Evaluation of drinking water quality in a water supply distribution network based on Grey correlation analysis

Tao Tao, Kunlun Xin, Cunzhen Lv and Suiqing Liu

ABSTRACT

The lack of access to clean drinking water adversely affects public health and life expectancy in many developing countries. However, not all cities' drinking water can currently meet drinking water standards. Therefore, determining reasonable water quality changes and the influence of various factors on water quality is important for improving drinking water quality. The objective of this study was to develop a water quality evaluation method based on Grey correlation analysis by evaluating water quality variations using tap water monitoring parameters and analysing the main factors that influence water quality throughout the water distribution network. A comprehensive evaluation system based on the proposed method has been implemented in drinking water quality control for water supply networks in the city of Zhenjiang. The results show that the main influencing factors are different at different monitoring locations. The main factor is the residence time at approximately half of the monitored locations. For the remaining locations, the main factors are pipe age and pipe material. Based on the evaluation results of water quality in the pipe network, the pipeline can be replaced, beginning with locations 4 and 8 in Zhenjiang city and followed by the remaining locations.

Key words | drinking water quality evaluation, Grey correlation analysis, Zhenjiang water pipe network

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INTRODUCTION

Safe and high-quality drinking water is essential for public health. In the past few years, with continuously improving living quality and a growing economy, public concerns about the quality of drinking water has grown considerably in China. China is now facing more challenges with drinking water than other developing countries worldwide. The water quality problems are mostly related to the effectiveness of water treatment and defects in the distribution networks. A survey showed that almost 80% of residents treated their tap water (e.g. boiled, reverse-osmosis filtered, activated-carbon adsorbed or other methods) before drinking (Lou & Han 2002). Safe drinking water can be obtained if water treatment complies with water quality standards. In China, the Ministry of the Environment has recently updated water quality standards (GB5749-2006). Water quality indices have increased from 35 to 106 parameters. The restrictions placed on some indices are more critical. Because of the different conditions in urban and rural areas, including water quality analysis, supervision capability, water disposal equipment, management and technology, financial input and living standards, the implementation of new water quality standards has been challenging.

Even with treatment in the plant, the quality of water varies along its path through the distribution network. Several investigations have demonstrated that water quality deteriorates as it moves from the treatment plant to the system extremities (Rodriguez *et al.* 2001; Turgeon *et al.* 2004). These variations have been clearly demonstrated to be closely related to variations in water residence time in the distribution system (Ozdemir & Metin 1999). But the water quality of the distribution system is not only related to residence time. It is also related to other factors, including water pipe age, water pipe material and management (Doria

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et al. 2005, 2009; Doria 2006). Under these circumstances, the customer perception of water quality varies spatially within a distribution system (Nare et al. 2006). The goal of the present study was to establish a water quality evaluation method based on the monitoring index to evaluate water quality variations based on consumers' perceptions of tap water quality and to analyse the main factors that influence the water supply. The methodology is presented in the next section, followed by its application to a case study with two sections: (1) spatial and temporal evaluation of water quality and (2) analysis of water quality-influencing factors.

APPROACH OF WATER QUALITY EVALUATION

Water quality evaluation system

The water quality evaluation system in urban distribution systems is one of the effective tools of water quality management in the pipe network. It includes the monitoring of data (real-time or laboratory analysis data) from water quality monitoring stations in the distribution system, data processing using a water quality evaluation method and the analysis of water quality changes in the pipe network, which provide basic information for water quality management. The system is typically divided into the following components:

(a) Selection of water quality indices. According to the 'Standards for Urban Water Supply Water Quality' (GB5749-2006), the reasonable water quality indices have been selected from monitoring index and validated data.
(b) New water quality grading standards. The water quality grading standards should be consistent with existing water quality standards, such as the 'Standards for Drinking Water Quality' (GB5749-2006), 'Standards for Urban Water Supply Water Quality' (CJ/T206-2005) and the existing water quality of the urban water supply.
(c) Data processing. Because of the diversity of monitoring indices in pipe networks, deviations in the different measured data are too large to affect the calculated results. Variations in water quality indices should be properly processed to eliminate the dimensional impact on the results.
(d) Water quality evaluation model. The water quality evaluation model in pipe networks involves a large number of water quality indices, and the model should consider all of the indices so that it can accurately reflect the water quality in the network.
(e) Result analysis. According to the results obtained from the evaluation model, spatial variations in water quality can be analysed accordingly, which will provide a basis for water quality management.

