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Comparative study of water quality evaluation methods in the mid- and down-stream unit basins of the Yeongsan River

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ABSTRACT

Managing river water quality requires the accurate analysis and evaluation of the achievement of various policies and systems. Here, we targeted total maximum daily load unit basins in the Yeongsan River. Various water quality evaluation methods were investigated along with their advantages, limitations, and applicability. Based on the findings, linear interpolation, arithmetic mean, and converted mean were applied to Yeongbon C, where the flow rate was controlled by beams; percentile evaluation method to Yeongbon D, where the variations in water quality was significant due to the influence of the flow rate; and percentile evaluation method to Yeongbon D, where the influence of water quality by flow rate was marginal due to estuary banks. The results were derived differently depending on the characteristics of the target site (water quality and flow rate, river shape, and natural conditions) and evaluation method. The results suggested that a careful approach is required in selecting and applying a water quality evaluation method. Application of an appropriate water quality evaluation method for each study site through a multifaceted approach was confirmed to be more reliable than the application of a single water quality evaluation method. This approach helps accurately analyze water quality by identifying the cause.

Keywords: Yeongsan River; Water quality; Water quality evaluation; Total maximum daily load

1. Introduction

The Yeongsan River is one of the five major rivers in South Korea. In its upstream area, the Damyang, Jangseong, and Pyeongnim Dams have been constructed to secure domestic, agricultural, and industrial water. In its downstream area, an estuary barrage has been installed and operated to use agricultural water and to prevent salt damage caused by seawater. The Yeongsan River originates from Damyang-gun, Jeollanam-do and flows to the Yellow Sea via Gwangju, a metropolitan city, and the Naju Plain.

The Yeongsan River is vulnerable to high-concentration point sources of pollution that are emitted from urban areas and non-point sources of pollution with different pollution loads per unit area. As a part of the river maintenance project to control flooding and secure agricultural

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water, environmental conditions, such as the flow velocity, have changed considerably. Due to the installation of the Seungcheon Weir (2012) in the upstream area (Gwangju) and the Juksan Weir (2012) in the midstream area (Naju city, Jeollanam-do), the development of an innovative city in Naju has gradually increased the inflow of water pollutants. These major changes in the environmental conditions of the Yeongsan River have also prompted the improvement or modification of the water environment management policies.

In the second master plan for water environment management (2016–2025), the main policies for water quality improvement include the expansion of total maximum daily loads (TMDLs), reinforcement of the target water quality, management of impervious layers, reinforcement of livestock manure management, and intensive management of tributaries and streams. These various policies aim to improve water quality and achieve the target water quality [1]. The achievement of the target water quality is determined by evaluating water quality based on the monitoring data according to the implementation of various policies and systems. In recent years, various water quality evaluation methods suitable for the characteristics of policies have been applied to determine the achievement of the target water quality. These methods include the annual average water quality method, converted average method applied to TMDLs, load duration curve (LDC) method in consideration of the flow rate to supplement the evaluation method that uses only water quality data, and the linear interpolation method of statistical and nonparametric statistical techniques.

Water quality evaluation is required to accurately analyze the achievement of various policies and systems for water quality management. However, it is difficult to develop and apply the optimal method that can reflect the geographical characteristics and influence factors (e.g., flow rate, pollution load, rainfall, and land use) of the target site.

In a study of the pollution load allocation method to achieve and maintain the target water quality in TMDLs, the Han River Watershed Management Committee (HRWMC, 2009) divided the 3-y average water quality and flow data measured by the Ministry of Environment (ME) into excess percentages and presented a water quality evaluation method through a comparison by flow range [2].

Park et al. [3] conducted a study to improve the statistical evaluation method of effluent quality in basic environmental facilities to achieve total water pollution management. The authors applied the interpolation technique, a nonparametric method, and proposed an alternative to improve the appropriate standard discharge water quality evaluation method according to the type of water quality data of basic environmental facilities.

Ha et al. [4] analyzed various methods of water quality evaluation and verified their validity by applying them to the TMDL Yeongbon A unit basin in the upstream area of the Yeongsan River and derived the optimal evaluation method.

Water quality evaluation is important in policy implementation, and the method must also be reliable and suitable for the identification of the cause. In this study, various water quality evaluation methods were applied and their advantages and limitations were compared to present a more scientific and reasonable water quality evaluation method.

2. Research method and data analysis

2.1. Target basin

The target sites of this study are the Yeongbon C, D, and E basins, which are TMDL unit basins in the Yeongsan River. These are the mid- and down-stream basins of the Yeongsan River, excluding the upstream basins used in a study by Ha et al. (2021) [4]. The target basins have various channel characteristics from a hydraulic perspective. Among the study sites, Yeongbon C is modified from a natural river type to a point controlled by a multifunctional weir during the evaluation period due to the installation of the Juksan Weir. Yeongbon E (Lake Yeongsan) is affected by the discharge of the estuary barrage as it is located at the estuary of the Yeongsan River. Fig. 1 shows the target basins.

2.2. Water quality evaluation methods

As for the evaluation method, basic data analyses, such as trend analysis and singularity analysis, were conducted based on the flow and water quality data. Based on the results, the conventional methods of water quality evaluation by arithmetic mean, converted average, linear interpolation and percentiles (95% to 50%), and exclusion of water quality in the upper and lower sections (5%–50%) were applied.

On the basis of the long-term monitoring data (2003–2015) of the target sites (Yeongbon C, Yeongbon D, and Yeongbon E), which were the unit basins for the total water pollution load of the Ministry of Environment, we applied various water quality evaluation methods to compare and analyze the advantages and disadvantages of the evaluation methods. In addition, these methods were discussed considering the characteristics of the evaluation (target) sites and relevant considerations were examined.

