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River Health Assessment Method Based on Water Quality Indices for the Dagujia River in China

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River health has become one of the major concerns today. This study develops a water quality index-based health assessment method to diagnose the status of the Dagujia River, China. The Dagujia River is the second largest river and the main source of drinking water in Yantai, China. The health status is classified into five levels – ideal, healthy, sub-healthy, unhealthy, and morbid. The assessment process includes four phases: 1) index layer grading, 2) criterion layer grading, 3) target layer grading, and 4) health diagnosis. The results show that eight sections are morbid, accounting for 66.3% of the entire assessed river. It also finds that higher water temperature variation (*WTV*) results in this poor health situation. However, the assessment excluding *WTV* reveals that all the other sections are in ideal states except for a sub-healthy river section caused by the higher concentrations of CODMn and COD in the high-flood season (June–September).

Keywords: health assessment, water quality index, health levels, grading method, water temperature variation

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1 INTRODUCTION

The river is the water source for life, providing a living environment for humans and other living organisms, while the river is also the most vulnerable ecosystem to human activities [1, 2]. With the development of human beings, the demand for water resources continues to increase. Meanwhile, many pollutants are discharged into the rivers, causing point and non-point source pollution. Human modernization has caused damage to riparian vegetation, soil and water loss, channel changes, blockages, and interruptions. These activities have greatly affected river and lake health, which on a long term impacts physical habitats, biodiversity, ecological functions, and services [3]. For example, algal blooms have frequently occurred since the late 1980s, and around 41 kinds of fish, 65 zooplanktons, and 16 macrophyte species have disappeared from the Taihu Lake in the Yangtze River Delta in China [4]. In the world, only a small fraction of the river systems remain unaffected [5–6, 8], and river systems have become one of the most endangered global systems at an alarming rate [7–9]; . In turn, the negative river health of water pollution has greatly affected human health, which remains a major source of morbidity and mortality in countries like China [10]. The poor water quality has led to 190 million people falling ill and 60,000 people dying from liver and gastric cancers every year in China [10, 11].

Similar to a healthy human body, only a healthy river can fully perform its various functions and services. River health is a helpful term for people to interpret the river status easily and thus evoke public concern about human impacts on river systems [8, 12]. However, there has not been a universal definition of river health so far. In a pioneer study [13], the concept of river health was proposed. A healthy river should stably maintain all its intrinsic values and be able to repair itself when exposed to external stress [1]. Furthermore, it is suggested that river health assessment includes

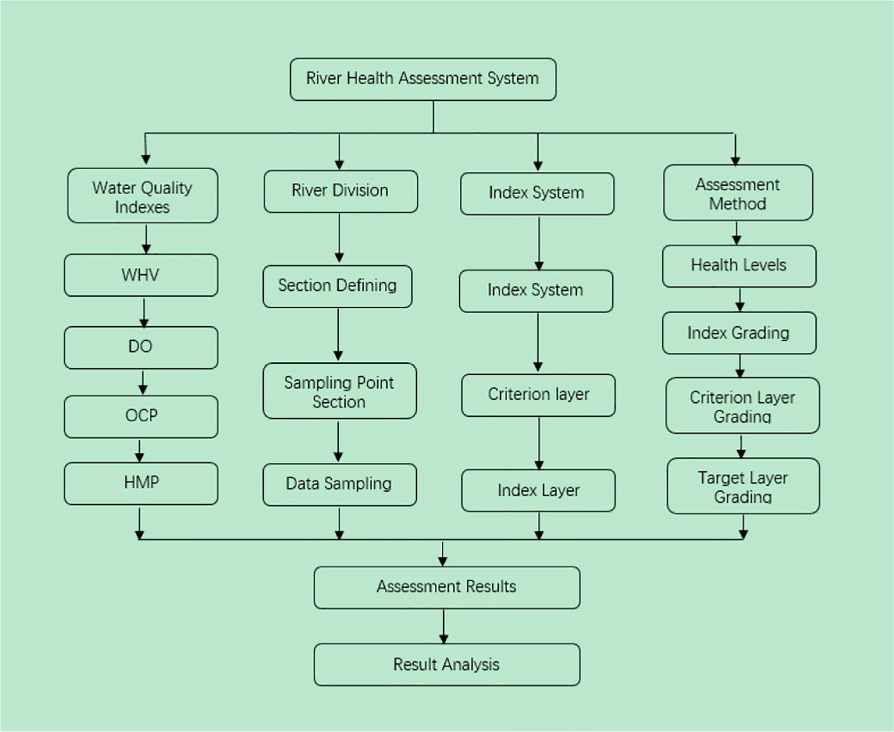

FIGURE 1 | Study content and the technical road of the river health assessment system method.

biological, physical, chemical, and socioeconomic contexts. Since the concept of river health was proposed by [13], river health assessment has become one of the major concerns for water resource protection. Maintaining and restoring the health of rivers have gradually been incorporated into the practice of river protection and management, and establishing an assessment index system has quickly become the goal and direction of river management [14].

Since the past decades, many countries in the world have assessed the health status and variation of the river system and evaluation of human impacts [8]. Consequently, different assessment methods and indices have been developed in multiple countries, such as the United Kingdom [15, 16], France [17], Zimbabwe [18], China [3, 19, 20], Swaziland [21], the United States [22], and Australia [23, 24], Flint et al., 2017, and so on. For example, in the United Kingdom, the Institute of Freshwater Ecology (IFE) developed a software package called "In Vertebrate Prediction and Classification System" (RIVPACS) for assessing the biological quality of rivers [15]. In France [17], applied logistic and multiple linear regression methods and fish-based index to assess river health were used. In Zimbabwe [18], river health related to lands based on macroinvertebrate data sampled from sites along a dry-land river in northwestern Zimbabwe was investigated. The [20] proposed an index system from five aspects, hydrology, physical forms, water quality, aquatic organisms, and social service functions, to assess river and lake health. In the United States [22], examples from Wyoming, Colorado, and Arizona in the western United States were used to quantify relations between driver and response variables on rivers affected by dams. In Australia [23], the ecosystem health of streams in Southeast Queensland was studied by using a river ecosystem health score composed of five component indicators: fish, macroinvertebrates, water quality, nutrients, and ecosystem processes.

In recent years, more studies on river health assessment have been conducted in the world. The methods applied in these studies can be roughly summarized into three categories: predictive model methods [6, 25, 26], multi-index comprehensive assessment methods [27, 28], Flint et al., 2017 [29], and mixed ones [3, 8, 26, 30]. For instance [25], multiple biological indices were developed using three groups of aquatic organisms, including benthic algae, macroinvertebrates, and fish, to assess the health of rivers in northeastern China [29]. An ecological health index method (EHI) was developed to evaluate the health status of the Poyang Lake in China from the four aspects of physical, chemical, ecological integrity, and social services [26]. The health of river ecosystems was evaluated by establishing a comprehensive river health index (RHI) determined by a fuzzy matter-element expansion evaluation model [3]. The chemical parameter model and the index of the biological integrity model were used to assess the ecological health of the Geum River watershed.

The Dagujia River is the second largest river and the main source of drinking water in Yantai, China. However, only a few studies on the health status of the river have been found in the

TABLE 1 | River health assessment system indices.

Target layer	Criterion Layer	Symbols	Index Layer	Symbols
River health	Water temperature variation (°C)	*WTV*	Monthly measured water temperature	T_m
			Multi-annual monthly average water temperature	$\overline{T}_m$
	Dissolved oxygen status (mg/L)	*DO*	Dissolved oxygen concentration	*DO*
	Oxygen consumption organic pollution status (mg/L)	*OCP*	Permanganate index	*CODMn*
			Chemical oxygen demand	*COD*
			5-day biochemical oxygen demand	BOD_5
			Ammonia nitrogen	NH_3N
	Heavy metal pollution status (mg/L)	*HMP*	Arsenic	*Ar*
			Mercury	*Hg*
			Hexavalent chromium	*Cr*
			Cadmium	*Cd*
			Lead	*Pb*

The italic value is the abbreviation.

