RESEARCH ARTICLE

The study on optimal design of river monitoring network using modified approaching degree model: a case study of the Liaohe River, Northeast China

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Abstract

This paper proposes a quantitative method to optimize the existing river monitoring network based on a modified approaching degree model, T test, and Euclidean distance. In this study, the Liaohe River located in Liaoning province, China, was taken as a research object. Samples were collected from 8 sampling sites throughout the monitoring network, and water quality parameters were analyzed every 2 months from January 2009 to December 2010. The results show that the average concentrations of the ammonia nitrogen (NH_4^+-N) and chemical oxygen demand (COD) were beyond grade III of the Environmental Quality Standards for Surface Water of China (GB3838-2002), and they were the main water quality parameters. After optimization, the number of monitoring sections along the Liaohe River was reduced to five from the original eight, thus saving 37.5% of the monitoring cost; meanwhile, there is no significant difference between the un-optimized and optimized monitoring networks, and the optimized monitoring network remains to be able to perform as good as the original one. In addition, the total data attainment rate was improved greatly, and the duplicate setting degree of monitoring points decreased significantly compared with other optimal methods. The optimized monitoring network proves to be more efficient, reasonable, and economically feasible, so this quantitative method can help optimize the changing orderly river monitoring networks.

Keywords Liaohe River · Approaching degree model · Optimal design · River monitoring network

Introduction

Rivers are an essential source of fresh water for socio-economic development, and the quality of river water is becoming a very sensitive topic (Mishra 2010). On the other hand, pollutants are being discharged into rivers in different ways, causing severe effects on the water environment and people's lives (Memet 2013; Ahmed et al. 2015). In order to protect our water environment, we must get accurate water quality data. The water quality monitoring has begun since

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the 1960s so as to better protect water resources and describe the general state of water quality (Boyer et al. 2000; Strobl and Robillard 2008), and some water quality assessment methods, such as water quality index (WQI) and National Sanitation Foundation WQI (NSFWQI), have been widely used to assess water quality (Akkoyunlu and Akiner 2012; Benouara et al. 2016; Noori et al. 2019). To prevent river pollution, it is required to monitor the river water data effectively (Bonde 1977; Ramteke et al. 1994). Monitoring network serves as the key link in carrying out water quality monitoring, and the design of surface water quality monitoring networks has been attracting wide attention since the 1970s (Moore 1973; Beckers and Chamberlain 1974; Lettenmaier 1978; Ward 1979). However, human activities have had a negative impact on the surface water quality (Telci et al. 2009), and this impact may last long as a result of the changes in land use patterns (Ning and Chang 2004). The representativeness of monitoring points may be subject to the changes in water quality, so the current monitoring networks need to be redesigned. At the same time, the optimal design of river monitoring networks helps save monitoring costs and ensures the accuracy of monitoring data (Xu et al. 2012). So, it is essential to optimize the existing monitoring networks regularly, in particular, ensure monitoring points are arranged reasonably.

Many studies have been conducted by others as an attempt to optimize water quality monitoring networks. Telci et al. (2009) used the genetic algorithm (GA) to determine where sampling sites should be located and judge the performance of the monitoring system, and further optimized the monitoring network of the Altamaha River system in the State of Georgia, USA. Wang et al. (2015) optimized the monitoring network of the Taizi River by the matter element analysis. Also, there are also some other methods that have been used to optimize water quality monitoring networks, such as the random sampling design (Li et al. 2015; Chen et al. 2016), the multivariate statistical analysis (Tanos et al. 2015; Chen et al. 2016), the artificial neural network method (Antanasijević et al. 2013), the fuzzy cluster analysis (Wang et al. 2012), the optimal partition analysis (Wang et al. 2019), and GIS (Bai 2013), etc. Nevertheless, the river water environment, as a complicated system, is prone to be affected by natural, social, and economic factors, etc., so there has not been a widely accepted logical design strategy or methodology (Strobl and Robillard 2008); meanwhile, it is hard to optimize the water quality monitoring network by a quantitative method for lack of a widely accepted quantitative method of determining which parameters need to be optimized. Therefore, it is essential to further study how to quantitatively optimize water quality monitoring networks.

