently, many studies have evaluated the water quality of the SNWDPC-ER. For example, Pan, Y. et al. [20] used an integrated water quality marker index to evaluate the water quality of the Xuzhou section of the delivery canal of the SNWDPC-ER (the SNWDPC-delivery ER's canal). Qu, X. et al. [21] used the WQI to evaluate the water quality of impounded lakes along the SNWDPC-ER. However, the current study mainly focuses on the Storage lakes along the route, which is difficult to reflect the water quality condition of the whole project. And for the long time series, spatial span of the water quality of the SNWDPC-delivery ER's canal is less research, the current lack of in-depth understanding and analysis of the water quality of it. [22]. Furthermore, the current research mainly uses conventional methods, which cannot make a simpler long-term comprehensive evaluation of water quality changes in rivers, and there is less water quality evaluation of the SNWDPC-delivery ER's canal with the WQI method. Hence, this study took 56 water quality stations along the route from Liuzhai Station to Dongping Lake as the research object and conducted a comprehensive water quality assessment for the SNWDPC-delivery ER's canal using WQI to understand the key water quality parameters, establish a scientific basis for water quality management and environmental restoration, and provide a reference for water quality evaluation for other long-distance water transfer projects.

2. Methods

2.1. Study Area and Background

SNWDPC-ER diverts water from the Yangtze River mainstream near Yangzhou City, Jiangsu Province, and lifts water through pumping stations step by step to supply water mainly to Jiangsu and Shandong provinces, improving the water conditions in northern Jiangsu and southwest Lu and providing an emergency water supply to Tianjin and eastern Hebei. The total length of the water transfer line is 1466.5 km, which began operation on 15 November 2013 [19]. The study area was the SNWDPC-delivery ER's canal south of the Yellow River, and there are 56 water quality stations set by the environmental protection department along the route. This study can be divided into four reaches from south to north according to the lakes along the route: Yangtze River–Hongze Lake reach (R1), Hongze Lake–Luoma Lake reach (R2), Luoma Lake–Nansi Lake reach (R3), and Nansi Lake–Dongping Lake reach (R4), see Figure 1.

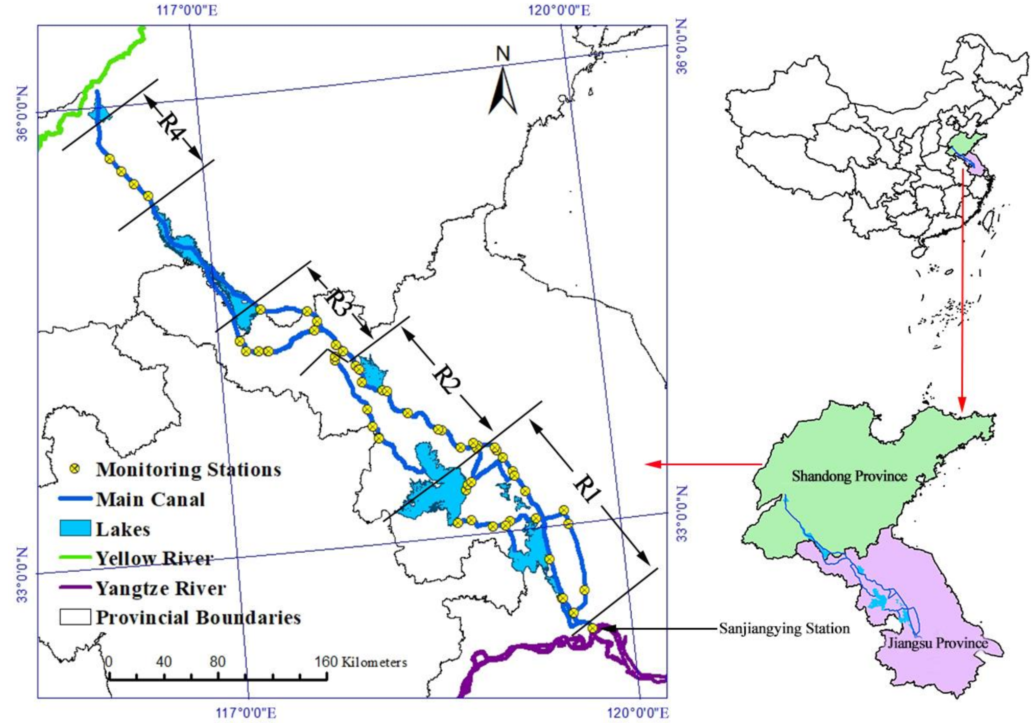

Figure 1. Map of the water quality monitoring stations along the mainline of the first phase of the SNWDPC-ER.

2.2. Data Collection

The SNWDPC-ER has been in operation since November 2013, so this study used month-by-month measured water quality data from 2014 to 2018, which were obtained from the water resources department, to discuss the overall water quality changes in the SNWDPC-delivered ER's canal for 5 years after the diversion. The eight commonly used water quality parameters for the study are listed in Table 1, including pH, dissolved oxygen (DO) (mg/L), the chemical oxygen demand of potassium permanganate (COD_{Mn}) (mg/L), five-day biochemical oxygen demand (BOD_5) (mg/L), nitrate nitrogen (NH_3-N) (mg/L), total nitrogen (TN) (mg/L), total phosphorus (TP) (mg/L), and F^- (mg/L), which had relatively complete data. Other water quality parameters without complete monitoring data were not considered.

Table 1. Monitoring variables are used to calculate the water quality index and their normalization scores and relative weights.