Grey correlation analysis method

Evaluations using fuzzy logic models are widely accepted in the evaluation of water quality. Grey system theory was developed on the basis of fuzzy logic, and it has the advantage of using fuzzy mathematics to overcome imperfections. Grey correlation analysis, which is an important tool derived from Grey system theory, can be applied to comprehensively evaluate many evaluation factors and complicated data (Deng 1985, 2010). Grey correlation analysis removes the subjective factors that influence the evaluation data, has high credibility and is objective and accurate.

Assume that the standard data sequence is $Y_1(k)$, $Y_2(k),\ldots, Y_n(k)$. After non-dimensional data processing, the corresponding sequence is $y_1(k), y_2(k), \ldots, y_n(k)$. The sample data sequence is $X_1(k), X_2(k), \ldots, X_m(k)$, and then the corresponding sequence is $x_1(k), x_2(k), \ldots, x_m(k)$, $k \in L = (1, 2,\ldots, l)$ after the data processing. The correlation matrix R (Equation (7)) is obtained by applying the following formulas:

$$\Delta\min = \min_i \min_j \min_k |x_i(k) - y_j(k)| \tag{1}$$

$$\Delta\max = \max_i \max_j \max_k |x_i(k) - y_j(k)| \tag{2}$$

$$\Delta_{ij} = |x_i(k) - y_j(k)| \tag{3}$$

$$\varepsilon_{ij}(k) = \frac{\Delta\min + \rho\Delta\max}{\Delta_{ij} + \rho\Delta\max} \tag{4}$$

$$r_{ij} = \frac{1}{L}\sum_{k=1}^{L} \varepsilon_{ij}(k) \quad (5)$$

$$R = (r_{ij})m \times n \quad (6)$$

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_n \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \quad (7)$$

where $\varepsilon_{ij}(k)$ is the correlation coefficient at the location where the sample sequence x_i and the standard sequence y_j are obtained, r_{ij} is the correlation degree of the sample sequence x_i and the standard sequence y_j at same location, ρ is the resolution coefficient and 0.5 is the recommended value (Deng 2010). R represents the $m \times n$ matrix that consists of the correlation degree. m is the total number of sample sequences. n is the total number of standard sequences. L is the total number of monitoring indices.

The elements in matrix R have bi-dimensional comparability (i.e. they can be analysed by lines or by columns). The correlation degree between the sample sequence and the standard sequence can be obtained by column comparisons, and its maximum value represents the maximum correlation degree.

CASE STUDY

The city of Zhenjiang is in northern Jiangsu Province, China, on the south bank of the Yangtze River. Zhenjiang covers 3,843 km^2, of which 1,964 km^2 is hilly land and 526 km^2 is water area. The urban area is approximately 60.2 km^2. The major source of drinking water is the main stream of the Yangtze River in the Zhenjiang section. Water quality reaches Class II based on National Surface Water Quality criteria. There is one water treatment plant in the centre of the city, with a water supply capacity of 30,000 t/d. Twenty-six water quality monitoring locations are arranged throughout the water distribution system, and four points are located in the rural area.

SPATIAL AND TEMPORAL EVALUATION OF WATER QUALITY

Zhenjiang Water Supply Company conducts analyses of 32 parameters of the samples from the water quality monitoring points monthly. The analysed parameters include colour, turbidity, smell, taste, visible objects, pH, free chlorine, total dissolved solids, iron, manganese, copper, zinc, cadmium, lead, mercury, arsenic, chloroform, carbon tetrachloride, fluoride, chloride, nitrate nitrogen, sulfate, total organic carbon, hardness, alkalinity, ammonia, nitrogen, sub-nitrate nitrogen, oxygen consumption, volatile phenol, cyanide, total bacteria and total coliform. Data from the Zhenjiang pipe network were collected and archived from 2006 to 2009. The 2006 data are documented from January to October, and the 2009 data are from January to May. The 2007 and 2008 data include all months. As there were no complete water quality monitoring data collected from four monitoring points located in the rural area, the studied area in the first section only includes 22 monitoring locations, as shown in Figure 1.