TABLE 2 | River health levels and grading standards.

Level	Status	Color	Grading	Description
1	Ideal	Blue	80 < Score ≤100	Close to the reference conditions or expected target
2	Healthy	Green	60 < Score ≤80	Minor difference from reference conditions or the expected target
3	Sub-healthy	Yellow	40 < Score ≤60	Moderate difference from reference conditions or the expected target
4	Unhealthy	Orange	20 < Score ≤40	Large difference from reference conditions or the expected target
5	Morbid	Red	0 ≤ score ≤20	Significant difference from reference conditions or the expected target

literature, and these studies were undertaken in 2008 and just focused on the ecological aspect [31, 32]. In this connection, it is urgently needed to develop a health system index to assess the health status of the river fast. The main purpose of this study is to scientifically evaluate the health status of the Dagujia River based on water quality indicators. The main goals are to diagnose the current health status of the Dagujia River and analyze the driving forces that cause the health problems to provide technical and decision support for government departments concerned.

2 METHODS

The proposed health assessment system is composed of three parts: 1) river section division, 2) system index definition, and 3) assessment method (**Figure 1**).

We divide the river into different sections first and then select sections for health assessment. Finally, sampling points are defined in each section. The system index includes defining the layers and indices for assessment, and the assessment method includes health level classification and grading methods for each level. Grading and health diagnosis are conducted using the *Python* programming language and its scientific computing libraries, *Numpy* and *Pandas.* In addition, Mapinfo 16 is used to visualize the river health assessment results spatially on the watershed GIS map.

2.1 Index System Definition

The index system includes three layers, that is, target, criterion, and indicator, and a total of 12 indices (**Table 1**). The target layer of the river health status is composed of four indicator layers, namely, water temperature variation (*WTV*), dissolved oxygen status (*DO*), oxygen consumption organic pollutants (*OCP*), and heavy metal pollutants (*HMP*).

WTV is the maximum absolute deviation of the monthly water temperature in the assessment year from the multi-year monthly average, reflecting the impact of river development activities on aquatic species. *DO* is the dissolved oxygen concentration in the water, which is essential to the growth of aquatic species. *OCP* refers to organic pollutants that cause a significant decrease in dissolved oxygen in water, and this study considers four indicators, including permanganate index (CODMn), chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD_5), and ammonia nitrogen (NH_3N). HMP refers to the pollutants of heavy metal elements and their compounds with significant biological toxicity, such as mercury (Hg), cadmium (Cd), hexavalent chromium (Cr), lead (Pb), and arsenic (Ar).

2.2 Health Levels

The health status of rivers is usually divided into five levels [20, 25, 29]. Based on this previous research, this study defines the health status as ideal, healthy, sub-healthy, unhealthy, and morbid, and each health level was graded with a score ranging from 0 to 100 points. The classification standard of the five health levels is based on the total target scores (**Table 2**).

2.3 Grading Method

The target layer score is assigned as the minimum score of the four criterion layers, and it is expressed by

$$T_L s = \min(C_X s) \tag{1}$$

where s stands for the score, T_Ls is the score to target layer, subscript $X \in [1, 2, 3, 4]$ stands for the four criterion layers, and C_Xs are the scores assigned to each of the four layers.

2.3.1 WTV Grading

Water temperature variation (WTV) is expressed by the maximum deviation of the measured monthly water temperature in the assessment year from the multi-year monthly average (**Eq. 2**), and the grade of WTV is determined based on its values by **Eq. 3**

$$T_V = \max\left(\left|T_m - \bar{T}_m\right|\right) \tag{2}$$

$$T_Vs = \begin{cases} 100 & 0 \le T_V \le 1 \\ 50 & 1 < T_V \le 2 \\ 25 & 2 < T_V \le 3 \\ 0 & 3 < T_V \le 4, \text{ or } T_V > 4 \end{cases} \tag{3}$$

where T_V refers to WTV (°C), T_m is the measured monthly average water temperature (°C) in the assessment year, $\bar{T}_m$ is the multi-year monthly average water temperature (°C), and T_Vs is the score obtained by WTV.

2.3.2 Grading of DO Index

The DO status index grade is defined as the minimum of the scores assigned to the DO concentration in the flood season and the non-flood season by the following equation

$$DOs = \min\left(DO_Fs, DO_Ns\right) \tag{4}$$

where DOs is the score of DO index, DO_Fs is the score of DO index in the flood season, DO_Ns is the score of DO index in the non-flood season, and subscripts F and N represent the flood season and non-flood season, respectively.

Too high and too low DO concentrations can both cause harm to aquatic organisms. The appropriate DO concentration value is 4–12 mg/L based on [20, 33], and the DO concentration of 5 mg/L is defined as the base point because it meets the basic water quality requirements of fish organisms [33]. The scores of DO index in the flood season and the non-flood season are defined according to its concentrations of these two seasons by the following equation

$$DO_Fr, DO_Nr = \begin{cases} 100 & 7.5 \le DO_F, DO_N \le 12 \\ 80 & 6 \le DO_F, DO_N < 7.5 \\ 60 & 5 \le DO_F, DO_N < 6 \\ 30 & 3 \le DO_F, DO_N < 5 \\ 10 & 2 \le DO_F, DO_N < 3 \\ 0 & 0 \le DO_F, DO_N < 2 \end{cases} \tag{5}$$

where DO_F is the average DO concentration in the flood season in the assessment year and DO_N is the average DO concentration in the non-flood season in the assessment year.

In this study, we define the DO concentration in the flood season (DO_F) as the monthly average concentration from May to September in the assessment year (**Eq. 6**) and the DO concentration in the non-flood season (DO_N) as the monthly average concentration from January to April and from October to December in the assessment year (**Eq. 7**)

$$DO_F = \frac{1}{m}\sum_{i=5}^{9}\left(DO_i\right) \tag{6}$$

$$DO_N = \frac{1}{n}\sum_{j=1}^{4}\sum_{j=10}^{12}\left(DO_j\right) \tag{7}$$

where DO_i is the DO concentration in the ith month of the flood season; DO_j is the DO concentration in the jth month of the non-flood season; subscripts i and j represent a certain month in the flood season and non-flood season, respectively; and m and n represent the total months of the flood season and non-flood season, respectively.

2.3.3 Oxygen Consumption Organic Pollutants

The oxygen consumption organic pollutant score is assigned by the average score of its four indices, that is, CODMn, COD, BOD$_5$, and NH$_3$H (**Eq. 8**). The score of each index is defined as the minimum one of the two scores assigned for this index in the flood season and non-flood season, expressed by **Eq. 9**

$$OCPs = \frac{1}{n}\sum_{k=1}^{4}\left(OCP_ks\right) \tag{8}$$

$$OCP_ks = \min\left(OCP_{kF}s, OCP_{kN}s\right) \tag{9}$$

where $OCPs$ is the score of the oxygen consumption organic pollutants (OCP); OCP_ks are the scores to the four indices; $OCP_{kF}s$ and $OCP_{kN}s$ refer to the score to each of the four indices in the flood season and non-flood season, respectively; and subscript k stands for each of the four indices.