Parameters		Weight (P_i)	Evaluation Standard				
			I	II	III	IV	V
			Ii,1 = 20	Ii,2 = 40	Ii,3 = 60	Ii,4 = 80	Ii,5 = 100
pH (dimensionless)		1			6~9		
DO/(mg/L)	≥	4	7.50	6.00	5.00	3.00	2.00
COD_{Mn}/(mg/L)	≤	3	2.00	4.00	6.00	10.00	15.00
BOD_5/(mg/L)	≤	3	3.00	3.00	4.00	6.00	10.00
NH_3-N/(mg/L)	≤	3	0.15	0.50	1.00	1.50	2.00
TN/(mg/L)	≤	2	0.20	0.50	1.00	1.50	2.00
TP/(mg/L)	≤	1	0.02	0.10	0.20	0.30	0.40
F^-/(mg/L)	≤	2	1.00	1.00	1.00	1.50	1.50

2.3. Water Quality Index Method

The calculation of WQI begins with the selection of the water quality parameters, which can be a fixed set or minimum water quality parameters selected according to the characteristics of the study area. Subsequently, each parameter is weighted and normalized, which converts water quality parameters with different units into unitless subindex values with the same scale. Subsequently, the subindices are aggregated via calculations to obtain a dimensionless number. Finally, the water quality is graded according to the range of the WQI values [11,17].

The WQI was calculated using the methods of Debles et al. and Nong et al. [18,23], as shown in Equations (1) and (2):

$$WQI = \frac{\sum_{i=1}^{n}(C_i P_i)}{\sum_{i=1}^{n} P_i} \tag{1}$$

where n is the total number of water quality parameters, C_i is the normalized value of the ith parameter, and P_i is the weight of the ith parameter. The weights used were based on relevant literature and are presented in Table 1 [15,18].

$$C_i = \begin{cases} 100 - \left[\frac{(T_i - S_{i,k})}{(S_{i,k+n} - S_{i,k})} \times 20n + I_{i,k}\right], T_i \in [S_{i,k}, S_{i,k+n}) \\ 100 - \frac{T_i}{S_{i,k+n}} \times 20n, T_i \in [0, S_{i,k}) \end{cases} \tag{2}$$

where T_i is the measured value of the ith parameter; $S_{i,k}$ and $S_{i,k+n}$ are the standard thresholds for the ith parameter at level k and level (k + n), respectively; $I_{i,k}$ is the standard normalization value of the parameter classification; and n is the number of values that are equal to the threshold. If no threshold exists, then $n = 1$.

For pH, when $6 \leq \text{pH} \leq 9$, $C_i = 100$; otherwise, $C_i = 0$ [24].

The calculation of WQI_{min} was based on key water quality parameters screened by the stepwise multiple linear regression method and calculated according to Equations (1) and (2). When unweighting was applied, this study let $P_i = 1$.

In this study, the water quality was categorized into five grades according to the WQI value [18], as shown in Table 2.

Table 2. Water quality classifications are based on WQI values.

Water Quality	Excellent	Good	Medium	Poor	Very Poor
WQI value	(80, 100]	(60, 80]	(40, 60]	(20, 40]	[0, 20]

2.4. Data Processing

The one-way ANOVA method (One-way ANOVA) and stepwise multiple linear regression analysis were completed in this study using IBM SPSS Statistics 25 software. The one-way ANOVA method was used to determine the spatial variability of water quality parameters in the SNWDPC-ER [25]. Stepwise multiple linear regression was used to select the model water quality parameters, and the determination coefficient (R^2) and the percentage error (PE) were used to determine the applicability of the model.

The WQI_{min} model was constructed as follows. The month-by-month total WQI values and the month-by-month WQI values for each parameter from January 2014 to December 2016 were used for model training. The key water quality parameters of the WQI_{min} model that applied to the SNWDPC-delivery ER's canal were screened by a stepwise multiple linear regression method. Subsequently, by comparing the R^2, PE, and mean values of the WQI_{min} model based on training data, the best WQI_{min} model and key water quality parameters were determined. The month-by-month total WQI values and the month-by-month WQI_{min} values for each model with different water quality parameters selected from January 2017 to December 2018 were used for model validation, and the applicability of the constructed WQI_{min} model was tested by calculating the R^2 and PE of the WQI_{min} model for the validation period.

3. Results

3.1. Water Quality Characteristics of the SNWDPC-ER Mainline

Table 3 gives the statistical results of eight water quality parameters for R1, R2, R3, and R4 for the SNWDPC-delivery ER's canal from 2014 to 2018. As can be seen from the table, the mean value of COD_{Mn} was the lowest in R1 (3.88 mg/L) and the highest in R4 (5.05 mg/L), showing an increasing trend from south to north. The mean values of BOD_5 and TN were the lowest in R1 (1.54 mg/L and 1.83 mg/L, respectively) and the highest in R3 (2.49 mg/L and 3.24 mg/L, respectively), with an overall trend of increasing from south to north. The mean value of TP was the lowest in R4 (0.08 mg/L) and the highest in R2 (0.12 mg/L), showing a decreasing trend from south to north. Overall, the water quality concentration in the SNWDPC-delivery ER's canal gradually increased from R1 to R4, and the water quality gradually deteriorated from south to north.

Table 3. The values of the eight water quality parameters in R1, R2, R3, and R4 of the SNWDPC-delivery ER's canal.