As a kind of fuzzy clustering method, the approaching degree model is used to describe the uncertain relation between one thing and another (Zadeh 2005). As a very useful calculation method in environmental impact assessment, this model is valuable for improving the accuracy of assessment, characterized by its simple principle, convenient calculation, and good reliability. Therefore, the approaching degree model has already been used in many aspects of environmental science. Guo (2005) used this model to optimize water quality monitoring. Zhang et al. (2006) used the fuzzy approaching degree model to assess the quality of the local water environment and the quality of the water environment of the Ningxia Hui Autonomous Region. Lu et al. (2007) used the fuzzy approaching degree model to assess the status of heavy metal pollution in soil. Yang et al. (2018) used the approaching degree model to optimize the water quality monitoring data of the Songhua River in Jilin province, China. As can be seen from the above description, progress has been made in using the approaching degree model to optimize water monitoring networks, but these efforts are still in the trial and exploratory stage. Moreover, these studies are lacking quantitative methods in optimizing the water quality monitoring networks changing orderly from the upstream to the downstream (Zhang et al. 2004).

This paper aims to propose an effective quantitative method to optimize river monitoring networks based on a modified approaching degree model, T test, and Euclidean distance. In this study, the Liaohe River located in Liaoning province, China, was taken a research object. We hope the results from this study may provide an efficient quantitative method to optimize the changing orderly river monitoring networks and help improve the management of water quality.

Methodology

Modified approaching degree model

The basic procedure to operate the approaching degree model is as below: first, establish and normalize a sample matrix; second, determine the most ideal point (A) and the least ideal point (B) and select a standard value point (θ_m); third, calculate the approaching degree between samples and the standard value point and divide the samples into different groups (Chen et al. 2009).

Establishment of the sample matrix

Suppose that there are $m-1$ monitoring sections (θ_1, θ_2,…,θ_{m-1}) and n monitoring indexes in each monitoring

section, then the initial sample matrix (R_{m-1}) can be expressed as below:

$$R_{m-1} = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_{m-1} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ c_{(m-1)1} & c_{(m-1)2} & \cdots & c_{(m-1)n} \end{bmatrix}$$
$$= (c_{ij})_{(m-1) \times n} \tag{1}$$

where C_{ij} is the value of the jth water monitoring index at the ith monitoring section, $i \in (1, 2,\ldots, m-1)$, $j \in (1, 2,\ldots, n)$.

The initial matrix (R_o) comprises the initial sample matrix (R_{m-1}) and the standard value point (θ_m), which comprises the expected monitoring values.

$$R_0 = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_m \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ c_{m1} & c_{m2} & \cdots & c_{mn} \end{bmatrix} = (c_{ij})_{m \times n} \tag{2}$$

where C_{mj} is the value of the jth water monitoring index at the mth monitoring section.

The sample matrix (R) can be obtained by normalizing the initial matrix (R_o) (Zhang et al. 2006).

$$R = \begin{bmatrix} \theta_1' \\ \theta_2' \\ \vdots \\ \theta_m' \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} = (r_{ij})_{m \times n} \tag{3}$$

$$r_{ij} = \frac{C_{ij}}{\sqrt{\sum_{i=1}^{m} C^2_{ij}}} \tag{4}$$

The approaching degree between the samples and the standard value point

According to the detected values of all water monitoring indexes, the most ideal point (A) and the least ideal point (B) can be expressed respectively as below:

the most ideal point (A) : $\left\{ \min_i x_{ij}, j \in J; \max_i x_{ij}, j \in J' \right\}$ (5)

the least ideal point (B) : $\left\{ \max_i x_{ij}, j \in J; \min_i x_{ij}, j \in J' \right\}$
(6)

where x_{ij} is the detected value of the jth water monitoring index at the ith monitoring section; n is the number of monitoring sections; J is a set of negative indexes; and J' is a set of positive indexes.

θ_A is a virtual point where the water quality is the best, and θ_B is also a virtual point where the water quality is the worst.