The scores to each of the four indices in the flood and non-flood seasons are assigned based on their concentrations in these two seasons (**Eqs 10–13**)

$$CODMn_Fs, CODMn_Ns = \begin{cases} 100 & 0 \le CODMn_F, CODMn_N \le 2 \\ 80 & 2 < CODMn_F, CODMn_N \le 4 \\ 60 & 4 < CODMn_F, CODMn_N \le 6 \\ 30 & 6 < CODMn_F, CODMn_N \le 10 \\ 0 & 10 < CODMn_F, CODMn_N \le 15 \end{cases} \tag{10}$$

$$COD_Fs, COD_Ns = \begin{cases} 100 & 0 \le COD_F, COD_N \le 15 \\ 80 & 15 < COD_F, COD_N \le 17.5 \\ 60 & 17.5 < COD_F, COD_N \le 20 \\ 30 & 20 < COD_F, COD_N \le 30 \\ 0 & 30 < COD_F, COD_N \le 40 \end{cases} \tag{11}$$

$$BOD_Fs, BOD_Ns = \begin{cases} 100 & 0 \le BOD_F, BOD_N \le 3 \\ 80 & 3 < BOD_F, BOD_N \le 3.5 \\ 60 & 3.5 < BOD_F, BOD_N \le 4 \\ 30 & 4 < BOD_F, BOD_N \le 6 \\ 0 & 6 < BOD_F, BOD_N \le 10 \end{cases} \tag{12}$$

$$NH_3N_Fs, NH_3N_Ns = \begin{cases} 100 & 0 \le NH_3N_F, NH_3N_N \le 0.15 \\ 80 & 0.15 < NH_3N_F, NH_3N_N \le 0.5 \\ 60 & 0.5 < NNH_3N_F, NH_3N_N \le 1 \\ 30 & 1 < NH_3N_F, NH_3N_N \le 1.5 \\ 0 & 1.5 < NH_3N_F, NH_3N_N \le 2 \end{cases} \tag{13}$$

where $CODMns$, $CODs$, $BODs$, and NH_3Ns are the scores to the four indices, CODMn, COD, BOD, and NH$_3$N,

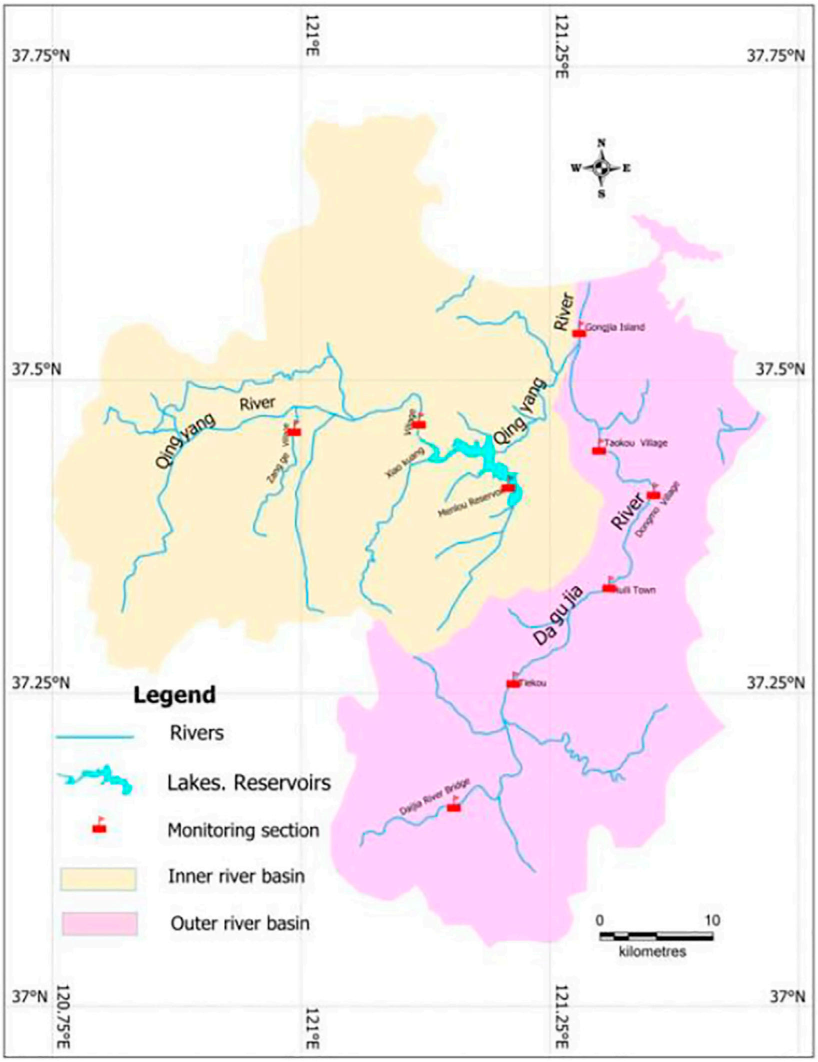

FIGURE 2 | River system of the Dagujia river watershed.

TABLE 3 | Section division of the Diagujia River.

Index	River Sections	Section length	Longitude	Latitude
1	Daijiahe Bridge	11.04	121.1589	37.14417
2	Tiekou	65.84	121.2378	37.25917
3	Huilizhen	19.41	121.3325	37.33611
4	Dongmotang	10.49	121.3608	37.41028
5	Zanggezhuang	12.29	120.9911	37.46083
6	Xiaokuang Village	112.8	121.1075	37.46667
7	Menlou Reservoir	38.98	121.2072	37.41639
8	Taokou	8.03	121.3058	37.44611
9	Gongjia Island	55.96	121.2864	37.53944

respectively; $CODMn$, COD, BOD, and NH_3N are the concentrations of these four indices, respectively; and subscripts F and N represent the flood season and non-flood season, respectively.

The concentrations of each index are defined as the monthly average concentrations of this index in the flood season and non-flood season, respectively (14–15). In this study, the flood season refers to May to September in the assessment year. The non-flood season refers to January to April and from October to December in the assessment year

$$OCP_{kF} = \frac{1}{m}\sum_{i=5}^{9}(OCP_{ki}) \tag{14}$$

$$OCP_{kN} = \frac{1}{n}\sum_{j-1}^{4}\sum_{j=10}^{12}\left(OCP_{kj}\right) \tag{15}$$

where OCP_{kF} and OCP_{kN} refer to the concentrations of one of the four indices, $CODMn$, COD, BOD, and NH_3N, in the flood season and non-flood season, respectively; subscripts i and j represent a certain month in the flood season and non-flood season, respectively; and m and n represent the total

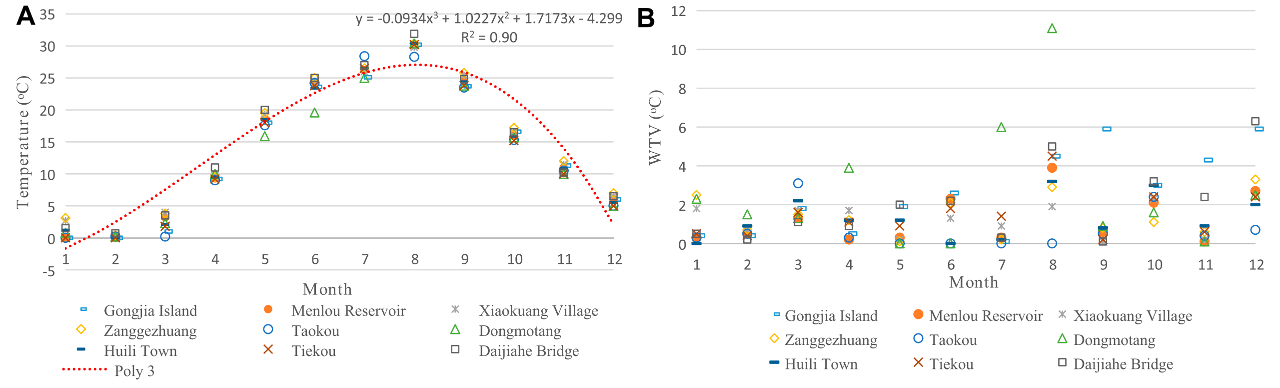

FIGURE 3 | Water temperature and water temperature variation of the Dangujia River in the 2008 assessment year: **(A)** monthly water temperature and **(B)** monthly water temperature variation.

TABLE 4 | Results of water temperature variations (°C) and grading.