Water Quality Parameters	**Water Quality Measurement Values (2014–2018)**				**Statistical Result**	
	R1	**R2**	**R3**	**R4**		
	Avg. ± S.D.	**Avg. ± S.D.**	**Avg. ± S.D.**	**Avg. ± S.D.**	**F**	***p***
pH	7.97 ± 0.21	8.00 ± 0.25	8.10 ± 0.17	8.06 ± 0.29	3.43	0.43
DO/(mg/L)	8.69 ± 2.05	9.02 ± 1.97	8.63 ± 1.99	9.17 ± 1.99	6.36	0.005 ***
COD_{Mn}/(mg/)	3.88 ± 1.09	4.11 ± 1.34	4.47 ± 0.97	5.05 ± 0.86	28.05	<0.001 ***
BOD_5/(mg/L)	1.54 ± 1.02	1.98 ± 0.78	2.49 ± 0.53	2.41 ± 1.17	8.34	<0.001 ***
NH_3-N/(mg/L)	0.22 ± 0.31	0.42 ± 0.59	0.41 ± 0.30	0.42 ± 0.33	3.38	0.044 **
TN/(mg/L)	1.83 ± 0.68	1.90 ± 0.90	3.24 ± 2.09	2.42 ± 1.50	10.12	<0.001 ***
TP/(mg/L)	0.09 ± 0.04	0.12 ± 0.11	0.11 ± 0.08	0.08 ± 0.07	3.33	0.046 **
F^-/(mg/L)	0.62 ± 0.15	0.75 ± 0.14	0.78 ± 0.16	0.67 ± 0.24	3.55	0.038 **

Notes: Data used for one-way ANOVA analysis were pre-processed. ***, ** indicate significant at the 1% and 5% levels, respectively.

In addition, the one-way ANOVA showed that the *p* for DO, COD_{Mn}, BOD_5, NH_3-N, TN, TP and F^- were all less than 0.05, indicating that they were significantly different spatially. The water quality variation pattern of the SNWDPC-delivery ER's canal was influenced by various factors such as the incoming water quality of the Yangtze River, pollution load input along the route, and storage in the lakes along the route [26,27].

SNWDPC passes through more economically developed areas such as Jiangsu and Shandong, and a large number of towns and farmlands are distributed along the route, with large industrial, domestic and agricultural surface source pollution load input. The overall water quality of the Yangtze River is better than that of the SNWDPC-delivery ER's canal. When the Yangtze River water enters SNWDPC-ER, a large amount of pollution load is imported along the route, and the water quality concentration caused by it increases beyond the self-purification capacity of water quality along the route. Therefore, SNWDPC-delivery ER's canal as a whole shows a trend of gradual deterioration of water quality from south to north. In recent years, the treatment of TP in lakes along the route has been strengthened, the input of TP pollution load along the route has been controlled, and the dilution and degradation effects of lakes along the route have been fully developed, which may be the reasons for the gradual improvement of TP of SNWDPC-delivery ER's canal from south to north. As a water chemistry index, pH tends to fluctuate in a small range and is mainly influenced by factors such as the pH of the inlet rivers along the route. The pH of SNWDPC did not show significant spatial variability, probably because the spatial variation of pH of the inlet rivers along SNWDPC-delivery ER's canal was not significant.

3.2. Water Quality Evaluation via the WQI Method

Evaluation via the WQI showed spatial and temporal trends in the water quality in the SNWDPC-delivery ER's canal. The water quality improved year by year, and the differences among all reaches decreased year by year, as shown in Figures 2–4. From 2014 to 2018, the average WQI (WQI_{ave}) was 67.14. Moreover, the WQI_{ave} of R1, R2, R3, and R4 were typically greater than 60 every year. Therefore, the overall water quality state was classified as "good".

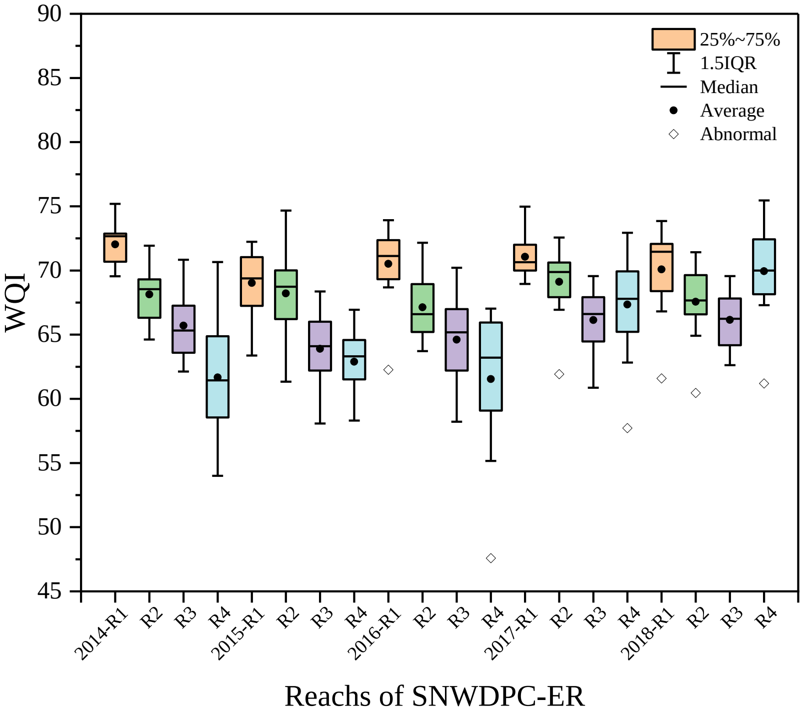

Figure 2. Spatial variations in the WQI in the SNWDPC-ER (from 2014 to 2018; orange: R1, green: R2, purple: R3, blue: R4).