2.2.1. Arithmetic mean

The river observation data obtained by the water quality monitoring network of ME were evaluated using the annual arithmetic mean as shown in Eq. (1) [5,6].

$$\text{Mean water quality} = \frac{\text{annual}\begin{pmatrix}\text{measured water quality}\\ +\text{measured water quality} + \cdots\end{pmatrix}}{\text{frequency of annual measurements}} \quad (1)$$

2.2.2. Natural logarithmic converted value

As for TMDLs, the target (water quality concentration) set under the low water flow condition was evaluated for the biochemical oxygen demand (BOD) and the target set under the ordinary/low water flow condition was evaluated for total phosphorus (T-P). The water quality was evaluated using Eqs. (2)–(4). The logarithmic mean of water quality was obtained from data observed for more than 30 times/y at 8-d intervals.

$$\text{Mean water quality} = e\left(\text{converted mean water quality} + \frac{\text{converted variance}}{2}\right) \tag{2}$$

$$\text{Converted mean water quality} = \frac{\text{1n}\left(\text{measured water quality}\right) + \text{1n}\left(\text{measured water quality}\right) + \cdots}{\text{frequency of measurements}} \tag{3}$$

$$\text{Converted variance} = \frac{\text{1n}\left(\text{measured water quality}\right) - \left(\text{converted mean water quality}\right)^2 + \cdots}{\text{frequency of measurements} - 1} \tag{4}$$

2.2.3. Linear interpolation method

Among the nonparametric statistical analysis techniques, the interpolation method generally estimates the percentile (P). It obtains the value of the k-th largest data by setting n as the analysis factor of all data and calculating the value of $k = P(n + 1)$. However, if the value of k is not an integer, it can be obtained using the linear interpolation method from two neighboring order statistics [7]. The method using Excel is given in Eq. (5), and the annual average water quality is calculated using the 1-y effluent water quality measurement data.

$$\text{Excel: } r = 1 + \frac{P\left(n - 1\right)}{100} \tag{5}$$

where r = ranking value in a descending order, P = percentile, and n = number of data.

Eq. (6) shows the linear interpolation method considering the case in which the value of Eq. (5) is not an integer.

$$Y = \left(1 - b\right)Xa + bX_{(a+1)} \tag{6}$$

where $a = r$ in Eq. (5) is the fractional part of 1 + P (probability distribution) × (number of measurements − 1)/100. [X_1, X_2, X_3, …, X_a, …, X_n] are the a-th of the effluent water quality in an ascending order, and $X_{(a+1)}$ (effluent water quality) is the (a + 1)th of the measurement data arranged in an ascending order.

2.2.4. Percentile

Based on the observation data, water quality was evaluated by applying the method of decreasing the upper probability ranking (95%, 90%, 85%, 80%, 75%, and 50%) in stages.

2.2.5. Exclusion of water quality in upper and lower sections

To minimize the influence of the extreme values of water quality in the observed data, water quality was evaluated by gradually excluding certain outliers with extremely high and lower values (5%, 10%, 20%, 30%, 40%, and 50%).

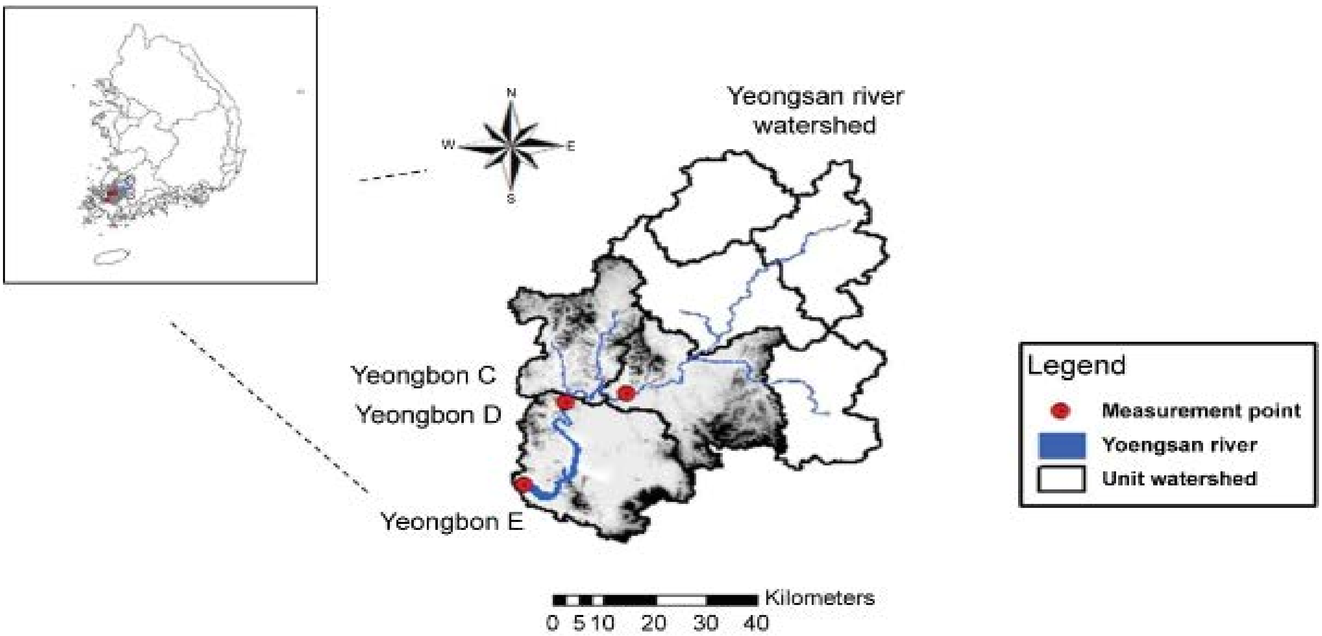

Fig. 1. Study area and locations of total maximum daily load measurement sites.

2.2.6. Flow conditions

BOD, a target pollutant for TMDLs, is evaluated under the low water flow condition. For T-P, the flow rate corresponding to the low water quality under the normal/low water flow conditions is the reference flow rate. As the flow rate has a major influence on water quality, water quality evaluation under the flow rate condition is important. Therefore, in this study, the average water quality was evaluated by selecting months with a high proportion of low flow conditions for BOD. Additionally, T-P was evaluated using data for months with a high proportion of normal flow conditions during the study period.

2.3. Basic data analysis of the target basins

For the application of the water quality evaluation method, the basic data of the target basins and the characteristics of the observation points that affect water quality evaluation were analyzed. The flow and water quality evaluation item (BOD and T-P) trends of the target sites were analyzed using the regional/seasonal Mann-Kendall test (S1).

The Mann–Kendall statistic for each season is:

$$\mathcal{S}_g = \sum_{i+1}^{n-1} \sum_{j=i+1}^{n} \mathcal{S}_{\text{gn}} \left(X_{\text{jg}} - X_{\text{ig}} \right) \tag{7}$$

where S_{gn} (season) = 1, 2 …, p [8].