Months	Gongjia Island Section			Menlong Reservoir			Xiaokuang Village			Zanggezhuang			Taokou		
	MWT	*MAT*	*ADV*	*MWT*	*MAT*	*ADV*	*MWT*	*MAT*	*ADV*	*MWT*	*MAT*	*ADV*	*MWT*	*MAT*	*ADV*
1	0.0	0.4	0.4	0.0	0.3	0.3	2.7	0.9	1.8	3.1	0.6	2.5	0.0	0.3	0.3
2	0.0	0.4	0.4	0.0	0.5	0.5	0.5	1.2	0.7	0.4	1.1	0.7	0.2	0.675	0.5
3	1.0	2.8	1.8	3.2	4.5	1.3	4.0	5.7	1.7	3.8	5.3	1.5	0.2	3.28	3.1
4	9.2	9.7	0.5	9.3	9.5	0.2	9.7	11.4	1.7	9.5	10.7	1.2	9.0	9.3	0.3
5	18.0	16.1	1.9	18.7	18.4	0.3	19.3	19.5	0.2	19.5	19.4	0.1	17.6	16.38	0.0
6	23.6	21.0	2.6	24.0	21.7	2.3	24.5	23.2	1.3	25.0	22.9	2.1	24.2	21.18	0.0
7	25.1	25.2	0.1	26.2	25.9	0.3	26.0	26.9	0.9	26.5	26.7	0.2	28.4	18.22	0.0
8	30.2	25.7	4.5	30.2	26.3	3.9	29.8	27.9	1.9	30.4	27.5	2.9	28.3	25.98	0.0
9	23.7	17.8	5.9	24.5	23.9	0.6	25.4	25.5	0.1	25.8	25.1	0.8	23.5	22.98	0.5
10	16.6	13.6	3.0	16.1	18.2	2.1	16.5	18.8	2.3	17.2	18.3	1.1	15.3	17.72	2.4
11	11.3	7.0	4.3	11.0	10.9	0.1	11.5	11.7	0.2	12.0	11.4	0.6	10.5	10.86	0.4
12	6.0	0.1	5.9	6.0	3.3	2.7	6.5	4.1	2.4	7.0	3.7	3.3	5.0	4.34	0.7
Max-ADV	5.9			3.9			2.4			3.3			3.1		
Grade	0			0			25			0			0		

MWT: Measured water temperature (°C).
MAT: Multi-year monthly average water temperature (°C).
ADV: Absolute deviation between measured water temperature and multi-annual average water temperature (°C).

months of the flood season and non-flood season, respectively.

2.3.4 Grading of Heavy Metal Pollutants

Heavy metal pollutant score ($HMPs$) is defined by the minimum score of its five indices, arsenic (Ar), mercury (Hg), cadmium (Cd), chromium(Cr), and lead (Pb) (**Eq. 16**). Each of the five indices is graded by the minimum one of its scores in the flood and non-flood seasons. The concentrations of each index in these two seasons are determined by **Eqs 23** and **24**

$$HMPs = \min\left(HMP_k s\right) \tag{16}$$

$$HMP_k s = \min\left(HMP_{kF} s, HMP_{kN} s\right) \tag{17}$$

$$Ar_F s, Ar_N s = \begin{cases} 100 & 0 \le Ar_F, Ar_N \le 0.05 \\ 0 & 0.05 < Ar_F, Ar_N \le 0.1 \end{cases} \tag{18}$$

$$Hg_F s, Hg_N s = \begin{cases} 100 & 0 \le Hg_F, Hg_N \le 0.00005 \\ 60 & 0.00005 < Hg_F, Hg_N \le 0.0001 \\ 0 & 0.0001 < Hg_F, Hg_N \le 0.001 \end{cases} \tag{19}$$

$$Cd_F s, Cd_N s = \begin{cases} 100 & 0 \le Cd_F, Cd_N \le 0.001 \\ 60 & 0.001 < Cd_F, Cd_N \le 0.005 \\ 0 & 0.005 < Cd_F, Cd_N \le 0.01 \end{cases} \tag{20}$$

$$Cr_F s, Cr_N s = \begin{cases} 100 & 0 \le Cr_F, Cr_N \le 0.01 \\ 60 & 0.01 < Cr_F, Cr_N \le 0.05 \\ 0 & 0.05 < Cr_F, Cr_N \le 0.1 \end{cases} \tag{21}$$

$$Pb_F s, Pb_N s = \begin{cases} 100 & 0 \le Pb_F, Pb_N \le 0.01 \\ 60 & 0.01 < Pb_F, Pb_N \le 0.05 \\ 0 & 0.05 < Pb_F, Pb_N \le 0.1 \end{cases} \tag{22}$$

$$HMP_{kF} = \frac{1}{m}\sum_{i=5}^{9}\left(HMP_{ki}\right) \tag{23}$$

TABLE 5 | Results of water temperature variations (°C) and grading (Continuation).

Months	Dongmotang			Huili town			Tiekou			Daijiahe Bridge		
	MWT	*MAT*	*ADV*	*MWT*	*MAT*	*ADV*	*MWT*	*MAT*	*ADV*	*MWT*	*MAT*	*ADV*
1	0.8	-1.5	2.3	1.2	1.2	0.0	0.0	0.5	0.5	1.5	0.98	0.5
2	0.2	-1.3	1.5	0.0	0.9	0.9	0.0	0.41	0.4	0.7	0.93	0.2
3	2.3	1.0	1.3	2.1	4.3	2.2	1.8	3.35	1.6	3.5	4.61	1.1
4	10.0	6.1	3.9	9.5	10.7	1.2	9.2	10.3	1.1	11.0	11.9	0.9
5	15.9	12.8	0.0	18.5	19.7	1.2	18	17.05	0.9	20.0	18.01	2.0
6	19.6	15.3	0.0	23.4	23.4	0.0	23.8	21.96	1.8	25.0	22.81	2.2
7	25.0	19.0	6.0	26.5	26.7	0.2	26.5	25.06	1.4	27.0	26.71	0.3
8	30.4	19.3	11.1	30.4	27.2	3.2	30.2	25.75	4.5	31.9	26.88	5.0
9	23.8	23.0	0.9	24.4	25.2	0.8	23.8	23.61	0.2	24.8	24.9	0.1
10	15.7	17.3	1.6	15.9	18.9	3.0	15.2	17.61	2.4	16.5	13.35	3.2
11	10.0	10.1	0.1	10.8	11.7	0.9	10	10.55	0.6	10.2	7.81	2.4
12	5.0	2.5	2.5	5.5	3.5	2.0	5	2.58	2.4	6.5	0.166	6.3
Max-ADV	11.1			3.2			4.5			6.3		
Grade	0.0			0.0			0.0			0.0		

MWT: Measured water temperature (°C).
MAT: Multi-annual average water temperature (°C).
ADV: Absolute deviation between measured water temperature and multi-annual average water temperature (°C).

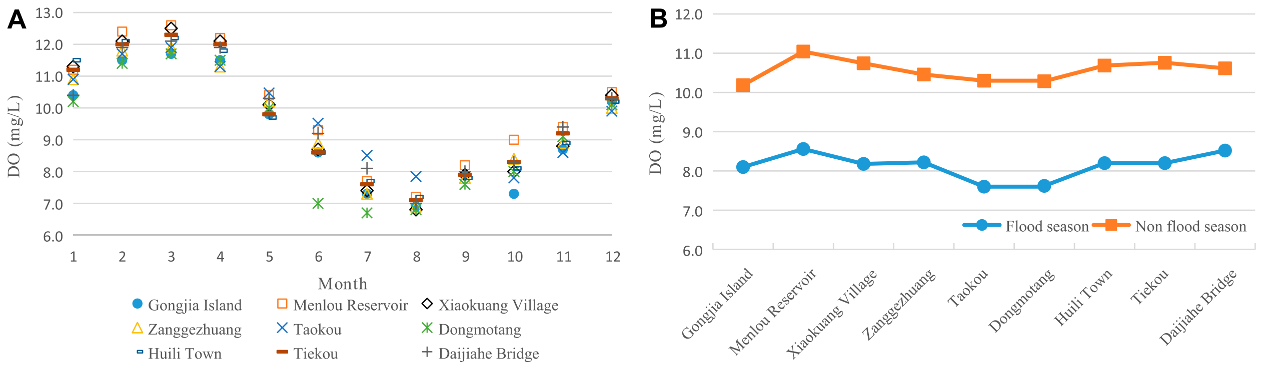

FIGURE 4 | DO concentrations in the Dangujia River in the 2008 assessment year: **(A)** monthly DO concentrations and **(B)** DO concentrations in the flood and non-flood seasons.

$$HMP_{kN} = \frac{1}{n}\sum_{j=1}^{4}\sum_{j=10}^{12}\left(HMP_{kj}\right) \tag{24}$$

where *HMPs* is the score assigned to HMP; OCP_{kF} and OCP_{kN} refer to the concentrations of the five indices in the flood season and non-flood season, respectively; subscript k is each of the four indices; i and j represent a certain month in the flood season and non-flood season, respectively; and m and n represent the total months of the flood season and non-flood season, respectively.