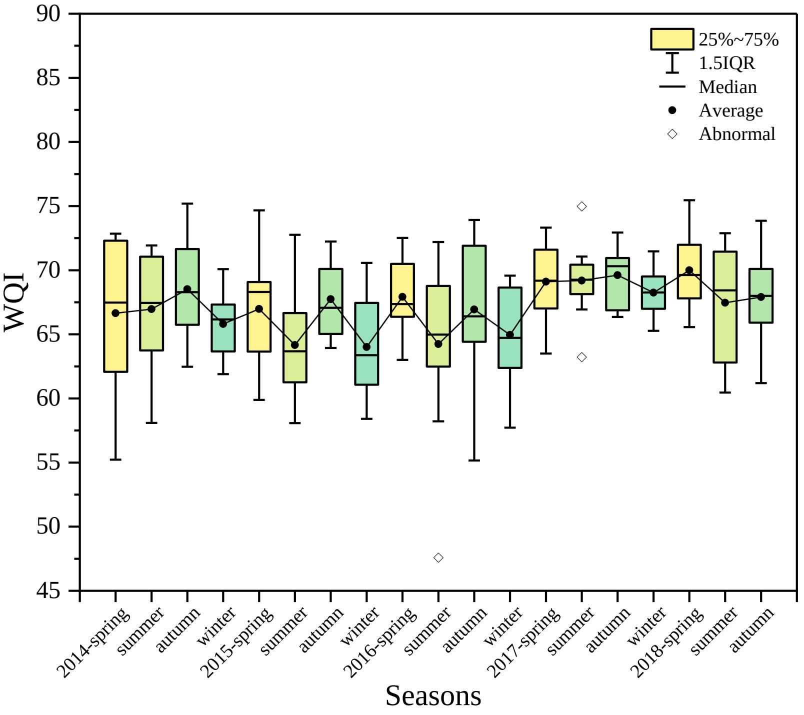

Figure 3. Seasonal variations in the WQI in the SNWDPC-ER (spring, summer, fall, and winter correspond to March–May, June–August, September–November, and December–February, respectively; yellow: spring, yellow-green: summer, blue-green: autumn, blue: winter).

The annual spatial variation map of the WQI of the delivery canal indicates that the WQI_{ave} gradually decreased from R1 to R4, and the water quality gradually deteriorated from south to north. The WQI_{ave} of R4 was lower than that of R3 in 2014, 2015, and 2016, and vice versa in 2017 and 2018. From 2014 to 2018, the water quality of R4 improved significantly. Thus, the difference among all reaches decreased and the water quality improved year by year.

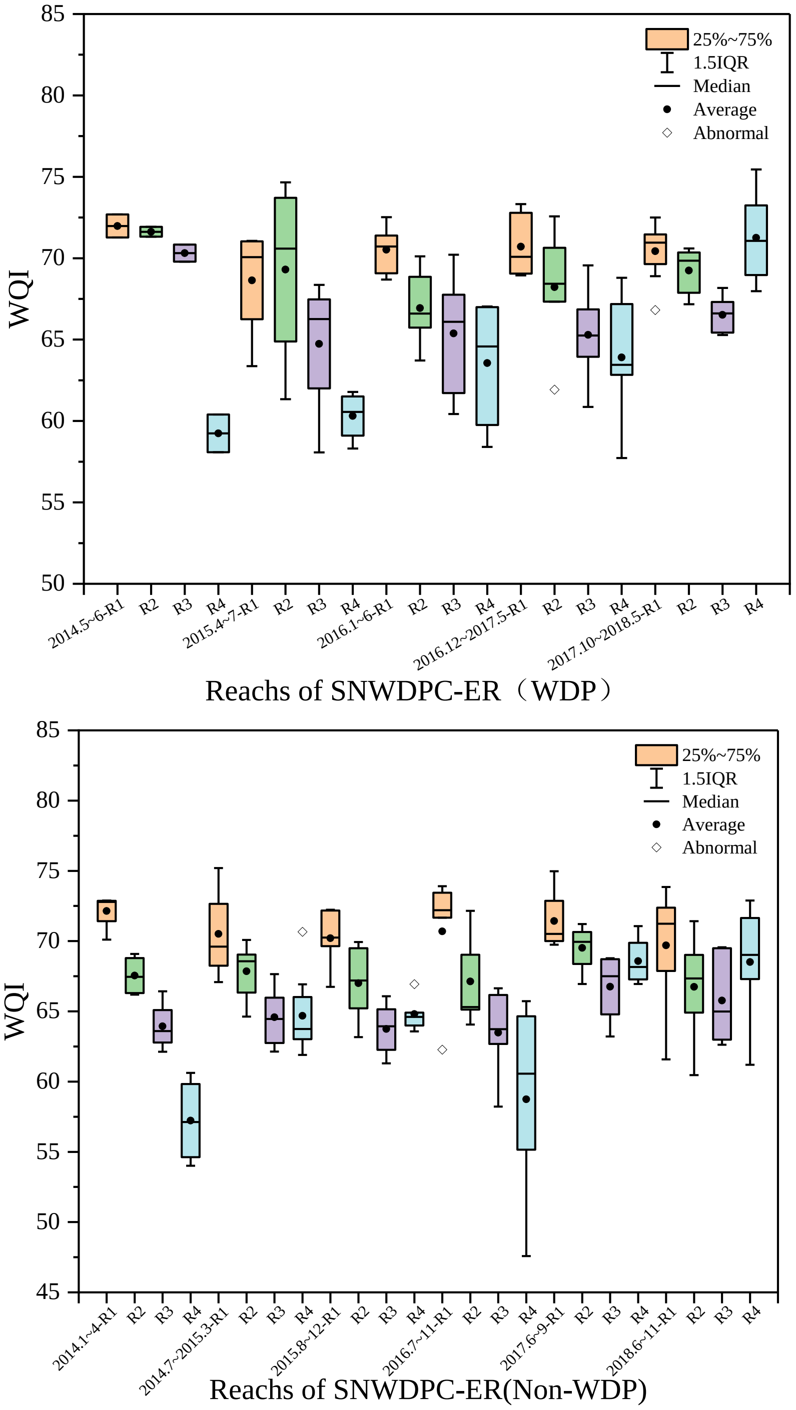

Figure 4. Comparison of water quality evaluations between the water diversion period (WDP) and non–water diversion period (non-WDP) for the SNWDPC-delivery ER's canal (orange: R1, green: R2, purple: R3, blue: R4).

Seasonally, the highest overall WQI_{ave} occurred during spring 2018, and the lowest occurred during winter 2015 (69.99 and 64.01, respectively), with better water quality in autumn than in other seasons. The pattern of seasonal WQI changes was similar each year, and was as follows: decreasing from spring to summer, increasing from summer to autumn, decreasing from autumn to winter, and increasing from winter to spring. This pattern implies that the SNWDPC-delivery ER's canal water environment is stable and that the SNWDPC-ER is operating stably.