Water quality indices

After analysing the water quality data from the Zhenjiang pipe network, the following parameters were selected as evaluating the system's basic parameters: colour, turbidity, free chlorine, total dissolved solids, iron, zinc, cadmium, mercury, arsenic, chloroform, fluoride, chloride, nitrate nitrogen, sulfate, total organic carbon, hardness, oxygen consumption and total bacteria, based on the effectiveness and expressiveness of the measured data.

Water quality grading method

The drinking water source of Zhenjiang is the downstream segment of the Yangtze River. The Yangtze River flows through Nanjing and other large or medium-sized cities before reaching Zhenjiang, which burdens the risk that the river may be polluted. The Yangtze River has a large flow and flows faster in the Zhenjiang segment. Therefore, the water source has good self-purification capabilities, resulting in good raw water quality. It is an ideal source that basically satisfies the Water Quality

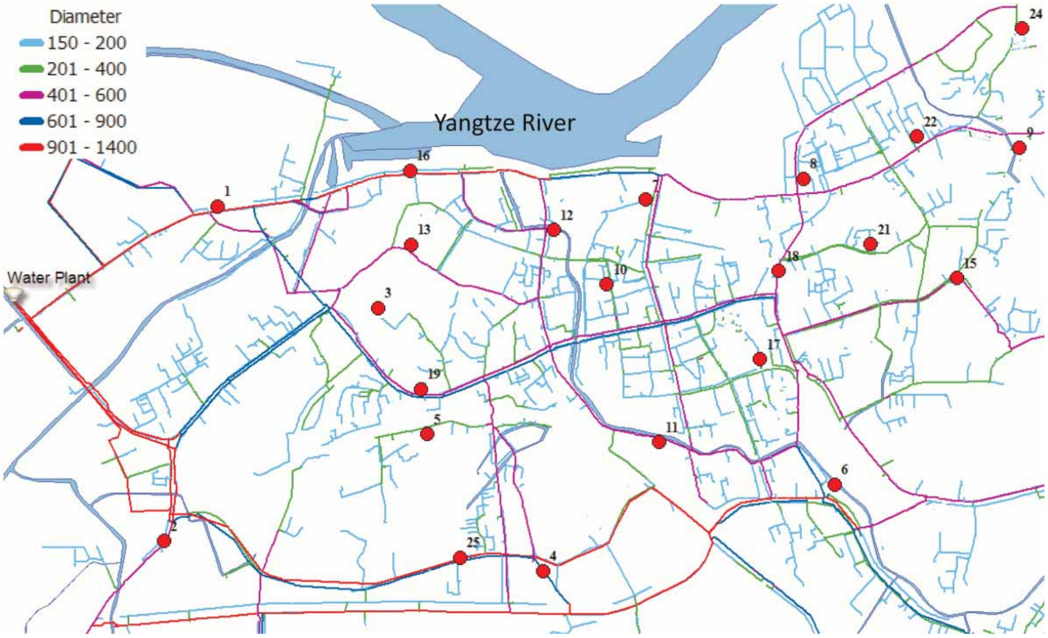

Figure 1 | Drinking water quality monitoring points in Zhenjiang city.

Standard for Ground Drinking Water Source. The water treatment plant applies advanced water treatment technology to further ensure the reliability of water supply quality. According to the monthly analysis reports provided by the Zhenjiang water quality monitoring stations, all water quality indices meet the new national standards, and many indices are even better than the national standards.

In summary, to grade tap water quality in Zhenjiang, it must comply with the following classification strategies. (1) The normal standard is Level 2. According to the 'Standards for Drinking Water Quality' (GB5749-2006) and 'Standards for Urban Water Supply Water Quality' (CJ/T206-2005), the index values can be determined accordingly. (2) The highest water quality is Level 1, and is an improvement from Level 2. (3) Level 3 is a deterioration from Level 2. According to the 'Standards for Drinking Water Quality' (GB5749-2006) and water quality monitoring values, Zhenjiang's water quality grading standards are shown in Table 1.

In addition to free residual chlorine, a negative correlation was found between the other indices. For example, in the water quality standard, the water quality worsens with increased index values.