3 STUDY AREA AND DATA

3.1 Area Description

The Dagujia River watershed is located in the north-central part of Yantai City in the Shandong Peninsula (**Figure 2**). It originates from Haiyang City and flows through Muping District, Qixia City, Fushan District, Laishan District, and Zhiyu District. It is the second largest river in Yantai City, China, with a length of 83 km and a basin area of 2,293 km^2.

The Dagujia River watershed is the continental climate in the warm temperate East-Asian monsoon region, accompanied by obvious maritime climate characteristics and four distinct seasons. It has an annual average rainfall of 683.9 mm, a frost-free period of 222 days, an average temperature of 11.5°C, and a wind speed of 4.5 m/s. The precipitation distribution is extremely uneven spatially and temporally in the watershed, and precipitation in the flood season (May to September) accounts for more than 70% of the annual total.

The local people honored the Dagujia River as the “Mother River”. It is the most important source of drinking water in Yantai City, raising 27 towns with 600 thousand people. Along the river is the import-producing place of the famous “Yantai Apple” and “Yantai Big Cherry”.

3.2 River Section Division

Based on the existing monitoring sections of the Dagujia River in the Yantai Hydrological Bureau, China, we divide the river into nine sections for health assessment, namely, the Menlou Reservoir,

TABLE 6 | Results of DO concentration (mg/L) and grading.

Months	Gongjia Island	Menlou Reservoir	Xiaokuang Village	Zanggezhuang	Taokou	Dongmotang	Huili Town	Tiekou	Daijiahe Bridge
1	10.4	11.2	11.3	10.9	10.9	10.2	11.5	11.2	10.4
2	11.5	12.4	12.1	11.8	11.7	11.4	12.1	12.0	11.9
3	11.7	12.6	12.5	11.9	11.9	11.7	12.2	12.3	12.1
4	11.5	12.2	12.1	11.3	11.3	11.5	11.8	12.0	11.9
5	9.8	10.4	10.1	10.2	10.5	10.0	9.7	9.8	10.3
6	8.6	9.3	8.7	8.9	9.5	7.0	8.6	8.6	9.2
7	7.3	7.7	7.4	7.3	8.5	6.7	7.7	7.6	8.1
8	6.9	7.2	6.8	6.9	7.8	6.8	7.2	7.1	7.0
9	7.9	8.2	7.9	7.8	7.6	7.6	7.8	7.9	8.0
10	7.3	9.0	8	8.4	7.8	8.0	8.1	8.3	8.3
11	8.7	9.4	8.8	8.9	8.6	9.1	8.9	9.2	9.4
12	10.2	10.5	10.4	10	9.9	10.1	10.2	10.3	10.3
DO_F	8.1	8.6	8.2	8.2	7.6	7.6	8.2	8.2	8.5
DO_N	10.2	11.0	10.7	10.5	10.3	10.3	10.7	10.8	10.6
$DO_F s$	100	100	100	100	100	100	100	100	100
$DO_N s$	100	100	100	100	100	100	100	100	100
DOs	100	100	100	100	100	100	100	100	100

DO_F: Average DO, concentration in the flood season in the assessment year (mg/L).
DO_N: Average DO, concentration during the non-flood season in the assessment year (mg/L).
$DO_F s$: Score of DO, index in the flood season in the assessment year.
$DO_N s$: Score of DO, index in the non-flood season in the assessment year.
DOs: Score of DO index in the assessment year.

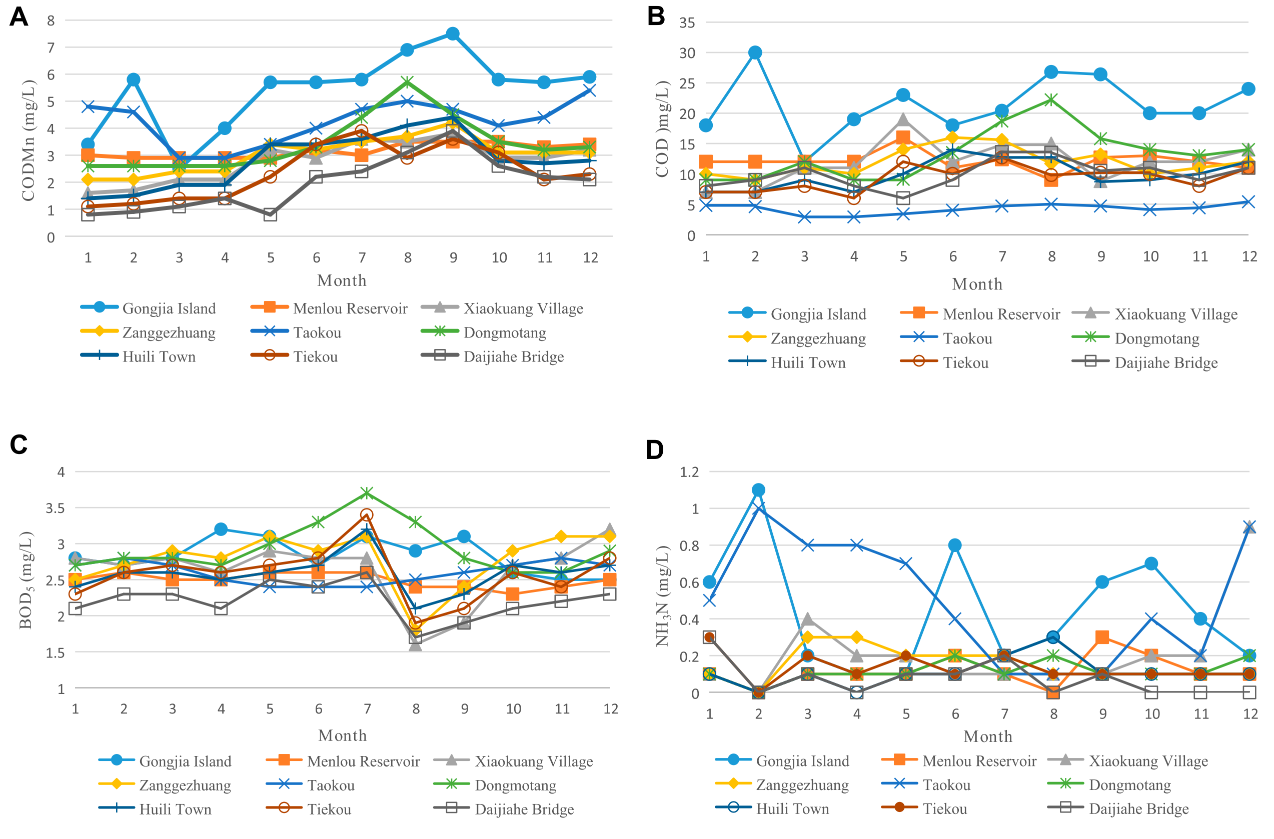

FIGURE 5 | Organic oxygen consumption pollutants (OCP) in the Dangujia River in the 2008 assessment year: **(A)** CODMn concentration, **(B)** COD concentration, **(C)** BOD5 concentrations, and **(D)** NH3N concentration.