The operation of the water diversion project determines the diversion period and the non-diversion period, and the different periods cause significant water quality differences due to water diversion [28]. However, in the long term, the water quality in the SNWDPC-delivery ER's canal has improved during both the diversion and non-diversion periods. The map of the spatial and temporal differences between the water diversion period and non-water diversion period shows that, from 2014 to 2018, it is obvious that the spatial differences between R1, R2, R3, and R4 of the non-diversion period decreased, and the water quality improved significantly. The WQI_{ave} gradually increased in the R4 section during the water diversion period, and the water quality improved significantly. Notably, the water quality in R4 during the non-diversion period in 2016 fluctuated greatly; however, the water quality of other non-diversion periods fluctuated less, probably due to point and surface source pollution.

3.3. Calculation of the WQI_{min} Model

Using the results of stepwise multiple linear regression of the training data, comparison of R^2 and PE values for the weighted and unweighted WQI_{min} models, and comparison of the WQI_{min} and WQI_{ave}, it was determined that the key water quality parameters for the construction of the WQI_{min} model for the SNWDPC-delivery ER's canal were DO, NH_3-N, BOD_5, and TN and their weights should be considered in the calculations. After verifying the test data, the constructed WQI_{min} model was applicable to the water quality evaluation of the East Main Line.

The results of stepwise multiple linear regression of the training data are presented in Table 4. The DO, NH_3-N, and BOD_5 greatly improved the R^2 of the models and contributed the most to the WQI values (models 1, 2, and 3). The TN and COD_{Mn} also slightly improved the R^2 (models 4 and 5). Therefore, the key water quality parameters for constructing the WQI_{min} model of the SNWDPC-delivery ER's canal were DO, NH_3-N, BOD_5, TN, and COD_{Mn}.

Table 4. Parameter selection results via stepwise multiple linear regression for the WQImin model based on the training dataset (n = 36).

Models	Linear Equation	R^2	*p*
1	$0.723 + 0.599 \lg(DO + 1)$	0.603	<0.001 ***
2	$0.639 + 0.433 \lg(DO + 1) + 0.212 \lg(NH_3\text{-N} + 1)$	0.869	<0.001 ***
3	$0.307 + 0.379 \lg(DO + 1) + 0.195 \lg(NH_3\text{-N} + 1) + 0.239 \lg(BOD_5 + 1)$	0.925	<0.001 ***
4	$0.336 + 0.395 \lg(DO + 1) + 0.188 \lg((NH_3\text{-N} + 1) + 0.207 \lg(BOD_5 + 1) + 0.015 \lg(TN + 1)$	0.949	<0.001 ***
5	$0.391 + 0.252 \lg(DO + 1) + 0.171 \lg((NH_3\text{-N} + 1) + 0.179 \lg(BOD_5 + 1) + 0.022 \lg(TN + 1) + 0.164 \lg(COD_{Mn} + 1)$	0.993	<0.001 ***

Notes: The data used for stepwise multiple linear regression analysis were pre-processed using log change: log (WQI + 1). *** indicates significant at the 1% level.

However, the R^2 of models 1 and 2 did not reach 0.9; therefore, instead of using the water quality parameter combinations of models 1 and 2, the weighted and unweighted WQI_{min} were only calculated for the four water quality parameter combinations where the R^2 of the models reached 0.9, as shown in Table 5.

As shown in Table 5 and Figure 5, when the same water quality parameters are selected, the R^2 of the weighted WQI_{min} model (0.907–0.988) was higher than the R^2 of the unweighted WQI_{min} model (0.817–0.928). Moreover, the PE values of the weighted WQI_{min} model were lower than those of the unweighted model; therefore, the weighted WQI_{min} model is more representative of the WQI for evaluating the SNWDPC-ER. Furthermore, among the weighted models, $WQI_{min\text{-}b2}$ had the lowest PE value (3.9%), below 5%, and its average value was the closest to the WQI_{ave}. Therefore, the $WQI_{min\text{-}b2}$ model is the best match for the WQI and can effectively replace the total WQI to evaluate the water quality of the SNWDPC-delivery ER's canal.

Table 5. The degree of explanation of WQI by the two WQImin models based on whether weights are considered (n = 36).

Parameters Selected	**$WQI_{min\text{-}a}$ (Unweighted)**				**$WQI_{min\text{-}b}$ (Weighted)**			
	Model	**R^2**	***p***	**PE (%)**	**Model**	**R^2**	***p***	**PE (%)**
DO, NH_3-N, BOD_5	a1	0.886	<0.001 ***	11.5	b1	0.907	<0.001 ***	10.9
DO, NH_3-N, BOD_5, TN	a2	0.817	<0.001 ***	10.9	b2	0.913	<0.001 ***	3.9
DO, NH_3-N, BOD_5, COD_{Mn}	a3	0.928	<0.001 ***	5.1	b3	0.934	<0.001 ***	5.1
DO, NH_3-N, BOD_5, TN, COD_{Mn}	a4	0.922	<0.001 ***	10.9	b4	0.988	<0.001 ***	6.0

Note: *** indicates significant at the 1% level.