Data processing

The monitoring indices have different units as shown in Table 1. Therefore, transforming the measured values to normalized values is essential. There are a few data normalization methods reported. For different assessment aims, different methods should be chosen. The generally accepted method to normalize is linear function transformation, which requires the maximum and minimum values of sample sequence. However, for different sample sequences, the normalized process of the standard sequence (the standard sequence and sample sequence will comply with the same normalized method) will obtain different results, which will lead to poor universality. Therefore, there is no recommended or generally accepted normalization method. The alternative way is to divide by a certain number to eliminate the impact of units and the magnitude of assessment indices. In this paper, considering Equation (4), for the purpose of all variables (Δmin, Δmax, Δ_{ij}) with the same magnitude, every index is multiplied by 10^n ($n \in$ integer) to make all indices of quality Level 3 between 0.1 and 0.9. On one hand it will eliminate the dimensional impact on the results, and on the other hand, the water quality grading dimensionless standards (Table 2) can also be

Table 1 | Water quality grading standards in Zhenjiang city

Grading	Standards for urban water Supply water quality	Quality Level 1 Good	Quality Level 2 Qualified	Quality Level 3 Poor
Parameter				
Colour	15	5	15	30
Turbidity (NTU)	1	0.2	1	2
Free residual chlorine (mg/L)	0.3	0.3	0.1	0.05
Total dissolved solids (mg/L)	1,000	300	1,000	1,500
Iron (mg/L)	0.3	0.1	0.3	0.5
Zinc (mg/L)	1	0.3	1	1.5
Cadmium (mg/L)	0.003	0.001	0.003	0.005
Mercury (mg/L)	0.001	0.0003	0.001	0.003
Arsenic (mg/L)	0.01	0.003	0.01	0.03
Chloroform (mg/L)	0.06	0.01	0.06	0.1
Fluoride (mg/L)	1	0.3	1	1.5
Chloride (mg/L)	250	100	250	500
Nitrate nitrogen (mg/L)	10	3	10	20
Sulfate (mg/L)	250	100	250	500
Total organic carbon (mg/L)	5	1	5	10
Hardness (mg/L)	450	150	450	600
Oxygen consumption (mg/L)	3	1.5	3	5
Total bacteria (CFU/mL)	80	0	80	100

applied to other areas for water quality comparison. The factors were chosen such that for parameter Colour the factor is 10^{-2}, and for parameter Turbidity the factor is 10^{-1}. After non-dimensional data processing, the dimensionless normalized value is shown in Table 2.

Water quality evaluation model

The Grey correlation model is then applied to evaluate water quality. Standard sequences $Y_1(k), Y_2(k),\ldots, Y_n(k)$ are the water quality standard value, whereas sample sequences $X_1(k), X_2(k),\ldots, X_m(k)$ are the measured values at the water quality monitoring location. The standard value and measured value use the same approach proposed above for normalization.

In the case of Zhenjiang water quality, Equations (1)–(7) were applied to calculate the correlation degree r_{ij}, which means the correlation between water quality of the ith monitoring location and the jth water quality level. The higher r_{ij} is, the closer the water quality of the ith monitoring location is to the jth water quality level. In these equations, k represents the total number of monitoring indices (equal to 18), n represents standard levels (equal to 3) and m represents the total number of monitoring locations (equal to 22). We can conclude from the calculated r_{ij} that Zhenjiang water quality generally reached Level 1 in 2008 and 2009. But the tendency towards temporal and spatial water quality variations in Zhenjiang distribution network is quite obvious. The statistical monthly average correlation degree values of 22 monitoring locations from 2006 to 2009 are shown in Figure 2. In the same way, the spatial distribution of 22 monitoring locations from 2008 to 2009 are shown in Figure 3.

The calculation of the results of the model shows that water quality in Zhenjiang is higher than the drinking water standard. The measured values of some indices are much smaller than the relative standard values, making the results of $\Delta_{i1} = |x_i(k) - y_1(k)|$ larger, eventually leading to lower r_{ij} values. In contrast, if the measured value is closer to the standard value, then the results of

Table 2 | Water quality grading dimensionless standards

Grading	Quality Level 1 Good	Quality Level 2 Qualified	Quality Level 3 Poor
Parameter			
Colour	0.05	0.15	0.30
Turbidity	0.02	0.1	0.2
Free residual chlorine[a]	0.03	0.10	0.20
Total dissolved solids	0.03	0.1	0.15
Iron	0.1	0.3	0.5
Zinc	0.03	0.1	0.15
Cadmium	0.1	0.3	0.5
Mercury	0.03	0.1	0.3
Arsenic	0.03	0.1	0.3
Chloroform	0.01	0.06	0.1
Fluoride	0.03	0.1	0.15
Chloride	0.1	0.25	0.5
Nitrate nitrogen	0.03	0.1	0.2
Sulfate	0.1	0.25	0.5
Total organic carbon	0.01	0.05	0.1
Hardness	0.15	0.45	0.6
Oxygen consumption	0.15	0.3	0.5
Total bacteria	0	0.05	0.1

Notes: [a]The values of free residual chlorine in the table are the reciprocals of free residual chlorine values followed by the non-dimensional data processing.