The seasonal Kendall statistic is:

$$\mathcal{S} = \sum_{g=1}^{p} \mathcal{S}_g \tag{8}$$

As shown in Eq. (8), when the sample is large ($n > 10$) [9], and it approaches a normal distribution with μ_{SK} (mean) and Var(S*) (variance), then: $\mu_{\text{SK}} = 0$,

$$\mathcal{V}_{\text{ar}}\left(\mathcal{S}^*\right) = \sum_i \mathcal{V}_{\text{ar}}\left(\mathcal{S}^*\right) = \frac{\sum_i \left[n_i \left(n_i - 1\right)\left(2n_i + 5\right) \right]}{18} \tag{9}$$

As shown in Eq. (3), if multiple data represent the same value, they are placed in groups and substituted, as shown below. If the mean is 0 and $n > 10$, then the standardized z-statistic using Var(S*) is:

$$\mathcal{V}_{\text{ar}}\left(\mathcal{S}^*\right) = \sum_i \mathcal{V}_{\text{ar}}\left(\mathcal{S}^*\right) = \sum_i \left[n_i \left(n_i - 1\right)\left(2n_i + 5\right) \right] - \sum_{t_i} \left[t_i \left(t_i - 1\right)\left(2t_i + 5\right) \right] / 18 \tag{10}$$

$$Z_{\text{sk}} = \begin{cases} \dfrac{S^* - 1}{\sqrt{\mathcal{V}\text{ar}\left(S^*\right)_{\text{sk}}}} & S_k > 0 \\ 0 & S_k = 0 \\ \dfrac{S^* + 1}{\sqrt{\mathcal{V}\text{ar}\left(S^*\right)_{\text{sk}}}} & S_k < 0 \end{cases} \tag{11}$$

where n_i = number of data in the ith season and t_i = number of tied groups (if $|Z_{\text{sk}}| > Z_{\alpha/2}$, then the null hypothesis is rejected). The null hypothesis H_0 is a slope of $b_i = 0$ (no trend); after obtaining the z-statistic and p-value, the significance was verified, and the presence or absence of a water quality trend was determined.

Table 1 tabulates the characteristics of the target sites, including the administrative districts, area, corresponding small basins, and first and second target water qualities for the total water pollution of the unit basin. Table 2 and Fig. 2 show the flow rates, BOD, and T-P (mg/L) of the target unit basins. Table 3 and Fig. 3 represent the variations in BOD and T-P. The BOD (mg/L) range of Yeongbon C was found to be 1.1–12.8, that of Yeongbon D was 0.8–8.3, and that of Yeongbon E was 0.3–3.4.

The regional/seasonal Mann–Kendall test was conducted to analyze the trends in the water quality parameters (BOD and T-P). In the regional Kendall test results for BOD in the target sites, the values of statistic S were found to be –246, –149, and –167, respectively, and the p was lower than the significance level (α) of 0.05 (95% confidence), indicating a significant "downward" trend. For T-P, the values of statistic S were also found to be –432, –430, and –381, respectively, and the p was lower than the significance level (α) of 0.05, showing a "downward" trend. These findings indicate that water quality was improved by the implementation of water quality management policies (Table 4).

3. Application and results of water quality evaluation methods

3.1. Results obtained using the water quality evaluation methods

The water quality of the first and second phases (2003–2015) of TMDLs was evaluated by applying the evaluation methods to the target sites. The most appropriate evaluation method was obtained by analyzing and evaluating the advantages and limitations of each method.

3.1.1. Application of water quality evaluation methods to Yeongbon C

3.1.1.1. BOD evaluation results

The BOD evaluation results at Yeongbon C showed that the results obtained using the linear interpolation method was lower than those obtained using the arithmetic mean and converted average. With an improvement in water quality, evaluation by percentiles and the exclusion of water quality in upper and lower sections reflected the observed values (concentration) and revealed a reduction in the difference between results, thereby showing stable results. The two evaluation methods were significantly affected by outliers. For BOD, the low flow condition occurred in January to April and November to December. The average concentration was 5.6 mg/L, which exceeded the target water quality (5.2 mg/L). The concentration was evaluated to be high under the dry condition (6.1 mg/L) and low under the high flow condition (4.5 mg/L), indicating a high correlation with the flow rate.

3.1.1.2. T-P evaluation results

For T-P evaluation results, the results of the linear interpolation method were lower than those of the arithmetic

Table 1
Characteristics of study area

Unit basin	Administrative district	Area (km^2)	No. of small basins	1st*, 2nd** phase (2004–2015) target water quality (mg/L)	
				BOD5	T-P
Yeongbon C (Y.B. C)	Gwangju Metropolitan City, Jeollanam-do, Naju City, Hwasun County, Yeongam County	629	35	5.2	0.428
Yeongbon D (Y.B. D)	Gwangju Metropolitan City, Jeollanam-do, Jangseong County, Naju City, Yeonggwang County, Hampyeong County, Muan County	465	17	5.2	0.350
Yeongbon E (Y.B. E)	Jeollanam-do, Yeongam County, Muan County	652	38	2.4	0.159

*First Master Plan for quantity regulation of water pollution in Jeollabuk-do Seomjin River, Jeollanam-do (2004) [9].
**Second Master Plan for quantity regulation of water pollution in Jeollanam-do Seomjin River, Jeollabuk-do (2011).
BOD: biochemical oxygen demand;
T-P: total phosphorus [10].