The distance (D_{i-A}) between the sampling point i and the most ideal point (A) and the distance (D_{i-B}) between the sampling section i and the least ideal point (B) can be calculated (Zhao et al. 2014; Guo 2005) as below:

$$D_{i-A} = \left[\sum_{j=1}^{n} \alpha_j \left(r_{ij} - (r_{ij})_A \right)^2 \right]^{\frac{1}{2}}, (i = 1, 2, \cdots m-1) \tag{7}$$

$$D_{i-B} = \left[\sum_{j=1}^{n} \alpha_j \left(r_{ij} - (r_{ij})_B \right)^2 \right]^{\frac{1}{2}}, (i = 1, 2, \cdots m-1) \tag{8}$$

where a_j is the weight of the jth water monitoring index.

The higher the standard-exceeding ratio of the jth water monitoring index is, the more important the jth water monitoring index is, and the bigger the weight of the jth water monitoring index is. So the weight of the jth water monitoring index (a_j) can be expressed as below:

$$\alpha_i' = \frac{A_i + 1}{B_i}, (i = 1, 2, \cdots m) \tag{9}$$

$$\alpha_j = \frac{\alpha_j'}{\sum_{i=1}^{m} \alpha_i'}, (i = 1, 2, \cdots m) \tag{10}$$

where A_i is the times of the ith water monitoring index in excess of the standard value; B_i is the monitoring times of the ith water monitoring index.

Likewise, the distance (D_{m-A}) between the standard value point (θ_m) and the most ideal point (A) and the distance (D_{m-B}) between the standard value point (θ_m) and the least ideal point (B) can be calculated (Zhao et al. 2014; Guo 2005) as below:

$$D_{m-A} = \left[\sum_{j=1}^{n} \alpha_j \left(r_{mj} - (r_{ij})_A \right)^2 \right]^{\frac{1}{2}} \tag{11}$$

$$D_{m-B} = \left[\sum_{j=1}^{n} \alpha_j \left(r_{mj} - (r_{ij})_B \right)^2 \right]^{\frac{1}{2}} \tag{12}$$

The approaching degree (C_{i-m}) between the sampling section i and the standard value point (θ_m) can be calculated as below:

$$C_{i-m} = \frac{1}{2} \left(\frac{D_{m-A}}{D_{i-A}} + \frac{D_{i-B}}{D_{m-B}} \right) \tag{13}$$

The closer the value of C_{i-m} to 1, the smaller the difference in water quality between the monitoring point i and the standard value point (θ_m). If the value of C_{i-m} is 1 plus, it means that the water quality at the monitoring point i is better than that at the standard value point (θ_m). The bigger the value of C_{i-m} is, the better the water quality at the monitoring point i is. If the value of C_{i-m} is less than 1, it means that the water

quality at the monitoring point i is worse than that at the standard value point (θ_m). The smaller the value of C_{i-m} is, the worse the water quality at the monitoring point i is. According to the values of C_{i-m} in different monitoring sections, the approaching degree between different monitoring sections and the standard value point can be compared with each other.

Determination of groups and the optimal section

In order to divide these monitoring sections in this orderly changed river system into different groups, a mean T test was conducted to analyze the neighboring monitoring sections based on the approaching degree model analysis results, with the significance level identified as 0.05. If no significant difference is identified between two neighboring monitoring sections, they belong to the same group of sections; but if there is any significant difference identified, they belong to different groups of sections. In this way, the monitoring sections can be divided, from the upstream to the downstream, into different groups according to the T test results.

Euclidean distance was also used to determine the optimal section in each group of sections. First, suppose that $G\,(i,j) = \{G_{ij1},\ldots, G_{ijk},\ldots, G_{ijm}\}$ is the barycenter of $\{X_i, X_{i+1},\ldots, X_j\}$ (Dong 2004; Wang et al. 2015), then $G\,(i,j)$ can be defined as $\{G_{ij1},\ldots, G_{ijh},\ldots, G_{ijm}\}$, and

$$G_{ijh} = \frac{\sum\limits_{l=1}^{M} y_{ijhl}}{M} \tag{14}$$

where M is the number of sections in the group $\{X_i, X_{i+1},\ldots, X_j\}$, and y_{ijkl} is the hth water monitoring index obtained at the monitoring section l.