$\Delta_{i1} = |x_i(k) - y_1(k)|$ are smaller, leading to higher r_{ij} values. To reduce the error caused by $\Delta_{i1} = |x_i(k) - y_1(k)|$, it is defined that if the measured value of the kth indices in the i-monitoring location $x_i(k) < y_1(k)$ or $x_i(k) > y_3(k)$, then $\varepsilon_{i1}(k) = 1$ or $\varepsilon_{i3}(k) = 1$. The provision states that if a particular index of a monitoring point is below the value of Level 1 or higher than Level 3, then the indices are limited to the values of Level 1 or Level 3.

Result analysis

The statistical monthly average values from 2006 to 2009 are shown in Figure 2, which shows that water quality gradually improved. For example, from 2007 to 2008, the data show a significant improvement. An accident occurred in April 2007, which had the worst water quality. From January 2008, water quality in the pipe network gradually improved, the main reasons for which are increasing drinking water quality concerns by the public and local government. Zhenjiang Water Company also upgraded the management of the drinking water quality, including upgrades in the drinking water treatment process and pipe network.

The tendency towards temporal water quality variations in the distribution networks in Zhenjiang is quite obvious. The present paper focuses on spatial water quality variations from 2008 to 2009. Figure 3 shows the average values of all monitoring points from 2008 to 2009, which were obtained by matrix-line comparisons. The worst water quality monitoring point is No. 24, followed by 4, 9, 6 and 11. Most of these monitoring points are located at the end of the pipe network and are far away from the water treatment plant. The best water quality point is No. 12, followed by 3, 18, 10 and 1. The water quality in the Zhenjiang urban water distribution network is more than acceptable based on the water quality analysis of the proposed evaluation system. However, the water quality in the north-eastern and southern regions is slightly lower.

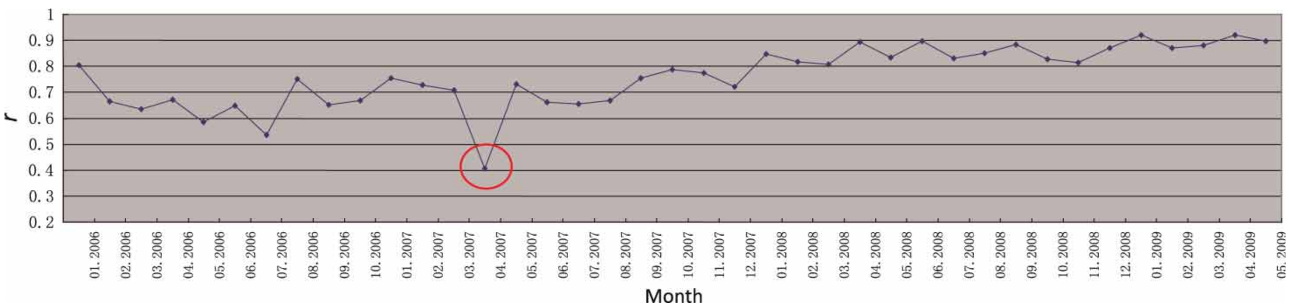

Figure 2 | Monthly average r of all monitoring points from 2006 to 2009.