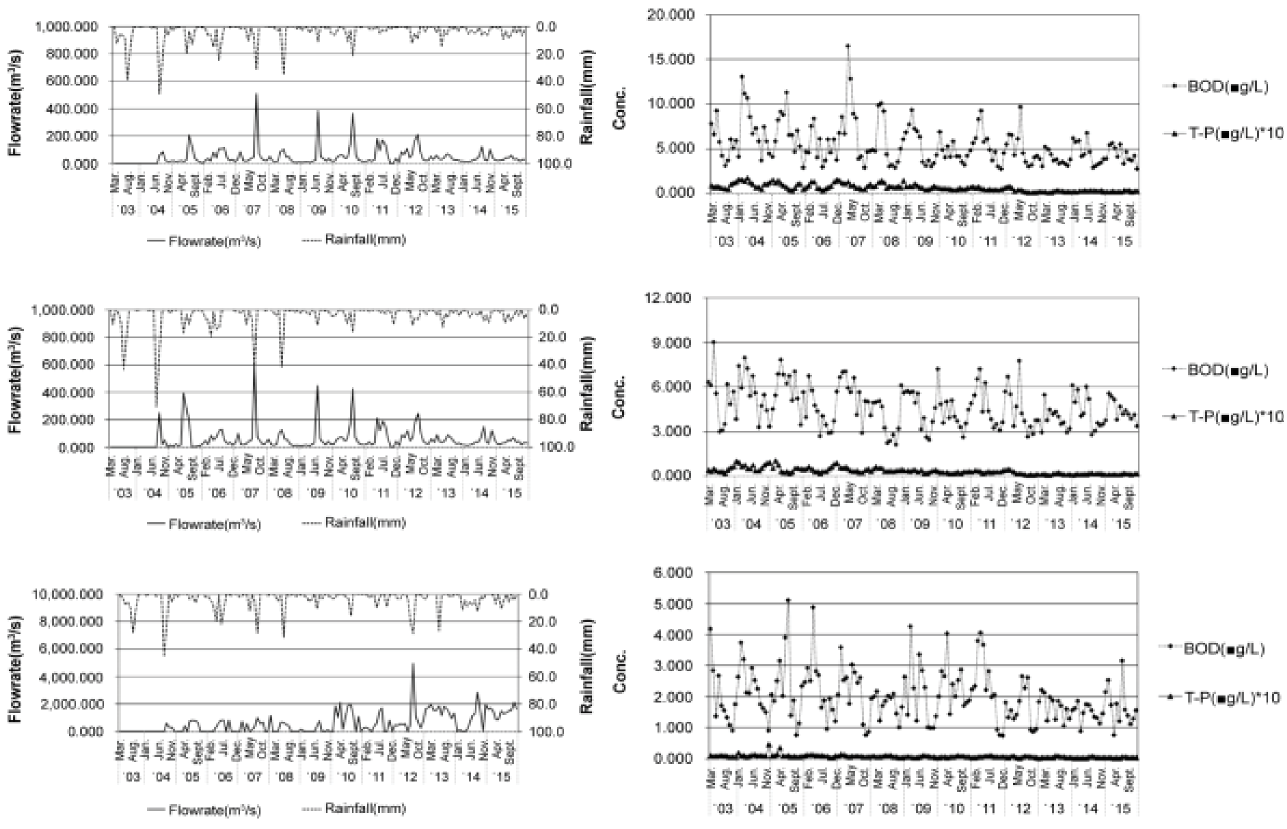

Fig. 2. Long-term variations in BOD, T-P, and flowrate in the Yeongsan River. BOD: biochemical oxygen demand; T-P: total phosphorus.

mean and converted average. As the stable water quality distribution was observed due to an improvement in water quality, it was found that the target water quality (0.428 mg/L) was achieved during the evaluation period, except at two time (2004 and 2005) in the evaluation by percentiles (50%). The exclusion of water quality in upper and lower sections achieved the target water quality under all conditions after 2009. The months with a high proportion of low flow condition were found to be April to June and September to November. The average concentration was 0.284 mg/L, which satisfied the target water quality. The average concentration was analyzed to be highest (0.357 mg/L) under the dry condition and lowest (0.237 mg/L) under the high flow condition.

For Yeongbon C, the change in water quality by flow rate was small due to the influence of downstream weirs.

Table 2
Annual average of water quality (BOD, T-P) and flow rates in the study areas

Measurement sites	Parameter	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15
Y.B.	BOD (mg/L)	5.6	7.5	6.8	5.4	7.7	5.7	5.5	4.5	5.4	5.2	3.8	4.5	4.4
C	T-P (mg/L)	0.383	0.554	0.449	0.414	0.454	0.463	0.368	0.246	0.250	0.175	0.106	0.125	0.118
	Flowrate (m^3/s)	–	40.420	53.798	56.820	70.814	41.498	55.784	69.117	88.632	2.813	42.536	41.174	35.257
Y.B.	BOD (mg/L)	5.2	5.7	5.8	4.4	5.6	3.6	4.4	4.2	4.7	4.5	3.9	4.4	4.4
D	T-P (mg/L)	0.320	0.516	0.435	0.348	0.381	0.351	0.270	0.198	0.244	0.174	0.106	0.114	0.108
	Flowrate (m^3/s)	–	82.884	100.737	57.349	82.282	47.458	64.635	79.964	103.059	2.600	51.544	48.096	39.899
Y.B.	BOD (mg/L)	1.9	2.3	2.3	2.4	2.2	1.7	2.0	2.4	2.3	1.6	1.6	1.4	1.7
E	T-P (mg/L)	0.133	0.180	0.200	0.141	0.137	0.119	0.090	0.098	0.101	0.091	0.071	0.060	0.053
	Flowrate (m^3/s)	–	353.159	331.022	333.866	355.792	329.750	146.015	1,485.059	482.200	5.183	1,574.052	1,314.591	1,459.184

BOD: biochemical oxygen demand; T-P: total phosphorus; Y.B. C: Yeongbon C; Y.B. D: Yeongbon D; Y.B. E: Yeongbon E.

Therefore, it is considered reasonable to apply the exclusion of water quality in upper and lower sections, arithmetic mean, converted average, and linear interpolation, which do not consider the flow rate. Tables 5 and 6 show the results of Yeongbon C by evaluation method, and Fig. 4 shows the results of applying each method.

3.2. Application of water quality evaluation methods to Yeongbon D

3.2.1. BOD evaluation results

Water quality was evaluated to be high in the period (y) when the variance of water quality was large. The months with a high proportion of low flow condition were May to July and September to November. The average BOD concentration was 4.2 mg/L, which satisfied the target water quality (5.2 mg/L). The average BOD concentration was evaluated to be high (5.7 mg/L) under the low flow condition and low (4.1 mg/L) under the high flow condition.

3.2.2. T-P evaluation results

For T-P, the results of converted average, arithmetic mean, and linear interpolation were evaluated to be similar. The results of the exclusion of water quality in the upper and lower sections achieved the target water quality (0.350 mg/L) under 5%–50% conditions during the 2008–2015 evaluation period. However, evaluation by percentiles could not achieve the target water quality under 75%–95% conditions in 2008 and 90%–95% conditions in 2009. This appears to be due to the influence of the water quality distribution (variance). The months with a high proportion of low flow condition were found to be April to June and September to November. The average T-P concentration was 0.232 mg/L, which satisfied the target water quality (0.350 mg/L). The average T-P concentration was analyzed to be the highest (0.404 mg/L) under the low flow condition and lowest (0.203 mg/L) under the mid-range flow condition. For Yeongbon D, it is deemed reasonable to apply a water quality evaluation method that considers the influence of flow rate and outflow conditions as well as the probability distribution. Tables 7 and 8 show the results by evaluation method, and Fig. 5 shows the results of applying each method.