The Euclidean distance (R_{iK}) between $G\,(i,j)$ and the monitoring section K can be calculated by the following formula:

$$R_{ik} = \left[\sum\limits_{j=1}^{m} \left(y_{ijk} - G_{ik}\right)^2\right]^{1/2} \tag{15}$$

where m is the number of monitoring indexes in each section. The smaller R_{iK}, the more representative the point K is to the group $G\,(i,j)$.

Study area

Description of the study area

In this study, a section of the Liaohe River was selected as the investigated object, which is located in the territory of Liaoning province, at latitude from 41° 3′ N to 42° 59′ N and longitude from 120° 38′ E to 124° 10′ E approximately, with a catchment area of about 69,200 km^2 (Han et al. 2009).

The river runs through the cities of Tieling, Shenyang, Anshan, and Panjin of Liaoning province, and at last empties into the Bohai Sea.

The Liaohe River basin is an economically developed region in Northeast China, where an industrial cluster covering petrochemical, metallurgical, and equipment manufacturing industries have been formed after half a century's development. As one of the most important rivers in Northeast China, the Liaohe River has long been an important source of fresh water and contributed greatly to the socio-economic development of the Liaohe River basin. With the excessive development and utilization of water resources, the quality of the water environment of the Liaohe River is becoming worse and worse. At the same time, more and more pollutants such as heavy metals, nutrients, and COD that originated from industrial wastewater and domestic sewage are being discharged into the mainstream and tributaries of the Liaohe River. So water pollution in the Liaohe River is becoming one of the issues that needs to be solved urgently (Zhang et al. 2008). Liu et al. (2013) detected heavy metals in sediments at the riparian zone from 10 sections along the Liaohe River and found that every such section has been polluted by heavy metals. Bu et al. (2014) assessed the ecological risks of heavy metals and characterized the toxicity of surface sediments in the Liaohe River, and the results revealed that there were potential ecological risks in the Laohe River and strong toxicity in the tributaries.

A monitoring network was set up for the Liaohe River mainstream in the 1990s, including eight monitoring points, that is, Fudedian (FDD), Sanhetun (SHT), Zhuershan(ZES), Mahushan (MHS), Hongmiaozi (HMZ), Panjinxingan (PJXA), Shuguangdaqiao (SGDQ), and Zhaoquanhe (ZQH) (Fig. 1) respectively from the upstream to the downstream. However, researches on the representativeness of the monitoring network are rarely found. In order to make full use of the limited funds and understand the real water quality situations of the Liaohe River, it is essential to optimize the design for the river monitoring network.