FIGURE 6 | Monthly organic oxygen consumption pollutants (OCP) in the Dangujia River in the flood and non-flood seasons in the 2008 assessment year: **(A)** CODMn concentrations, **(B)** COD concentrations, **(C)** BOD5 concentration, and **(D)** NH3N concentration.

Taokou, Dongmotang, Huili Town, Tiekou, Daijiahe Bridge, Zanggezhuang, Xiaokuang Village, and Gongjia Island. The river sections assessed are 334.838 km long, and the geographical location and length of each river section are displayed in **Table 3**.

3.3 Data Sampling and Collection

This study conducted monthly field sampling of the indices of the nine river sections throughout the whole 2018 assessment year. We collected the index samples from 7:00 a.m. to 12:00 a.m. on 1 day randomly selected in each month. Besides the sampling data, local monthly temperature data in 2018 were collected from [19] and the multi-year monthly average temperature data were collected from [34].

4 RESULT ANALYSIS AND DISCUSSION

The health levels of the nine selected river sections of the Dagujia River were assessed based on the developed health assessment index system and the monthly sampling data.

4.1 Water Temperature Variation

The analysis results of sampling data show that the water temperature of the nine sections displays a similar trend of polynomial order three lines with the maximum temperature in August and the minimum in January and February, and the Daijiahe Bridge section has the highest temperature among the nine sections (**Figure 3A**). The results of the water temperature variation (*WTV*) reveal that the Xiaokuang Village section has a relatively lower WTV, say 2.4°C. In contrast, the Dongmotang section has the largest WTV, say 11.1°C. The Daijiahe Bridge section, Gongjia Island section, and Tiekou section are followed, with *WTVs* of 6.3°C, 5.9, and 4.5°C, respectively (**Figure 3B**; **Table 4** and **5**). In addition, the *WTV* of the rest four sections is between 3 and 4°C (**Figure 3**).

Based on the *WTV* grading method, the Xiaokuang Village obtains 25 points, and all the other eight sections have 0 points due to the higher *WTV* (**Table 4** and **5**). These analysis results indicate that human development activities have greatly influenced the river's water temperature.

A higher *WTV* will impact the living environment of local fishes in the river, which further influences the fish behaviors of feeding, reproduction, and migrations [35]. Consequently, the body efficiency of many physiological processes will change from 6 to 10% when the body temperature of fish changes by 1°C [36], and the pregnancy period of a pregnant female fish will decrease by 2 weeks for every 1°C increase in temperature in a relatively stable environment [37].

TABLE 7 | Results of organic oxygen consumption pollutants (mg/L) and grading.

Months	Gongjia Island				Menlou Reservoir				Xiaokuang Village				Zanggezhuang				Taokou			
	CODMn	COD	BOD_5	NH_3N	CODMn	COD	BOD_5	NH_3N	CODMn	COD	BOD_5	NH_3N	CODMn	COD	BOD_5	NH_3N	CODMn	COD	BOD_5	NH_3N
1	3.4	18.0	2.8	0.6	3.0	12.0	2.5	0.1	1.6	7.0	2.8	0.1	2.1	10.0	2.5	0.1	4.8	15.0	2.7	0.5
2	5.8	30.0	2.7	1.1	2.9	12.0	2.6	0.0	1.7	7.0	2.7	0.0	2.1	9.0	2.7	0.0	4.6	16.0	2.8	1.0
3	2.5	12.0	2.8	0.2	2.9	12.0	2.5	0.1	2.1	11.0	2.8	0.4	2.4	11.0	2.9	0.3	2.9	14.0	2.7	0.8
4	4.0	19.0	3.2	0.1	2.9	12.0	2.5	0.1	2.1	11.0	2.6	0.2	2.4	10.0	2.8	0.3	2.9	14.0	2.5	0.8
5	5.7	23.0	3.1	0.1	2.9	16.0	2.6	0.1	3.2	19.0	2.9	0.2	3.4	14.0	3.1	0.2	3.4	13.6	2.4	0.7
6	5.7	18.0	2.7	0.8	3.2	11.0	2.6	0.2	2.9	12.0	2.8	0.1	3.2	16.0	2.9	0.2	4.0	12.2	2.4	0.4
7	5.8	20.4	3.1	0.2	3.0	12.4	2.6	0.1	3.6	14.8	2.8	0.1	3.5	15.6	3.1	0.2	4.7	10.0	2.4	0.1
8	6.9	26.8	2.9	0.3	3.5	9.0	2.4	0.0	3.5	15.0	1.6	0.1	3.7	11.7	1.8	0.1	5.0	8.5	2.5	0.1
9	7.5	26.4	3.1	0.6	3.5	12.7	2.4	0.3	3.8	8.8	1.9	0.1	4.2	13.2	2.4	0.1	4.7	7.9	2.6	0.1
10	5.8	20.0	2.6	0.7	3.5	13.0	2.3	0.2	2.9	12.0	2.7	0.2	3.1	10.0	2.9	0.1	4.1	8.0	2.7	0.4
11	5.7	20.0	2.5	0.4	3.3	12.0	2.4	0.1	2.9	12.0	2.8	0.2	3.1	11.0	3.1	0.1	4.4	9.0	2.8	0.2
12	5.9	24.0	2.5	0.2	3.4	11.0	2.5	0.1	3.2	14.0	3.2	0.9	3.1	12.0	3.1	0.1	5.4	20.0	2.7	0.9
Flood season	6.3	22.9	3.0	0.4	3.2	12.2	2.5	0.1	3.4	13.9	2.4	0.1	3.6	14.1	2.7	0.1	4.4	10.4	2.5	0.3
Non-flood season	4.7	20.8	2.8	0.4	3.1	12.5	2.5	0.1	2.5	11.6	2.8	0.3	2.6	10.4	2.9	0.1	4.2	13.7	2.7	0.7
Flood season scores	30	30	100	80	80	100	100	100	80	100	100	100	80	100	100	100	60	100	100	100
Non-flood season scores	60	30	100	80	80	100	100	100	80	100	100	80	80	100	100	100	60	100	100	60
Annual scores	30	30	100	80	80	100	100	100	80	100	100	80	80	100	100	100	60	100	100	60
OCP score	60				95				90				95				80			

4.2 DO Water Quality

The analysis results show that the change behaviors of DO concentrations in the assessed nine river sections have a general pattern. DO shows an increasing trend from January to March and then decreases until August, followed by another increase (**Figure 4A**). The results also reveal that the average concentration of DO in each section in the flood season is much lower than that in the non-flood season (**Figure 4B** and **Table 6**). This is mainly because of the following two reasons: (1) an increase in water flow during the flood season would dilute the DO content and (2) a large amount of oxygen-consuming organic matter pollutants entered into the river with precipitation and flow during the flood season, which consumed much more DO. **Figure 4B** also illustrates that the Menlou Reservoir section has the highest DO concentration compared with other sections in the two seasons, while the Dongmotang section and the Taokou section have the lowest concentrations (**Figure 4B** and **Table 6**).

The average concentrations of DO in the flood and non-flood seasons in the nine river sections are between 7.5 and 12 mg/L (**Figure 4B**), which confirms that the nine river sections are all assigned to 100 points according to the grading equation of DO index (**Figure 4B**). This result indicates that the DO status in the Dagujia River is excellent in the 2018 assessment year, which is very suitable for the growing needs of aquatic species.

4.3 Oxygen Consumption Organic Pollutants

The analysis and grading results of the oxygen consumption organic pollutants (*OCP*) of the nine sections in the Dagujia River in the assessment year are displayed in **Figures 5**, **6** and **Tables 7** and **8**.

The results display that the Gongjia Island section has higher CODMn, COD, BOD_5, and NH_3N in the nine sections. This is also illustrated obliviously in terms of the average concentrations of the food season and non-flood season (**Figure 6**).