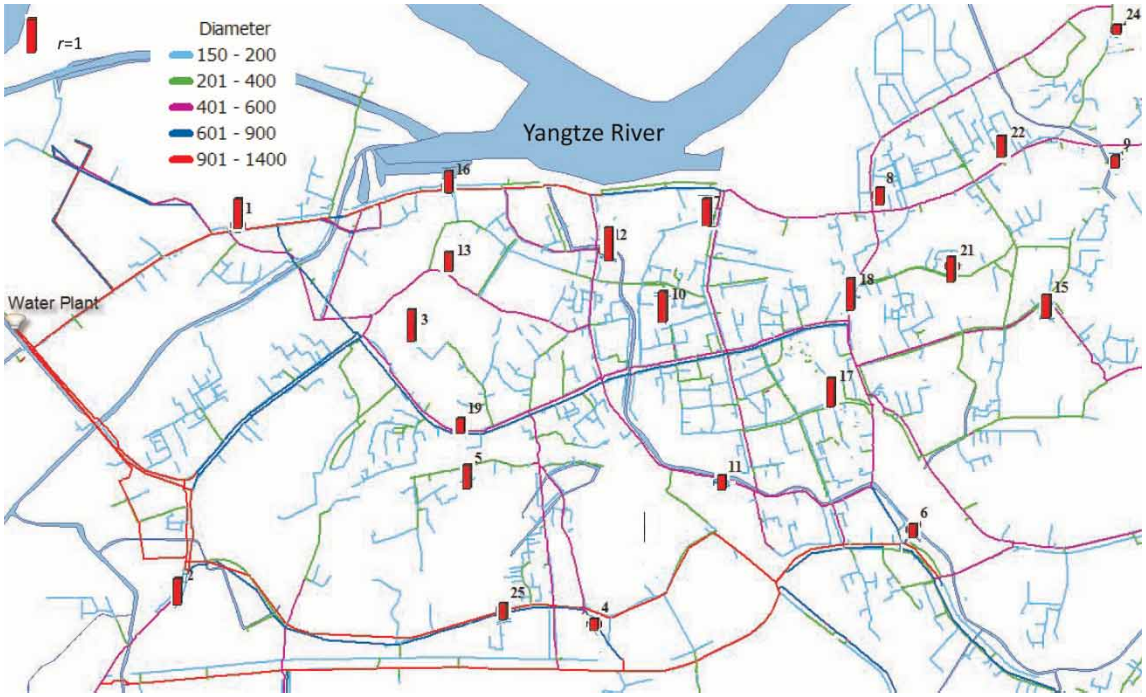

Figure 3 | Spatial difference of average values from 2008 to 2009.

This conclusion is consistent with consumer complaints of water quality. Water quality, however, was not completely related to residence time (e.g. at monitoring points 21, 18, 17, etc.). At these locations, the residence time is long, but the water quality is not lowered. In the present paper, the factors that impact water quality based on Grey correlation analysis are proposed.

ANALYSIS OF WATER-QUALITY-INFLUENCING FACTORS

The transport of the water from the treatment plant to the consumer can significantly affect water quality. The operation, management and regulations of water utilities affect water quality in the distribution network. Previous research identified several factors that influence public perceptions of drinking water quality (Jardine *et al.* 1999; Levallois *et al.* 1999; Doria *et al.* 2005; Jones *et al.* 2007). In China, the common accepted factors are pipe material, residence time and pipe age. In this paper, these three factors were chosen for analysis. It is worth noting that the previous section focused on the analysis of spatial and temporal evaluation of water quality based on water quality monitoring indices, and this part aims to analyse which factors are most influencing on water quality of the monitoring location.

According to the data in Table 3, pipe material, pipe age and residence time are graded into three levels. Level 1 means that the pipe material is steel pipe or ductile iron pipe, which does not affect water quality as much as prestressed concrete pipe and cast iron pipe. Pipe age in Level 1 is less than 10 years old, and residence time is less than 3 h. The non-dimensional data processing results are shown in Table 4. In order to reduce the gaps among the factors, we set the standard values of residence time to 0.3, 1.0, 2.0 (i.e. divided by 10^1) rather than 0.03, 0.1, 0.2 (divided by 10^2).

The Grey correlation ε_{ij} is used to identify the factor that influences water quality the most (Table 5). We supposed that factors below or close to standards of Level 1 represent relatively good water quality, while factors over standards of Level 3 mean poor quality. The higher $\varepsilon_{i,1}$ is, the closer the ith factor is to Level 1. The lower ε_{i1} is, the further the ith factor is from Level 1, which is a key factor to improve the water quality.