3.3. Application of water quality evaluation methods to Yeongbon E

3.3.1. BOD evaluation results

The Yeongbon E evaluation results showed that BOD achieved the target water quality of 2.4 mg/L, which improved by 13 times from 2003 to 2015 based on the evaluation results of the arithmetic mean, converted average, linear interpolation, and exclusion of water quality in the upper and lower sections. Evaluation by percentiles showed different results due to the wide range of the water quality distribution (variance). As Yeongbon E was the observation point at the end of the Yeongsan River, the discharge of the estuary barrage was utilized as flow data and water quality was evaluated under relevant flow conditions.

Table 3
Annual variations in water quality (BOD and T-P) in the study areas

Measurement point	Parameter	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15
Y.B. C	BOD	7.6	12.8	7.5	5.1	21.0	9.6	6.1	1.7	5.4	5.6	1.3	3.0	1.1
	T-P	0.023	0.053	0.049	0.037	0.032	0.043	0.018	0.004	0.007	0.016	0.002	0.001	0.001
Y.B. D	BOD	8.3	5.8	4.6	2.8	3.9	2.1	3.4	1.7	2.7	3.8	1.6	3.4	0.8
	T-P	0.017	0.056	0.067	0.018	0.032	0.012	0.009	0.003	0.005	0.016	0.003	0.002	0.001
Y.B. E	BOD	1.3	1.0	3.4	1.7	1.9	0.6	1.6	0.8	1.7	0.7	0.4	0.3	0.8
	T-P	0.001	0.020	0.107	0.003	0.002	0.002	0.001	0.001	0.002	0.001	0.002	0.001	0.001

BOD: biochemical oxygen demand; T-P: total phosphorus; Y.B. C: Yeongbon C; Y.B. D: Yeongbon D; Y.B. E: Yeongbon E.

Table 4
Seasonal Mann–Kendall/regional Kendall test results with BOD and T-P

Measurement point	Seasonal Mann–Kendall trend							
	Item	Statistic S	Z	p	Kendall's tau	Slope (mg/L/y)	Trend	
Y.B. C	BOD	–246	–5.052	0.0000	–0.354	6.875	downward	▼
Y.B. D		–149	–3.055	0.0023	–0.216	5.450	downward	▼
Y.B. E		–167	–3.448	0.0006	–0.242	2.391	downward	▼
Y.B. C	T-P	–432	–8.872	0.0000	–0.626	0.5090	downward	▼
Y.B. D		–430	–8.831	0.0000	–0.623	0.4150	downward	▼
Y.B. E		–381	–7.824	0.0000	–0.552	0.1675	downward	▼

BOD: biochemical oxygen demand; T-P: total phosphorus; Y.B. C: Yeongbon C; Y.B. D: Yeongbon D; Y.B. E: Yeongbon E.

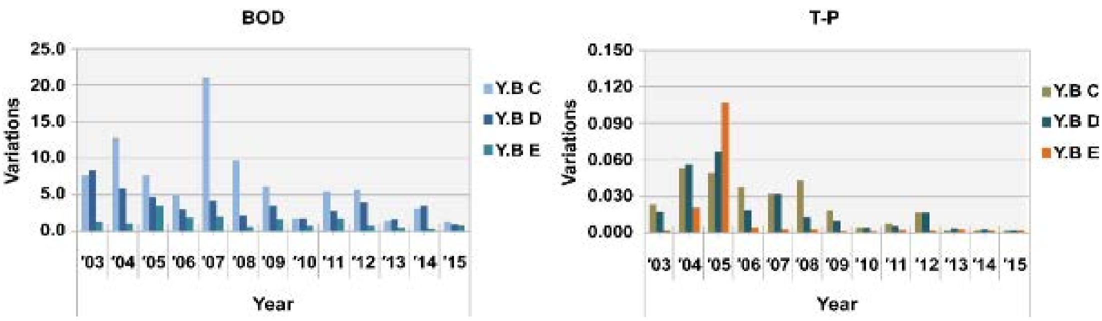

Fig. 3. Annual variations in water quality (BOD, T-P) in the study areas. BOD: biochemical oxygen demand; T-P: total phosphorus.

The proportion of low flow condition, which was the condition to be evaluated, was found to be high in February to July, and the average concentration (2.2 mg/L) satisfied the target water quality (2.4 mg/L). The average BOD concentration was analyzed to be high (2.2 mg/L) under the low flow and dry conditions and low (1.7 mg/L) under the mid-range flow condition.

3.3.2. T-P evaluation results

In the T-P water quality evaluation results, the converted average and the arithmetic mean were analyzed to be identical in the evaluation period except for some periods (2013), and linear interpolation was evaluated to be low. As the stable distribution (0.8 to 1.3) was observed due to an improvement in the concentration of T-P, the results of evaluation by percentiles and exclusion of water quality in the upper and lower sections were analyzed differently. For T-P, the months with a high proportion of low flow condition were found to be June to August and October to December, and the average T-P concentration (0.0.094 mg/L) satisfied the target water quality (0.159 mg/L). The T-P concentration was evaluated to be the highest under the high flow condition (0.130 mg/L)

Table 5a
Results of water quality evaluation using BOD at the Yeongbon C measurement sites

Evaluation method \ Water quality evaluation		Water quality evaluation (mg/L)												
		‘03	‘04	‘05	‘06	‘07	‘08	‘09	‘10	‘11	‘12	‘13	‘14	‘15
Arithmetic mean		5.6	7.5	6.8	5.4	7.7	5.7	5.5	4.5	5.4	5.2	3.8	4.5	4.4
Natural logarithmic converted value		5.6	7.8	6.8	5.4	7.8	5.8	5.5	4.5	5.4	5.3	3.8	4.6	4.4
Linear interpolation		5.4	7.3	6.6	5.2	7.4	5.5	5.4	4.4	5.2	5.0	3.7	4.5	4.3
Evaluation by percentiles	95%	10.7	13.6	11.4	9.2	16.8	11.3	9.8	7.1	9.1	8.9	5.9	7.7	6.2
	90%	9.3	12.4	10.5	8.0	12.6	10.4	9.4	6.5	8.4	8.1	5.1	6.9	5.5
	85%	8.5	11.2	10.0	7.7	12.0	9.6	8.5	5.7	7.9	7.5	4.7	6.1	5.4
	80%	7.9	9.9	8.5	7.4	11.8	9.4	7.7	5.3	7.3	7.4	4.4	5.7	5.3
	75%	6.3	9.5	7.9	6.9	9.6	8.6	7.6	5.2	7.0	7.2	4.3	5.5	5.3
	50%	5.2	6.9	6.5	4.7	6.6	4.6	4.9	4.2	4.8	4.8	3.6	4.3	4.2
Exclusion of upper and lower sections	5%	5.5	7.4	6.7	5.3	7.5	5.7	5.5	4.5	5.3	5.1	3.8	4.5	4.4
	10%	5.4	7.6	6.8	5.2	7.6	5.7	5.4	4.5	5.3	5.2	3.8	4.6	4.4
	20%	5.2	7.4	6.7	5.3	7.2	5.6	5.5	4.4	5.2	5.1	3.7	4.5	4.4
	30%	5.3	7.3	6.7	4.9	7.2	5.5	5.0	4.4	5.2	5.1	3.7	4.5	4.4
	40%	5.2	7.3	6.6	5.2	7.1	5.2	5.3	4.4	5.2	5.1	3.6	4.5	4.4
	50%	5.1	7.3	6.5	5.2	6.9	5.2	5.3	4.4	5.2	5.0	3.7	4.5	4.4