The results further reveal that the Daijiahe Bridge has lower CODMn, BOD_5, and NH_3N (**Figures 5A,C,D**), and the Taokou section has the lowest COD (**Figure 5B**), although it seemly has the second highest CODMn and NH_3N (**Figures 5A,D**). It also finds that the Dongmotang section has the highest BOD_5 in July, August, and September (**Figure 5C**) and the second highest CODMn, COD, and NH_3N during the same period (**Figures 5A,B,D**).

Besides, the analysis results show that the average CODMn and COD concentrations of the nine sections are higher in the flood season than in the non-flood season (**Figures 6A,B**). In contrast, the BOD_5 and NH_3N concentrations are opposite, except for a few river sections like Gonjia Island, Tongmotang, and Huili Town (**Figures 6C,D**). It suggests that CODMn and COD enter the water body of the river mainly through the high flow during the flood season, while BOD_5 and NH_3N are higher in the non-flood season mainly because of lower flow and higher mainly in the flood season due to flow dilution.

The OCP grading results of the nine river sections show that Gongjia Island is assigned the lowest score of 60 points due to the

TABLE 8 | Results of organic oxygen consumption pollutants (mg/L) and grading.

Months	Dongmotang				Huili Town				Tiekou				Daijiahe Bridge			
	CODMn	COD	BOD_5	NH_3N	CODMn	COD	BOD_5	NH_3N	CODMn	COD	BOD_5	NH_3N	CODMn	COD	BOD_5	NH_3N
1	2.6	9.0	2.7	0.1	1.4	7.0	2.4	0.1	1.1	7.0	2.3	0.3	0.8	8.0	2.1	0.3
2	2.6	9.0	2.8	0.0	1.5	7.0	2.6	0.0	1.2	7.0	2.6	0.0	0.9	9.0	2.3	0.0
3	2.6	12.0	2.8	0.1	1.9	9.0	2.6	0.1	1.4	8.0	2.7	0.2	1.1	11.0	2.3	0.1
4	2.6	9.0	2.7	0.1	1.9	7.0	2.5	0.0	1.4	6.0	2.6	0.1	1.4	8.0	2.1	0.0
5	2.8	9.1	3.0	0.1	3.4	10.0	2.6	0.1	2.2	12.0	2.7	0.2	0.8	6.0	2.5	0.1
6	3.3	13.5	3.3	0.2	3.4	14.0	2.7	0.1	3.4	10.0	2.8	0.1	2.2	9.0	2.4	0.1
7	4.4	18.7	3.7	0.1	3.6	12.7	3.2	0.2	3.9	12.7	3.4	0.2	2.4	13.6	2.6	0.2
8	5.7	22.2	3.3	0.2	4.1	12.8	2.1	0.3	2.9	9.8	1.9	0.1	3.1	13.5	1.7	0.0
9	4.5	15.8	2.8	0.1	4.4	8.7	2.3	0.1	3.6	10.2	2.1	0.1	3.9	10.5	1.9	0.1
10	3.5	14.0	2.6	0.1	2.8	9.0	2.7	0.1	3.1	10.0	2.6	0.1	2.6	11.0	2.1	0.0
11	3.2	13.0	2.6	0.1	2.7	10.0	2.6	0.1	2.1	8.0	2.4	0.1	2.2	9.0	2.2	0.0
12	3.3	14.0	2.9	0.2	2.8	12.0	2.7	0.1	2.3	11.0	2.8	0.1	2.1	11.0	2.3	0.0
Flood season	4.1	15.9	3.2	0.2	4.1	11.6	2.6	0.2	3.2	10.9	2.6	0.1	2.5	10.5	2.2	0.1
Non-flood season	2.9	11.4	2.7	0.1	2.1	8.7	2.6	0.1	1.8	8.1	2.6	0.1	1.6	9.6	2.2	0.1
Flood season scores	60	80	80	80	80	100	100	100	80	100	80	100	80	100	100	100
Non-flood season scores	80	100	100	100	80	100	100	100	100	100	80	100	100	100	100	100
Annual scores	60	80	80	80	80	100	100	100	80	100	80	100	80	100	100	100
OCP score	75				95				90				95			

TABLE 9 | Results of grading and health assessment including water temperature variation.

Sections	Scores					Health Status
	WTs	*DOs*	*OCPs*	*HMPs*	*TLs*	
Gongjia Island	0	100	60	100	0	Morbid
Menlou Reservoir	0	100	95	100	0	Morbid
Xiaokuang Village	25	100	90	100	25	Unhealthy
Zanggezhuang	0	100	95	100	0	Morbid
Taokou	0	100	80	100	0	Morbid
Dongmotang	0	100	75	100	0	Morbid
Huili Town	0	100	95	100	0	Morbid
Tiekou	0	100	90	100	0	Morbid
Daijiahe Bridge	0	100	95	100	0	Morbid
Average	2.8	100.0	86.1	100.0	2.8	Morbid

WTs*: Score assigned to the water temperature variation index.*
DOs*: Score assigned to the dissolved oxygen index.*
OCPs*: Score assigned to oxygen consumption organic pollution index.*
HMPs*: Score assigned to heavy metal pollution index.*
TLs*: Score assigned to the water layer.*

TABLE 10 | Results of grading and health assessment excluding water temperature variation.

Sections	Scores				Health Status
	DOs	*OCPs*	*HMPs*	*TLs*	
Gongjia Island	100	60	100	60	sub-healthy
Menlou Reservoir	100	95	100	95	Ideal
Xiaokuang Village	100	90	100	90	Ideal
Zanggezhuang	100	95	100	95	Ideal
Taokou	100	80	100	80	Ideal
Dongmotang	100	75	100	75	Healthy
Huili Town	100	95	100	95	Ideal
Tiekou	100	90	100	90	Ideal
Daijiahe Bridge	100	95	100	95	Ideal
Average	100.0	86.1	100.0	86.1	Ideal

WTs*: Score assigned to the water temperature variation index.*
DOs*: Score assigned to the dissolved oxygen index.*
OCPs*: Score assigned to oxygen consumption organic pollution index.*
HMPs*: Score assigned to heavy metal pollution index.*
TLs*: Score assigned to the target layer.*

lower score of CODMn (30 points) in the flood season and the lower score of COD (30 points) in both seasons (**Table 7**). Dongmotang obtains a score of 75 points due to the lower scores of CODMn (60 points) in the flood season (**Table 8**). The scores of *OCPs* in the other seven river sections are all above 80 points (**Tables 7** and **8**).

4.4 Heavy Metal Pollutants

The monthly heavy metal pollutant (HMP) data sampling results show that the concentrations of the five indices, that is, arsenic, mercury, cadmium, chromium, and lead, are all zero in the nine river sections in the assessment year. Therefore, the scores of HMP in the nine river sections are all assigned to 100 points.

4.5 Health Assessment

Table 9 displays the grading results of the four-index layer and health assessment results of the target layer. The health assessment results show that the nine sections of the Dagujia River in the assessment year are very bad. The Xiaokuang Village section is unhealthy, and the rest eight sections are all in morbidity. The average score of the nine sections is only 2.8 points, which indicates that the Dagujia River in the 2018 assessment year is in the morbid status (**Table 9**). The spatial analysis results of the health