Analytical methods

Water samples were collected every 2 months from January 2009 to December 2010, and three parallel samples were collected from each sampling point. Water samples were collected from a depth of 30 cm below the water surface, then kept in acid-leached polythene bottles preserved with concentrated HNO$_3$ at an ambient temperature of 4 °C [24, 25] after filtration using a 0.45-μm micropore membrane, at last, sent to the laboratory as soon as possible. Fifteen water quality parameters, including ammonia nitrogen (NH$_4^+$-N), chemical oxygen demand (COD), mercury (Hg), volatile phenol (VP), lead (Pb), copper (Cu), zinc (Zn), arsenic (As), cadmium (Cd), hexavalent chromium (Cr^{6+}), fluoride, petroleum, total
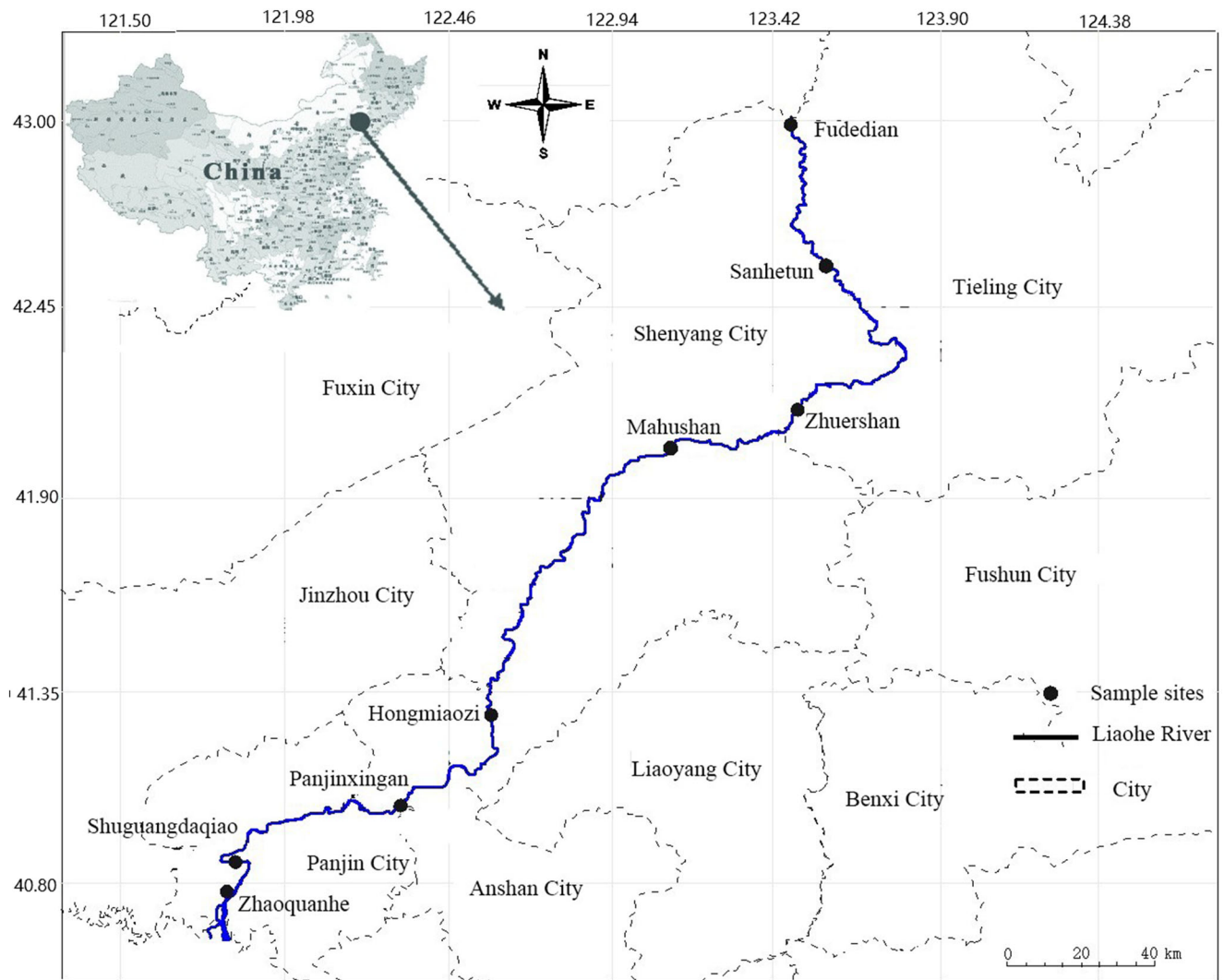
Fig. 1 Distribution of monitoring stations along the Liaohe River