Table 5b
Results of water quality evaluation using BOD at the Yeongbon C measurement sites

Selected hydrological condition	Water quality (mg/L)											
	Hydrological condition					Average of the selected months						Average of the selected dry condition
	High flows	Moist condition	Mid-range flow	Dry condition	Low flows	1	2	3	4	11	12	
Dry condition	4.5	5.0	5.6	6.1	6.4	4.7	5.7	6.6	7.9	4.3	4.2	5.6

Table 6a
Results of water quality evaluation using T-P at the Yeongbon C measurement sites

Evaluation method \ Water quality evaluation		Water quality evaluation (mg/L)												
		′03	′04	′05	′06	′07	′08	′09	′10	′11	′12	′13	′14	′15
Arithmetic mean		0.383	0.554	0.449	0.414	0.454	0.463	0.368	0.246	0.250	0.175	0.106	0.125	0.118
Natural logarithmic converted value		0.385	0.560	0.465	0.418	0.456	0.463	0.369	0.247	0.251	0.176	0.106	0.125	0.118
Linear interpolation		0.375	0.541	0.438	0.402	0.446	0.445	0.359	0.243	0.245	0.167	0.102	0.123	0.115
Evaluation by percentiles	95%	0.653	1.005	0.781	0.791	0.764	0.766	0.643	0.350	0.391	0.433	0.161	0.200	0.167
	90%	0.622	0.861	0.744	0.640	0.733	0.683	0.547	0.342	0.370	0.353	0.148	0.169	0.157
	85%	0.539	0.768	0.700	0.608	0.704	0.605	0.485	0.318	0.350	0.316	0.138	0.159	0.156
	80%	0.523	0.709	0.673	0.592	0.601	0.572	0.458	0.296	0.327	0.272	0.127	0.144	0.142
	75%	0.499	0.667	0.651	0.559	0.566	0.520	0.432	0.280	0.305	0.227	0.126	0.136	0.129
	50%	0.347	0.561	0.447	0.382	0.424	0.416	0.375	0.239	0.229	0.136	0.102	0.121	0.110
Exclusion of upper and lower sections	5%	0.381	0.549	0.447	0.409	0.451	0.459	0.364	0.246	0.249	0.169	0.104	0.124	0.116
	10%	0.379	0.558	0.456	0.404	0.457	0.459	0.361	0.249	0.250	0.172	0.104	0.124	0.116
	20%	0.374	0.550	0.452	0.407	0.450	0.437	0.363	0.248	0.247	0.158	0.102	0.122	0.115
	30%	0.378	0.548	0.445	0.377	0.445	0.430	0.339	0.246	0.244	0.153	0.103	0.122	0.115
	40%	0.375	0.375	0.441	0.404	0.440	0.418	0.359	0.244	0.241	0.147	0.102	0.121	0.112
	50%	0.373	0.373	0.436	0.401	0.441	0.426	0.359	0.244	0.236	0.143	0.103	0.120	0.113

Table 6b
Results of water quality evaluation using T-P at the Yeongbon C measurement sites

Selected hydrological c	Water quality (mg/L)											
	Hydrological condition					Average of the selected months						Average of the selected dry condition
	High flows	Moist condition	Mid-range flow	Dry condition	Low flows	4	5	6	9	10	11	
Mid-range flow	0.237	0.265	0.278	0.357	0.282	0.365	0.313	0.255	0.196	0.256	0.317	0.284

Table 7a
Results of water quality evaluation using BOD at the Yeongbon D measurement sites

Water quality evaluation / Evaluation method		Water quality evaluation (mg/L)												
		'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15
Arithmetic mean		5.2	5.7	5.8	4.4	5.6	3.6	4.4	4.2	4.7	4.5	3.9	4.4	4.4
Natural logarithmic converted value		5.2	5.9	5.9	4.5	5.6	3.7	4.4	4.2	4.7	4.6	3.9	4.4	4.4
Linear interpolation		4.9	5.6	5.7	4.4	5.5	3.6	4.3	4.1	4.6	4.4	3.8	4.3	4.3
Evaluation by percentiles	95%	9.0	9.7	9.1	7.4	8.6	5.7	7.6	7.1	7.0	7.8	6.5	8.1	6.0
	90%	7.6	9.3	8.6	6.6	7.3	5.6	7.1	6.0	6.9	7.3	5.5	6.7	5.5
	85%	7.3	8.7	7.6	6.2	7.1	5.3	6.6	5.3	6.5	6.6	5.0	5.6	5.2
	80%	6.5	8.1	7.5	5.7	7.0	5.2	5.9	5.1	6.1	6.2	4.9	5.4	5.1
	75%	6.4	7.0	6.9	5.6	6.9	4.9	5.0	5.0	5.8	6.1	4.4	5.3	5.0
	50%	5.1	5.6	5.7	4.4	5.6	3.5	4.2	4.0	4.2	4.2	3.6	4.2	4.2
Exclusion of upper and lower sections	5%	5.0	5.7	5.8	4.6	5.5	3.6	4.3	4.2	4.6	4.5	3.8	4.3	4.4
	10%	4.9	5.8	5.8	4.6	5.6	3.7	4.3	4.2	4.7	4.6	3.8	4.4	4.4
	20%	4.9	5.7	5.8	4.5	5.6	3.7	4.3	4.1	4.7	4.5	3.7	4.3	4.4
	30%	4.9	5.7	5.7	4.2	5.6	3.7	4.0	4.1	4.6	4.4	3.7	4.2	4.4
	40%	4.9	5.7	5.7	4.5	5.7	3.7	4.2	4.0	4.6	4.4	3.7	4.2	4.4
	50%	4.9	5.7	5.7	4.5	5.7	3.7	4.1	4.1	4.5	4.3	3.6	4.3	4.4