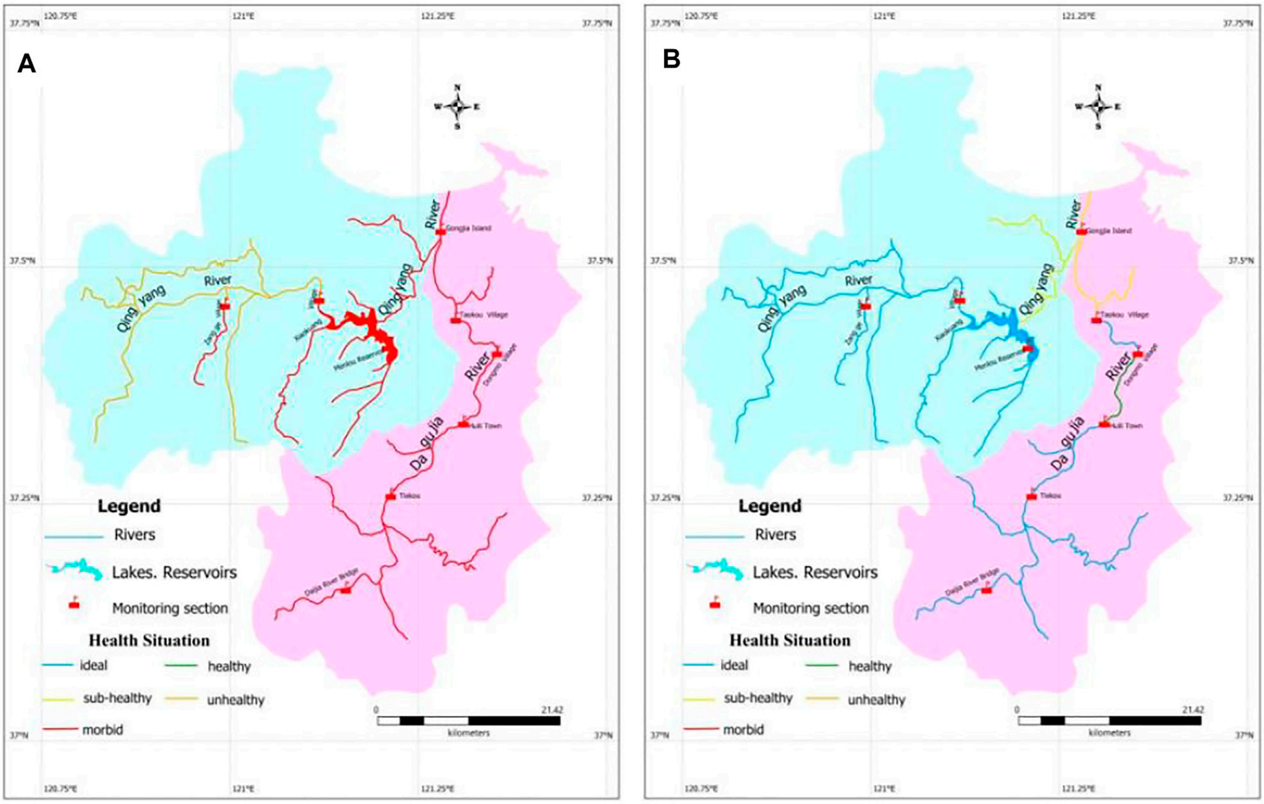

FIGURE 7 | Health assessment results of the Dagujia River: **(A)** results including water temperature variation and **(B)** results excluding heavy metal pollutants.

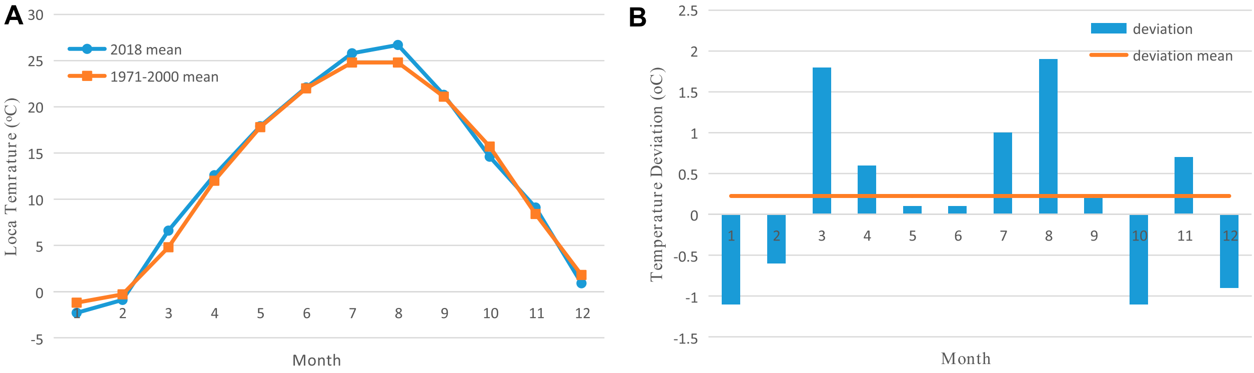

FIGURE 8 | Monthly temperature in Yantai City, China: **(A)** comparison between the average in 2018 and the average of multi-year series (1971–2000) and **(B)** comparison deviation.

assessment display that the unhealthy river section is 112.8 km long, accounting for 33.7% of the total assessed river section length, and the morbid section is 222.038 km long, accounting for 66.3% of the total assessed river section (**Figure 7A**).

The results excluding WTV, however, are quite different. The Gongjia section is in a sub-health state, the Dongmotang section is healthy, and the other seven river sections are all under ideal conditions. The sub-health status of the Gongjia section is mainly caused by the lower score of *OCP* (60 points) in the flood season (**Table 10**) due to the higher concentrations of CODMn and COD (**Table 7**). The complete target layer grading results show that the average score of the nine sections is 85.3, confirming that the Dagujia River is under ideal health conditions (**Table 10**). The spatial analysis result of the health assessment reveals the heath of the river. The 268.39 km river section is in an ideal state of health, the 10.49 km river section is in a healthy state, and the 55.96 km river section is in a sub-healthy state, which respectively accounted for 80.2, 3.1, and 16.7% of the total assessed river length (**Figure 7B**).

This assessment suggests that higher changes in water temperature variation (*WTV*) are the main factor resulting in the lower score and the poor health condition of the river (**Table 9**). The higher *WTV* could result from human development activities as assumed in this study. Meanwhile, the extreme temperatures are probably also the driving factor leading to the higher *WTV* in the assessment year, which causes the higher deviation of monthly water temperature from the monthly average of multiple years. In order to check if it is the influence of climate change, a comparison analysis is made based on the local monthly average temperature data in 2018 [9] and the multiple-year monthly average data from 1970 to 2000 [34]. The analysis result illustrates that the average monthly temperatures in the assessment year are close to the multi-year monthly average values (**Figure 8A**) with the maximum deviation of 1.9 °C and the minimum deviation of −1.1°C (**Figure 8B**). This comparison result indicates that the local temperature is not the driving factor leading to the higher *WTV*.

5 CONCLUSION

This study develops a river health assessment system based on water quality indices, and this system is applied to assess the health situations of the Dagujia River in China in 2018.

The main findings of the study are as follows: 1) the DO index of all assessed river sections in the flood season and the non-flood season are between 7.5 and 12 mg/L, which is very suitable for the growth needs of aquatic species, and hence, the DO index obtained a full score of 100; 2) the heavy metal pollutant indices of the nine assessed sections in the flood and non-flood seasons are both zero, and thus, they are also assigned full marks; (3) The CODMn and COD in the Gongjia Island section and Dongmotang section in the flood season are higher, making the scores of oxygen consumption organic pollutant index (*OCP*) in these two sections lower, 53 points and 70 points, respectively; (4) the water temperature variation (*WTV*) index of the assessed river sections is high, which resulted in the poor health status of the nine assessed river sections, where one section is in an unhealthy state and the other eight river sections are all in morbidity, and the morbid river sections accounted for 66.3% of the total assessed river sections; and (5) without considering the index of *WTV*, only one section is in a sub-health state, accounting for an assessment of 16.7% of the total length of the assessed river sections, and other river sections are all in the healthy and ideal states.

Therefore, the higher *WTV* plays a vital role in the health assessment results of the Dagujia River. The analysis results also confirm that the local monthly temperatures in the assessment year are not deviated from their multi-year average, suggesting that climate change is not the driving force of the higher WTV in the study area. In addition, CODMn and COD in certain river sections in the flood season are relatively higher, playing an important role in some sections' sub-health status. In this sense, WTV, CODMn, and COD should draw the management department concerned for planning and managing the Dagujia River.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Conception and design of this study were mainly contributed by XY and YS. Numerical simulations were mainly contributed by LJ and CF. Drafting the manuscript was mainly contributed by YX and ZY.

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