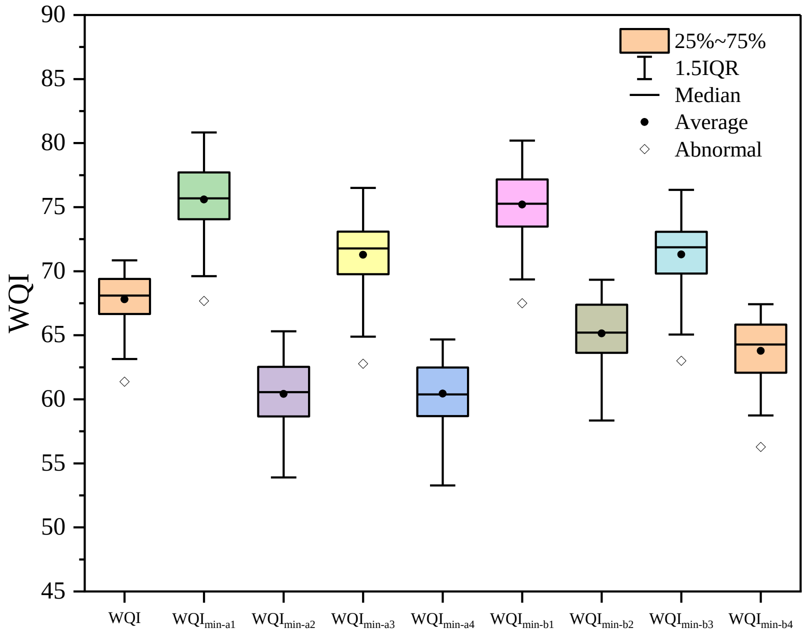

Figure 5. Comparison of WQI and WQI_{min} values based on the training dataset.

The results for the test dataset are shown in Figure 6. Considering PE and R^2, the weighted WQI_{min} model outperformed the unweighted WQI_{min} model when the same water quality parameters were chosen. The lowest PE value (3.7%) was obtained for $WQI_{min\text{-}b2}$, which is consistent with the results of the training data.