Table 1 Water quality parameters of the Liaohe River

	Mean ± SD	Range	Median	National standard grade III
N_4^+-N (mg/L)	2.833 ± 2.957	0.025–16.840	1.188	1
COD (mg/L)	23.001 ± 8.880	11.000–44.500	23.760	20
Hg (µg/L)	0.024 ± 0.006	0.020–0.035	0.020	0.1
VP (mg/L)	0.005 ± 0.004	0.001–0.025	0.005	0.005
Pb (mg/L)	0.0050 ± 0.0001	0.004–0.005	0.005	0.05
Petroleum (mg/L)	0.147 ± 0.103	0.022–0.420	0.110	0.05
TP (mg/L)	0.285 ± 0.457	0.040–3.220	0.200	0.2
Cu (mg/L)	0.008 ± 0.012	0.005–0.080	0.005	1
Cyanide (mg/L)	0.0020 ± 0.0001	0.001–0.002	0.002	0.2
Zn (mg/L)	0.027 ± 0.007	0.025–0.060	0.025	1
Fluoride (mg/L)	0.294 ± 0.252	0.030–0.970	0.330	1
Se (µg/L)	1.872 ± 0.220	1.500–2.000	2.000	10
As (mg/L)	0.004 ± 0.001	0.001–0.004	0.004	0.05
Cd (µg/L)	0.491 ± 0.059	0.100–0.500	0.500	5
Cr^{6+} (mg/L)	0.011 ± 0.013	0.002–0.044	0.002	0.05

Table 2 Data availability rate (%) at monitoring sections of the Liaohe River

Year	FDD	SHT	ZES	MHS	HMZ	PJXA	SGDQ	ZQH
2009	91.10%	62.56%	91.10%	83.78%	91.10%	91.10%	71.12%	63.11%
2010	96.00%	96.00%	96.00%	88.07%	96.00%	96.00%	95.21%	62.36%

phosphorus (TP), selenium (Se), and cyanide, were analyzed as required in the Environmental Quality Standards for Surface Water of China (GB3838-2002) and according to the actual situations of the Liaohe River. Recovery was also conducted, with a recovery rate > 90%. Standard reference materials and reagent blanks were inserted randomly to control analytical quality and precision. Instruments were recalibrated when there was a deviation beyond 10%.

Results

The water quality characteristics and monitoring network

The results of water quality parameters were shown in Table 1. As can be seen from this table, (a) the contents of Pb, cyanide, Se, and Cd are stable; (b) the concentrations of COD, Hg, Zn, and As vary in a wide range; (c) the other 7 parameters, including N_4^+-N, VP, petroleum, TP, Cu, fluoride, and Cr^{6+}, vary significantly at different monitoring points. According to grade III of the Environmental Quality Standards for Surface Water of China (GB3838–2002), the standard-exceeding ratios of N_4^+-N and COD are 56.25% and 57.14%, respectively, thus they can be regarded as the main pollution factors.

In order to analyze the situations of the existing monitoring network, the data availability rates at each monitoring section and the correlation between adjacent monitoring sections were calculated by reference to academic literature (Dong 2004; Xiao 2008), as shown in Table 2 and Table 3. For the

correlation between adjacent monitoring points, it is very significant only when the correlation coefficient > the threshold value of correlation coefficients ($p = 0.05$) ($r_{0.05}$). Table 2 shows that there were 4 monitoring points where the data compliance rates exceed 90% in 2009, and the data compliance rate rose dramatically in 2010 compared with that in 2009, while the data compliance rates obtained by ZQH were always lower than those obtained by others, whether in 2009 or 2010, which is because the Liaohe River is a seasonal river, sampling would be very hard in winter. Table 3 shows the correlation between adjacent N_4^+-N monitoring points in the mainstream of the Liaohe River is very significant, and the correlation between adjacent COD monitoring points is not significant except FDD-SHT and SHT-ZES. The correlation between adjacent monitoring points can reflect whether monitoring points are established repeatedly (Dong 2004; Xiao 2008), this means that there were repeated arrangement of monitoring sections in the monitoring network of the Liaohe River.

Optimal design for the river monitoring network using the approaching degree model

Based on the water quality monitoring data obtained from the Liaohe River from 2009 to 2010, the approaching degree of each monitoring point in the monitoring network of the Liaohe River was calculated, and a mean T test was conducted to analyze the approaching degree between adjacent monitoring points after optimization using the approaching degree model, with the test results as shown in Table 4. By paired comparison between FDD-SHT, ZES-MHS, and PJXA-SGDQ, respectively, the significance level of the T test was over 0.05, so there was no significant difference between

Table 3 Correlation coefficient of major pollution factors between adjacent monitoring points along the Liaohe River mainstream