Table 3 | Data of water quality influencing factors in monitoring points

Monitoring point	Pipe material	Pipe age (years)	Residence time (h)
1	Ductile iron pipes	8	2.31
2	Ductile iron pipes	11	1.88
3	Steel pipe	50	5.63
4	Pre-stressed concrete pipe	20	3.89
5	Steel pipe	17	5.47
6	Steel pipe	50	5.91
7	Cast iron pipe	50	6.15
8	Steel pipe	50	6.28
9	Steel pipe	50	9.38
10	Steel pipe	16	6.55
11	Steel pipe	35	6.21
12	Steel pipe	50	6.08
13	Steel pipe	50	4.35
14	Ductile iron pipes	7	7.15
15	Pre-stressed concrete pipe	21	8.54
16	Steel pipe	8	3.59
17	Cast iron pipe	50	9.84
18	Pre-stressed concrete pipe	31	8.05
19	Ductile iron pipes	3	3.97
20	Steel pipe	9	7.24
21	Steel pipe	50	9.82
22	Steel pipe	50	7.81
23	Cast iron pipe	14	5.13
24	Others	50	14.11
25	Steel pipe	20	3.57
26	Steel pipe	6	6.64

Note: Some of the pipes have no record of pipe age, so are recorded as 50 years.

Table 5 | Grey diagnosis of water quality influencing factors

Monitoring point	Pipe material	Pipe age (years)	Residence time (h)
1	1	1	1
2	1	0.989083	1
3	1	0.642378	0.732043
4	0.668187	0.889564	0.900503
5	1	0.912116	0.746276
6	1	0.637845	0.707685
7	0.434851	0.633867	0.687345
8	1	0.631676	0.676529
9	1	0.570354	0.454234
10	1	0.918089	0.654501
11	1	0.733901	0.682335
12	1	0.635036	0.693227
13	1	0.661734	0.852861
14	1	1	0.607565
15	0.5889	0.838946	0.508429
16	1	1	0.932916
17	0.360795	0.559471	0.426174
18	0.598997	0.739938	0.54195
19	1	1	0.892042
20	1	1	0.600753
21	1	0.559956	0.427372
22	1	0.603764	0.558918
23	0.452388	0.948947	0.777313
24	0.381656	0.581371	0.333333
25	1	0.891481	0.935117
26	1	1	0.647287

Table 4 | Grading standard of water quality influencing factors and the dimensionless form

	Standard sequence			Dimensionless standard sequence		
Level	One	Two	Three	One	Two	Three
Factors						
Pipe material	Steel pipe, ductile iron pipes	Pre-stressed concrete pipe	Cast iron pipe	0.1	0.5	1
	1	5	10			
Pipe age (year)	10	30	50	0.1	0.3	0.5
Residence time (h)	3	10	20	0.3	1	2

Note: The original sequence and the standard sequence employed the same non-dimensional approach.

Table 6 | The order of Grey diagnosis of water quality influencing factors

Monitoring point	Primary factor	Second factor	Third factor
1	Pipe material	–	–
	Pipe age		
	Residence time		
2	Pipe age	Pipe material	–
		Residence time	
3	Pipe age	Residence time	Pipe material
4	Pipe material	Pipe age	Residence time
5	Residence time	Pipe age	Pipe material
6	Pipe age	Residence time	Pipe material
7	Pipe material	Pipe age	Residence time
8	Pipe age	Residence time	Pipe material
9	Residence time	Pipe age	Pipe material
10	Residence time	Pipe age	Pipe material
11	Residence time	Pipe age	Pipe material
12	Pipe age	Residence time	Pipe material
13	Pipe age	Residence time	Pipe material
14	Residence time	Pipe age	–
		Pipe material	
15	Residence time	Pipe material	Pipe age
16	Residence time	Pipe material	–
		Pipe age	
17	Pipe material	Residence time	Pipe age
18	Residence time	Pipe material	Pipe age
19	Residence time	Pipe material	–
		Pipe age	
20	Residence time	Pipe material	–
		Pipe age	
21	Residence time	Pipe age	Pipe material
22	Residence time	Pipe age	Pipe material
23	Pipe material	Residence time	Pipe age
24	Residence time	Pipe material	Pipe age
25	Pipe age	Residence time	Pipe material
26	Residence time	Pipe age	–
		Pipe material	

Taking point 24 for example, for the ith factor, the Grey correlation ε_{ij} is calculated from Equation (8):

$$\varepsilon_{i,1}(24) = (\Delta\min + \rho\Delta\max)/(\Delta_{i,1}(24) + \rho\Delta\max) \quad (8)$$

where $\Delta\min = 0$, $\Delta\max = 1.11$, $\rho = 0.5$, $\Delta_{i,1}(24) = |x_i(24) - y_{i,1}|$, $y_{i,1}$ is the standard value of Level 1 for the ith factor.