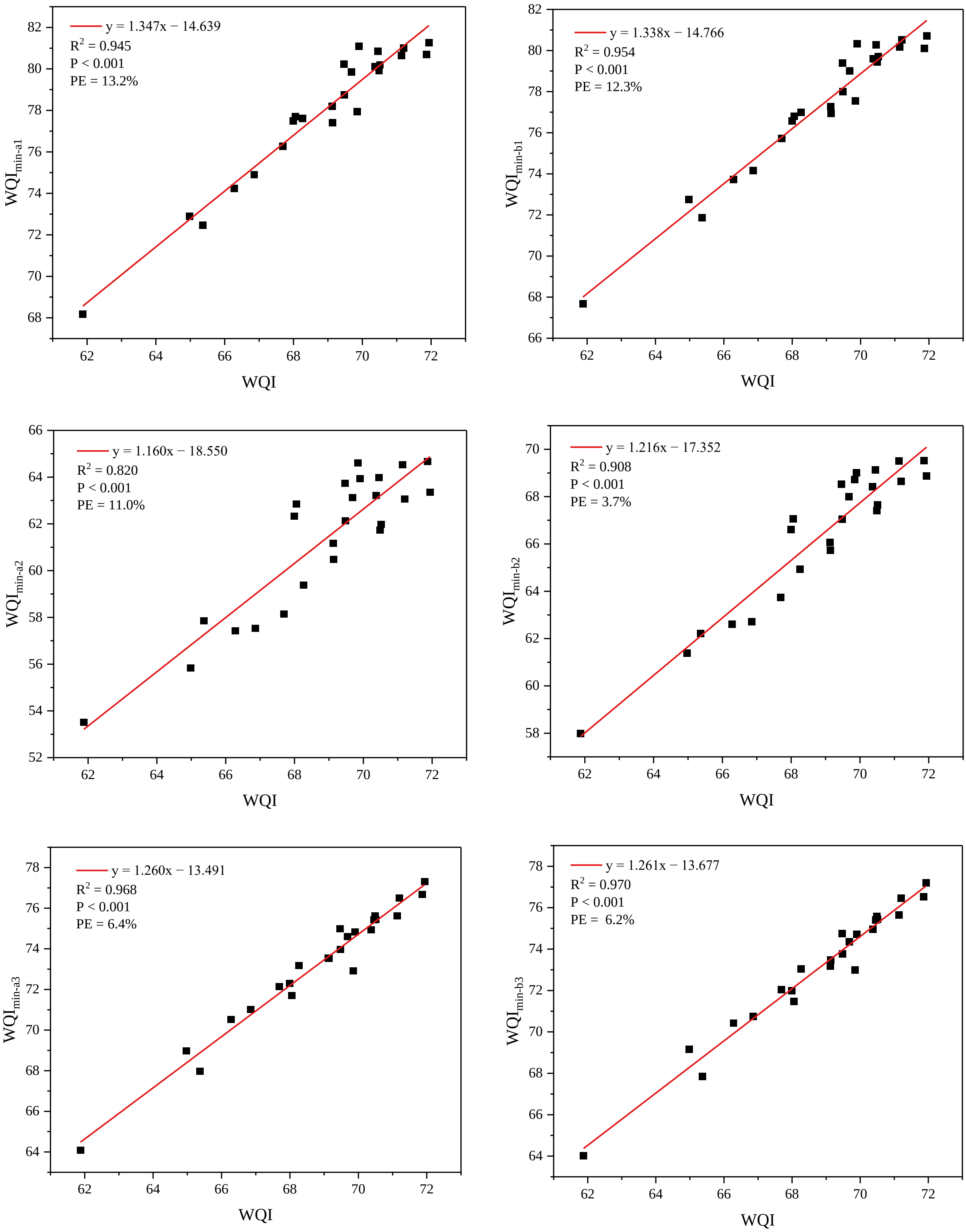

Figure 6. *Cont.*

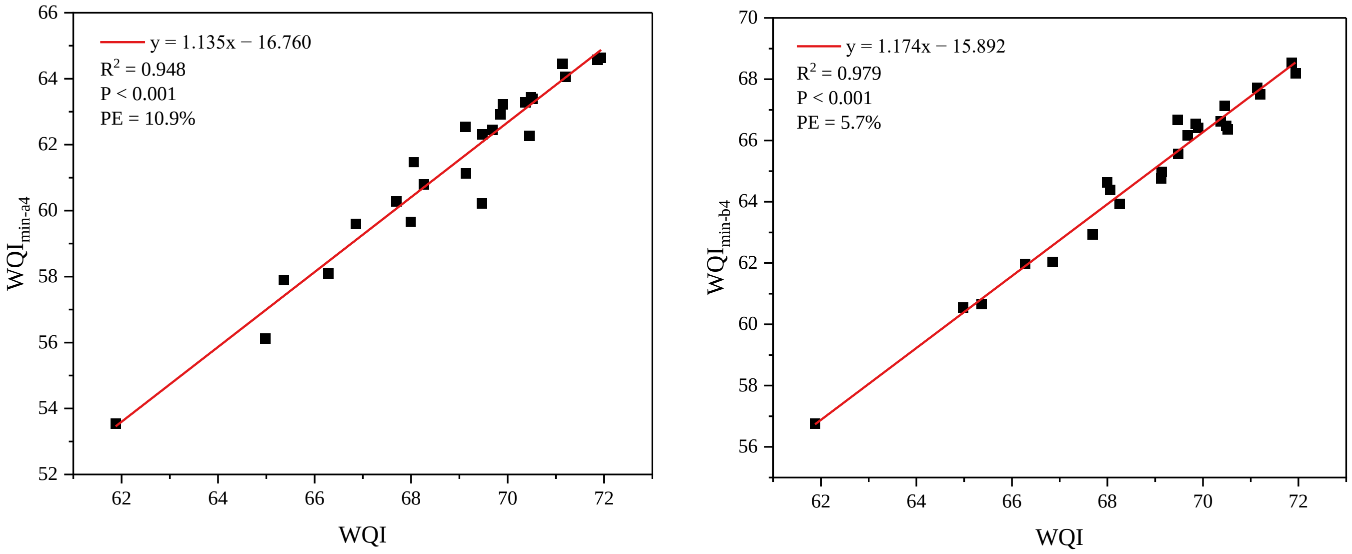

Figure 6. Comparison of the WQI and WQI_{min} values based on the testing dataset (n = 24).

4. Discussion

4.1. Water Quality Characteristics and Influencing Factors

The WQI for the SNWDPC-delivery ER's canal during 2014–2018 indicated that the overall water quality state was classified as "good". However, average WQI for TN, COD_{Mn}, and TP were low, at 13.46, 58.68, and 60.98, respectively, and were more polluted, as shown in Figure 7. Additionally, the lowest WQI during the diversion period was higher than the lowest WQI during the non-diversion period (57.72 and 47.58, with standard deviations of 4.11 and 4.46, respectively); therefore, the water quality was more stable during the diversion period.

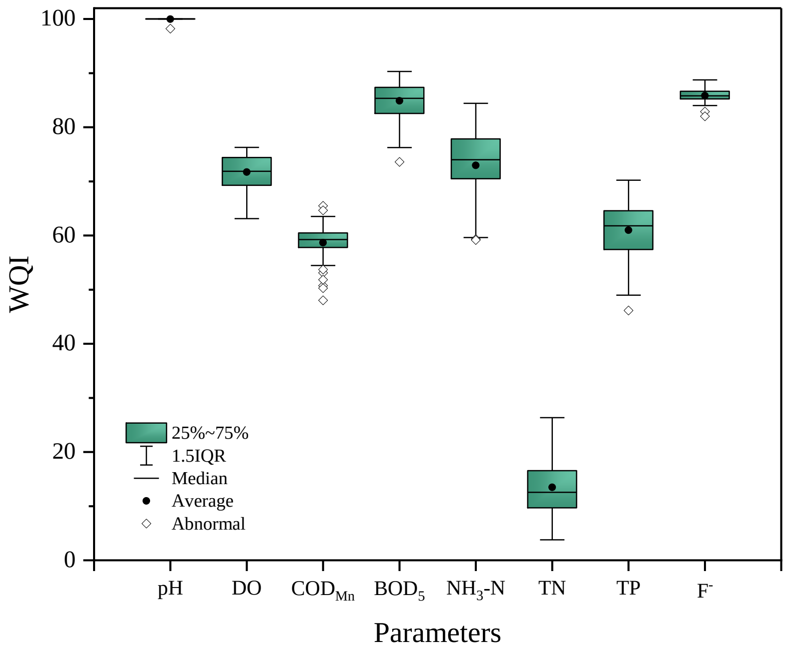

Figure 7. Graph of the WQI for each water quality parameter during 2014–2018.

As shown in Figures 1 and 8 and Table 6, the WQI of the SNWDPC-delivery ER's canal during the diversion period was consistent with the trend of WQI of the Sanjiangying station on the Yangtze River, with a significant positive correlation with a correlation coefficient of 0.625. Therefore, the quality of the SNWDPC-delivery ER's canal is influenced by the water quality of the diversion source water.

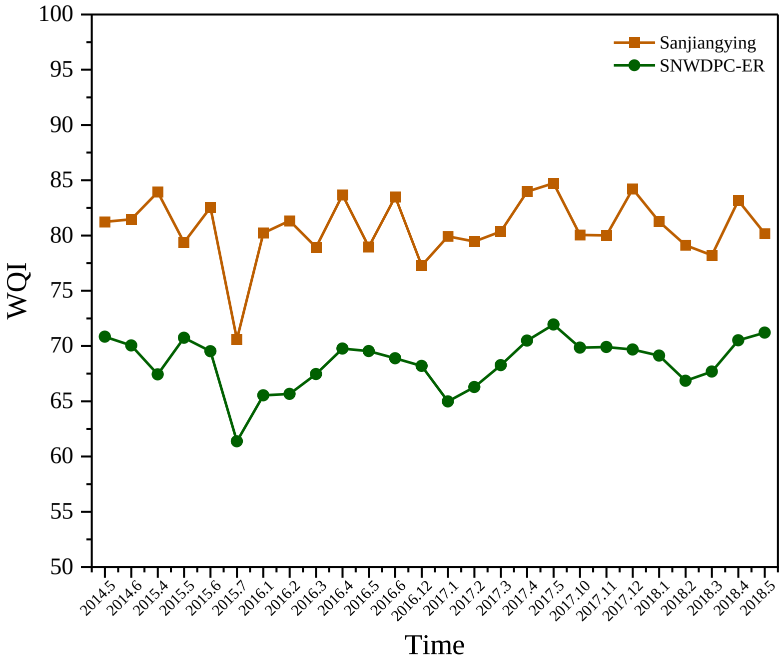

Figure 8. Comparison of the WQI of the SNWDPC-delivery ER's canal and WQI of the Sanjiangying station on the Yangtze River during the water diversion periods in 2014–2018.