	N_4^+-N	COD	$r_{0.05}$
FDD-SHT	0.630	0.687	0.602
SHT-ZES	0.671	0.606	0.602
ZES-MHS	0.842	− 0.060	0.632
MHS-HMZ	0.853	− 0.170	0.632
HMZ-PJXA	0.838	0.030	0.602
PJXA-SGDQ	0.929	0.515	0.602
SGDQ-ZQH	0.657	0.103	0.666

Table 4 T test results between adjacent monitoring sections after optimization using the approaching degree model. (Sig > 0.05: means no significant difference; Sig < 0.05: means the difference is significant)

	T	Sig.
FDD-SHT	2.088	0.091
SHT-ZES	− 2.585	0.049
ZES-MHS	− .933	0.393
MHS-HMZ	− 4.453	0.007
HMZ-PJXA	.009	0.009
PJXA-SGDQ	.195	0.195
SGDQ-ZQH	.001	0.001

Table 5 Tests on the results of Liaohe River water quality monitoring after optimization

Sample variable	F test			T test	
	F	Sig.	Result	T	Result
NH_4^+-N	0.486	0.488	Homogeneous variance	0.422	No significant difference
COD	0.104	0.749	Homogeneous variance	-0.132	No significant difference

FDD-SHT, ZES-MHS, and PJXA-SGDQ, respectively. By paired comparison between SHT-ZES, MHS-HMZ, HMZ-PJXA, and SGDQ-ZQH, respectively, the significance level of the T test is less than 0.05, so there was a significant difference between SHT-ZES, MHS-HMZ, HMZ-PJXA, and SGDQ-ZQH, respectively.

According to the above results, 8 monitoring points in the monitoring network of the Liaohe River mainstream were divided into 5 groups, 2 (FDD and SHT) in group I, another 2 (ZES and MHS) in group II, 1 (HMZ) in group III, 2 (PJXA and SGDQ) in group IV, and 1 (ZQH) in group V. There was only 1 monitoring point in groups III and V, so HMZ and ZQH should be retained in the monitoring network.

There were 2 monitoring points in groups I, II, and IV, respectively, and the Euclidean distances from the 2 monitoring points to the monitoring section were equal. Therefore, we cannot only depend on the Euclidean distances to the representative section in each group; instead, we must consider other factors, such as the management factor and the characteristics of the monitoring points. In group I, FDD is the first monitoring section at the Liaohe River's upper stream, where the river flows into Liaoning province, so FDD should be retained, while SHT should be removed. In group II, ZES is a cross-border water quality monitoring section located between Tieling city and Shenyang city, so ZES should be retained, while MHS should be removed. In group IV, SGDQ is the last water quality monitoring section along the Liaohe River mainstream before the river runs through Panjin city, so SGD should be retained, and PJXA should be removed.

Therefore, after optimization based on the approaching degree model, Euclidean distance and the characteristics of the monitoring points, the number of monitoring sections along the Liaohe River mainstream dropped from 8 to 5 (FFD, ZES, HMZ, SGDQ, and ZQH), saving 37.5% of the monitoring cost. Therefore, this monitoring network would be more effective and economically feasible. Meanwhile, the optimized water quality monitoring network remains to meet the requirements of environmental management and also presents the characteristics of all the monitoring sections.

Discussion

A well-designed water quality monitoring network is a key link in identifying water quality problems and establishing baseline values for short- and long-term trend analysis (Strobl and Robillard 2008). However, a monitoring network is usually based on subjective criteria (Ward 1996; Harmancioglu and Alpaslan 1992), and the design of a water quality monitoring network tends to be arbitrary at the beginning (Strobl et al. 2006). There is still a lack of in-depth research on how to determine the optimal section quantitatively (Dong 2004). With the development of society, human activities have had a negative impact on the surface water quality (Telci et al. 2009), and the representativeness of monitoring points may be subject to the changes in water quality. However, there were no re-assessment and optimization options for the established monitoring networks at the beginning (Ward 1996; Harmancioglu and Alpaslan 1992). So the current monitoring networks need to be redesigned. Meanwhile, rivers are a typical system that changes orderly from the upstream to the downstream, so it is not enough to just pay attention to the arrangement of monitoring points as we attempt to optimize the monitoring network using the existing optimization methods (Zhang et al. 2004). In this study, an