Thus, $\varepsilon_{1,1}(24) = 0.381656$, $\varepsilon_{2,1}(24) = 0.581371$, $\varepsilon_{3,1}(24) = 0.3333$.

From the results, it can be concluded that the third factor (residence time) in location 24 is the most important one to improve the water quality.

Based on the analysis of water-quality-influencing factors shown in Table 6, action should be taken at each location to improve water quality.

At monitoring locations 5, 9–11, 14–16, 18–22, 24 and 26, the main factor of deteriorated water quality is residence time. Because the drinking water from the water plant still contains traces of iron, manganese, other metal ions, carbonates, other inorganic substances, organic compounds and residual microorganisms, a longer residence time more likely results in various physical, chemical and biochemical changes in the pipe network. Water quality is obviously affected by the pipe network. The main reason for a long residence time is a low flow rate. Almost no water flow causes the formation of pools of stagnant water. Adding oxygen to the water is difficult with seriously rusted pipes. Another reason is that the end of this section does not form a loop pipe network, but rather a dendritic pipe network. In these locations, the better suggestion is to increase the pipe flow rates through the operation of a water distribution network. Again taking location 24 as an example, the water quality is relatively poor according to the analysis results under *Water quality evaluation system*, and the main influencing factor is residence time according to the Grey correlation calculation under *Grey correlation analysis method*, thus reducing the residence times preferred to improve the water quality near the monitoring location 24.

As for monitoring locations 2, 3, 4, 6, 7, 8, 12, 13 and 17, the main influencing factors are pipe age and pipe material. From the water quality evaluation results, the water quality at monitoring locations 4, 6 and 8 is slightly worse. Pipe replacement is the primary strategy for these locations to improve water quality. Laying new pipes might be difficult, but the company should take action to control growth rings to reduce pipeline deposition and control total alkalinity. Studies have shown that the growth of bacteria can be controlled in the growth rings by controlling the concentration of ferrous ions (Powell *et al*. 2000). The major reasons for growth ring formation are iron bacteria and sulfate-reducing bacteria that form during corrosion. Additionally, high-pressure water jet washing and gas-water pulse cleaning can be used to remove growth rings, which will maintain the culverts and improve water quality.

CONCLUSIONS AND DISCUSSION

Tap water quality varies spatially within a distribution system. The new drinking water standards (2006) for the municipal water supply specified that the water must be safe and acceptable to the consumer. However, the implementation of new standards still faces difficulties in some areas of China. Many factors impact water quality in the distribution pipeline network. To some extent, analysing the spatial distribution of water quality in the pipe network system is difficult. Assessing water quality, analysing the assessment results and making recommendations to improve water quality in the pipe network are currently key issues in an effort to solve water quality problems. This paper proposed an evaluation method and analysed the impact factors. The main conclusions are the following:

1. The Grey correlation analysis method is applied to construct an evaluation model and assess water quality. The case study of Zhenjiang shows that, using several evaluation indices, the results of the Grey correlation evaluation method have strong legitimacy. The overall water quality in Zhenjiang gradually improved, with spatial variations attributable to the water pipeline and residence time. Water quality was worse in the northeastern and southern regions.
2. A method of assessing the influencing factors, based on Grey correlation analysis, is further proposed, including pipe age, pipe material and residence time, in the Zhenjiang network. The results show that the influencing factors are different at different monitoring locations. The main influencing factor is residence time at approximately half of the monitoring locations. A longer residence time is associated with inferior water quality. Therefore, one possible option is to adjust the valves in the nearby areas to increase water flow and solve the water quality problem. Residence time was not the only factor that influenced water quality; pipe age and pipe material were also contributing factors.

3. For the locations where the water quality is mainly affected by pipe material and pipe age, pipe replacement is the most effective way to ensure water quality. However, the replacement of all pipes is not economically feasible. According to the analysis of the evaluation results, one feasible approach is firstly to replace the pipelines near monitoring stations 4 and 8, followed by gradual replacement of the remaining pipes.
4. The classification of the evaluation indices is empirical. The focus of the results is the relative water quality in the entire pipeline system. The classification in the same pipeline network has a relatively small effect. To analyse the impact factors, the classification can be used to determine key factors. In this paper, only three key factors were selected for analysis. Other factors, such as temperature, flow velocity and residual chlorine, etc., will be studied in the future. The normalization process in the proposed methodology still has some uncertainty; the sensitivity of different methods needs further study.

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