Table 7b
Results of water quality evaluation using BOD at the Yeongbon D measurement sites

Selected hydrological condition	Water quality (mg/L)											
	Hydrological condition					Average of the selected months						Average of the selected dry condition
	High flows	Moist condition	Mid-range flow	Dry Condition	Low flows	5	6	7	9	10	11	
Dry condition	4.1	4.5	4.4	4.9	5.7	4.9	5.3	4.5	3.3	3.7	3.6	4.2

and lowest under the low flow condition (0.096 mg/L). For Yeongbon E, the change in water quality by the flow rate was small due to the influence of the estuary barrage. Therefore, it is considered that evaluation by percentiles and linear interpolation, which do not consider the flow rate, are appropriate. Tables 9 and 10 show the results of Yeongbon E by evaluation method, and Fig. 6 shows the results of applying each method.

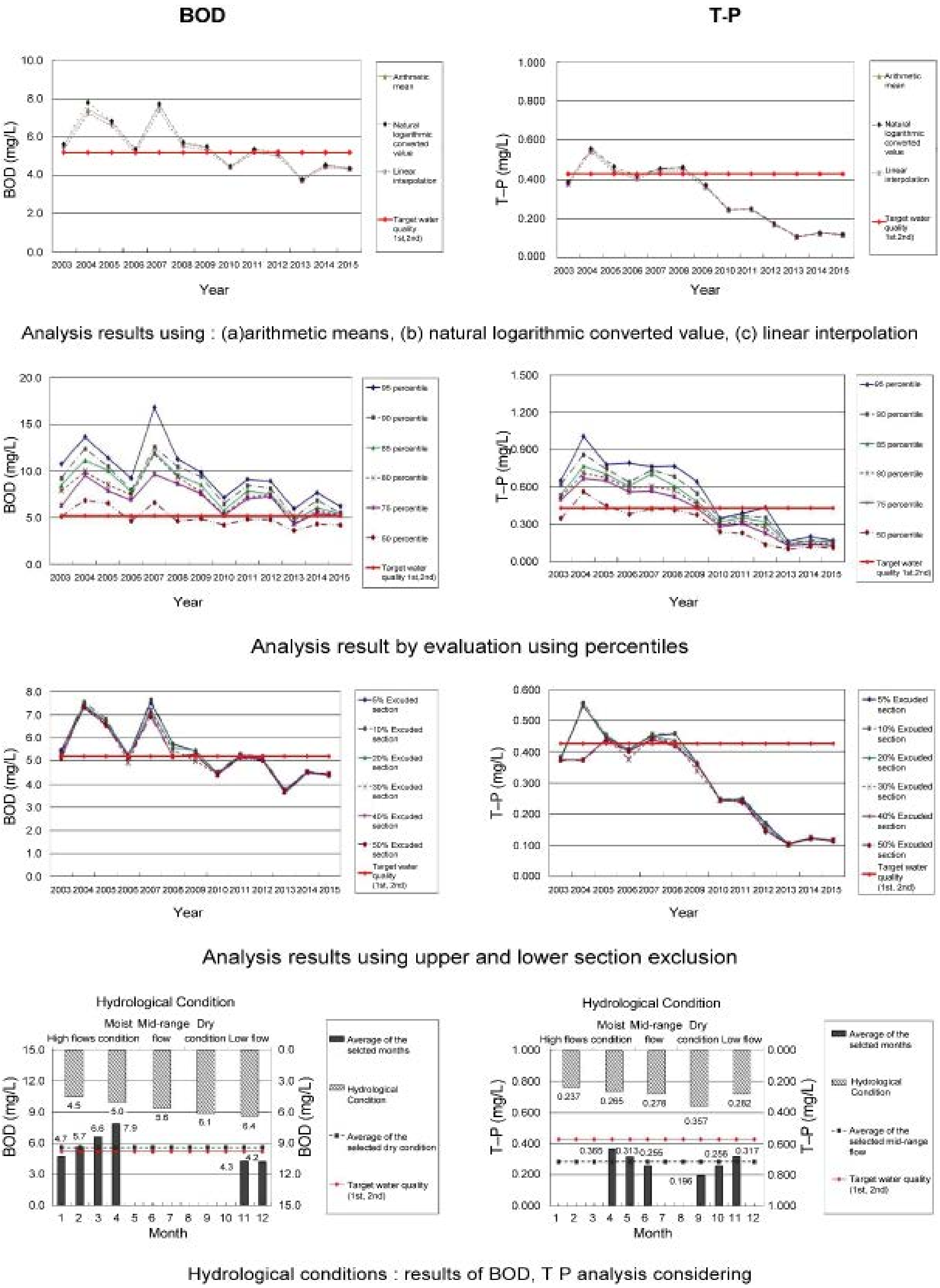

Fig. 4. Long-term variations in BOD, T-P, and flow rate at Yeongbon C watershed. BOD: biochemical oxygen demand; T-P: total phosphorus.

Table 8a
Results of water quality evaluation using T-P at the Yeongbon D measurement sites

Evaluation method \ Water quality evaluation		Water quality evaluation (mg/L)												
		'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15
Arithmetic mean		0.320	0.516	0.435	0.348	0.381	0.351	0.270	0.198	0.244	0.174	0.106	0.114	0.108
Natural logarithmic converted value		0.320	0.518	0.444	0.350	0.380	0.352	0.270	0.199	0.245	0.175	0.105	0.114	0.108
Linear interpolation		0.307	0.497	0.420	0.350	0.367	0.345	0.262	0.195	0.240	0.167	0.101	0.112	0.105
Evaluation by percentiles	95%	0.500	0.920	0.899	0.577	0.709	0.583	0.400	0.273	0.379	0.430	0.212	0.193	0.162
	90%	0.472	0.859	0.874	0.524	0.687	0.519	0.372	0.259	0.343	0.385	0.154	0.184	0.153
	85%	0.457	0.773	0.732	0.517	0.572	0.467	0.345	0.247	0.311	0.347	0.143	0.157	0.139
	80%	0.403	0.651	0.606	0.495	0.435	0.441	0.327	0.240	0.303	0.299	0.133	0.146	0.125
	75%	0.388	0.591	0.582	0.477	0.426	0.411	0.315	0.230	0.289	0.253	0.123	0.129	0.121
	50%	0.304	0.455	0.407	0.366	0.351	0.307	0.260	0.198	0.243	0.137	0.094	0.108	0.100
Exclusion of upper and lower sections	5%	0.311	0.505	0.428	0.362	0.371	0.350	0.265	0.197	0.244	0.170	0.102	0.113	0.106
	10%	0.309	0.512	0.436	0.362	0.376	0.354	0.260	0.200	0.245	0.173	0.102	0.113	0.105
	20%	0.313	0.499	0.422	0.359	0.363	0.345	0.263	0.199	0.243	0.162	0.097	0.112	0.105
	30%	0.311	0.490	0.404	0.337	0.353	0.339	0.250	0.199	0.241	0.154	0.098	0.110	0.104
	40%	0.308	0.308	0.399	0.358	0.346	0.335	0.262	0.197	0.241	0.147	0.096	0.109	0.103
	50%	0.309	0.309	0.399	0.357	0.348	0.331	0.262	0.199	0.240	0.140	0.097	0.108	0.102