Table 6 Comparison of optimization results as different optimization methods were adopted

	Monitoring network	Total data availability rate (%)	Total correlation degree between adjacent monitoring sections (%)
Original network	FFD, SHT, ZES, MHS, HMZ, PJXA, SGDQ, and ZQH	85.50%	64.29%
In this study	FFD, ZES, HMZ, SGDQ, and ZQH	87.30%	62.50%
Matter element analysis	ZES, MHS, SGDQ, and ZQH	83.13%	66.67%%
Mean divagation	ZES, MHS, and ZQH	79.67%	75%
Fuzzy clustering	SHT, ZES, HMZ, SGDQ, and ZQH	84.40%	62.50%

effective quantitative method was proposed to optimize the existing river monitoring network based on the modified approaching degree model, and a mean T test was used to analyze the correlation between neighboring monitoring sections based on the approaching degree model analysis results. Therefore, the quantitative method proposed in this paper is effective for optimizing orderly changed river monitoring networks, and its application prospect is sure to be broad.

Monitoring cost is an issue that needs to be considered when a water quality monitoring network is designed, but what is more important is the reliability and trueness of the monitoring data. To examine the reliability and trueness of the monitoring data after optimization based on the main water quality parameters (NH_4^+-N, and COD) of the Liaohe River mainstream from January 2009 to December 2010 (Table 5), Wang et al. (2019) and Wang et al. (2015) assessed the difference between un-optimized and optimized monitoring networks by variance test (F test) and mean test (T test). Table 5 shows their variances are homogeneous, and no significant difference is identified between the un-optimized and optimized monitoring networks of the Liaohe River mainstream. That means the optimized monitoring network can correctly represent the original monitoring network, and the reliability and trueness of the monitoring data after optimization are acceptable. Therefore, the method proposed in this study is an effective quantitative method of optimizing water quality monitoring networks.

Data availability rates at the monitoring section and the correlation between adjacent monitoring sections in the monitoring network can be used to assess whether a water quality monitoring network is established reasonably (Dong 2004; Xiao 2008), and to compare different optimization methods. Table 6 shows the conditions of the water quality monitoring network of the Liaohe River after optimization using the matter element analysis (Wang et al. 2015), the fuzzy clustering (Wang et al. 2012), and mean divagation (Li et al. 2017), respectively. Compared with the original network, there are less monitoring points in the optimized monitoring network, and the total data compliance rate decreases after optimization, except in this study, where the total data availability rate is the highest. The total correlation degree between adjacent water quality data (NH_4^+-N, and COD) monitoring points dropped after optimization using the method proposed in this study or the fuzzy clustering method was used, but rose after optimization using the matter element analysis or mean divagation, compared with the original network. The drop in total correlation degree between adjacent monitoring points means that monitoring sections were repeatedly arranged at a lower degree (Dong 2004; Xiao 2008). The total correlation degree between adjacent monitoring points was the lowest after optimization using the method proposed in this study or the fuzzy clustering method. That indicates that the optimized results are more rational. In summary, the modified approaching degree

model proposed in this study is more feasible, and the optimized monitoring network is more economic and efficient, after considerations are given to the data availability rate at the monitoring section and the correlation between adjacent monitoring sections in the monitoring network.

Conclusions

In this paper, an effective quantitative method was proposed to optimize orderly changed river monitoring networks based on the approaching degree model, T test, and Euclidean distance. In this study, the Liaohe River located in Liaoning province, China, was taken as a research object. After optimization, the number of monitoring sections along the Liaohe River was reduced to 5. Therefore, the optimized monitoring network can correctly represent the original one, and after optimization, the monitoring network became more efficient, reasonable, and economically feasible. Compared with other optimization methods, the method proposed in this study was a valuable and high-efficiency strategy to optimize river monitoring networks, and can provide guidance for the optimization of river monitoring networks in China and other countries.

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