Table 6. Correlation analysis between the WQI of the SNWDPC-delivery ER's canal and the WQI of Sanjiangying station on the Yangtze River during the water diversion periods in 2014–2018.

WQI	SNWDPC-ER
Sanjiangying Station	0.625 **

Note: ** At the 0.01 level (two-tailed), correlation is significant.

In Figure 8, the total WQI values of the Yangtze River and the SNWDPC-ER suddenly dropped in July 2015, and it was found that their WQI values of DO, COD_{Mn}, BOD_5, and NH_3-N also dropped compared to those around July 2015. This may be due to the impact of heavy rainfall, during which the Huai River and Yangtze River basins experienced mega-floods, carrying a large number of pollutants into the bodies of water, resulting in an increase in pollutant concentrations and a drop in WQI values.

4.2. Key Water Quality Parameters for Selecting the WQI_{min} Model

The proposed WQI_{min} model, which was based on a stepwise multiple linear regression model of the SNWDPC-delivery ER's canal, contains four key water quality parameters: DO, NH_3-N, BOD_5, and TN. The parameters selected for the WQI_{min} model should be able to comprehensively explain the overall changes and characteristics of water quality and should be able to effectively evaluate water quality at a relatively low cost [17]. In this study, the four parameters screened to meet the requirements of easy detection, which are conducive to efficient water quality assessment, and the overall selected parameters can reflect the water quality condition of the SNWDPC-delivery ER's canal.

According to the principal component analysis of the SNWDPC-ER by Ting-ting Zhang [22], the main water quality parameters affecting the water quality of the delivery canal were NH3-N, BOD_5, COD, TN, COD_{Mn}, and TP; this is consistent with the results of this study, which found that the concentrations of NH_3-N, BOD_5, and TN were the main factors affecting the WQI. Moreover, DO was the first parameter selected by the regression model (model 1, $R^2 = 0.603$, $p < 0.001$) and was the most important parameter in the calculation of the WQI model. Furthermore, other researchers have selected DO as a key parameter when constructing WQI_{min} models for rivers [17,23,29,30].

On the spatial scale, the overall WQI values of BOD_5, NH_3-N, and TN were highest in R1 and lowest in R3 or R4, and the SNWDPC-delivery ER's canal water quality was better in the south than in the north, which was consistent with the pattern of total WQI. On the time scale, the WQI of BOD_5, NH_3-N, and TN are consistent with the trend of total WQI, and the overall WQI of each water quality parameter in R1, R2, R3, and R4 becomes better year by year as time rises, which is consistent with the pattern of total WQI.

4.3. Effect of Weights on the WQI_{min}

This study compared the R^2, PE, and mean values of the weighted and unweighted WQI_{min} models. The results showed that the weighted WQI_{min} model was better than the unweighted WQI_{min} model at representing the WQI for evaluating the water quality of the SNWDPC-ER and whether the WQI_{min} model considered the weight also affected the parameter selection. As shown in Table 5 and Figure 7, in the unweighted WQI_{min} models, the PE of $WQI_{min\text{-}a3}$ was the lowest (5.1) when the key water quality parameters were DO, NH_3-N, BOD_5, and COD_{Mn}. When parameter weights were considered, the PE of $WQI_{min\text{-}b2}$ was the lowest (3.9) when the key water quality parameters were DO, NH_3-N, BOD_5, and TN. When changing the weights of the water quality parameters, the water quality evaluation results will also differ [31]. Moreover, the determination of the weights of each parameter for the WQI calculation is subjective and, thus, needs to consider the literature and characteristics of the study area. In the subsequent studies, objective weights can be considered.

5. Conclusions

In this study, the WQI technique was used to evaluate the spatial and temporal water quality features in the SNWDPC-delivery ER's canal from January 2014 to December 2018, and a weighted WQI_{min} model appropriate for this study region was built.

The overall water quality status was rated as "good" from 2014 to 2018, and it improved every year after that. The south has better water quality than the north, and the discrepancies in water quality along each river reach are getting smaller every year. There is a seasonal variation pattern, with fall having better water quality than other seasons. Additionally, the water quality is steadier throughout the diversion time than it is during the non-diversion period, and the quality of the water in the SNWDPC-delivery ER's canal is influenced by the quality of the water at the source of the diversion.

The WQI_{min} model suitable for the SNWDPC-delivery ER's canal proposed in this study is a weighted model based on four key water quality parameters of DO, NH_3-N, BOD_5, and TN, which is screened by the stepwise multiple linear regression method.

The TN, COD_{Mn}, and TP levels in the canal of the SNWDPC-delivery ER were high, indicating severe pollution. As a result, it's essential to improve non-point and point sources of pollution prevention and control along the line and to plan suitable water diversions according to scientific and ecological principles.

This study offers a theoretical framework for the management of the SNWDPC-water ER's quality as well as a reference to help other projects identify important water quality criteria and effectively carry out thorough water quality analyses. Additionally, a long-term comprehensive evaluation system using the WQI can in the future offer technical assistance for the examination of rivers and lakes.

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