Table 8b
Results of water quality evaluation using T-P at the Yeongbon D measurement sites

Selected hydrological condition	Water quality (mg/L)											
	Hydrological condition					Average of the selected months						Average of the selected dry condition
	High flows	Moist condition	Mid-range flow	Dry condition	Low flows	4	5	6	9	10	11	0.232
Mid-range flow	0.215	0.275	0.203	0.269	0.404	0.292	0.256	0.181	0.170	0.218	0.272	

Table 9a
Results of water quality evaluation using BOD at the Yeongbon E measurement sites

Evaluation method \ Water quality evaluation		Water quality evaluation (mg/L)												
		'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15
Arithmetic mean		1.9	2.3	2.3	2.4	2.2	1.7	2.0	2.4	2.3	1.6	1.6	1.4	1.7
Natural logarithmic converted value		2.0	2.3	2.3	2.4	2.3	1.7	2.0	2.4	2.4	1.6	1.7	1.4	1.7
Linear interpolation		1.8	2.2	2.1	2.3	2.2	1.7	2.0	2.3	2.2	1.6	1.6	1.4	1.4
Evaluation by percentiles	95%	3.9	4.0	5.9	4.1	4.8	2.9	4.8	3.9	4.8	3.6	2.5	2.6	3.1
	90%	3.2	3.8	4.1	3.6	4.2	2.7	4.0	3.4	4.5	2.8	2.5	2.1	2.6
	85%	2.8	3.5	3.3	3.3	3.7	2.7	3.6	3.1	3.6	2.5	2.4	1.9	2.4
	80%	2.6	3.2	3.1	3.0	3.5	2.5	3.1	3.0	3.1	1.9	2.2	1.8	2.3
	75%	2.6	3.0	2.8	2.9	3.1	2.1	2.5	2.9	3.0	1.8	2.1	1.7	2.2
	50%	1.7	2.1	1.7	2.4	1.9	1.7	1.6	2.1	2.1	1.4	1.7	1.3	1.6
Exclusion of upper and lower sections	5%	1.8	2.3	2.2	2.3	2.2	1.7	2.0	2.4	2.3	1.6	1.6	1.4	1.6
	10%	1.9	2.3	2.2	2.4	2.2	1.7	2.0	2.4	2.3	1.6	1.7	1.4	1.6
	20%	1.8	2.3	1.9	2.3	2.1	1.7	1.9	2.3	2.2	1.5	1.6	1.4	1.5
	30%	1.8	2.3	1.9	2.3	2.1	1.7	1.8	2.3	2.2	1.5	1.6	1.4	1.5
	40%	1.8	2.3	1.8	2.3	2.1	1.7	1.7	2.3	2.1	1.4	1.6	1.3	1.5
	50%	1.8	2.3	1.8	2.3	2.0	1.6	1.7	2.3	2.2	1.4	1.6	1.3	1.4

Table 9b
Results of water quality evaluation using BOD at the Yeongbon E measurement sites

Selected hydrological condition	Water quality (mg/L)											
	Hydrological condition					Average of the selected months						Average of the selected dry condition
	High flows	Moist condition	Mid-range flow	Dry Condition	Low flows	2	3	4	5	6	7	2.2
Dry condition	2.1	1.9	1.7	2.2	2.2	2.5	2.1	2.2	1.8	2.2	2.5	

Table 10a
Results of water quality evaluation using T-P at the Yeongbon E measurement sites

Evaluation method \ Water quality evaluation		Water quality evaluation (mg/L) '03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15
Arithmetic mean		0.133	0.180	0.200	0.141	0.137	0.119	0.090	0.098	0.101	0.091	0.071	0.060	0.053
Natural logarithmic converted value		0.133	0.174	0.171	0.143	0.137	0.120	0.089	0.098	0.102	0.093	0.070	0.060	0.053
Linear interpolation		0.131	0.162	0.158	0.138	0.134	0.118	0.087	0.097	0.099	0.089	0.069	0.058	0.045
Evaluation by percentiles	95%	0.181	0.328	0.264	0.224	0.258	0.192	0.166	0.161	0.183	0.149	0.152	0.126	0.093
	90%	0.173	0.253	0.246	0.209	0.199	0.179	0.142	0.145	0.155	0.131	0.131	0.107	0.078
	85%	0.167	0.248	0.177	0.189	0.175	0.170	0.121	0.133	0.142	0.120	0.119	0.093	0.068
	80%	0.165	0.206	0.172	0.181	0.159	0.165	0.108	0.123	0.127	0.115	0.105	0.079	0.063
	75%	0.162	0.191	0.164	0.180	0.147	0.149	0.095	0.116	0.120	0.107	0.090	0.074	0.061
	50%	0.135	0.147	0.123	0.144	0.126	0.110	0.080	0.100	0.095	0.089	0.056	0.057	0.049
Exclusion of upper and lower sections	5%	0.133	0.164	0.160	0.141	0.135	0.119	0.088	0.098	0.100	0.091	0.069	0.059	0.051
	10%	0.135	0.166	0.163	0.143	0.136	0.120	0.087	0.098	0.100	0.091	0.069	0.058	0.049
	20%	0.135	0.155	0.131	0.144	0.131	0.120	0.085	0.098	0.097	0.091	0.067	0.057	0.047
	30%	0.137	0.152	0.127	0.144	0.129	0.118	0.082	0.097	0.097	0.091	0.064	0.055	0.046
	40%	0.136	0.136	0.126	0.145	0.127	0.118	0.081	0.097	0.095	0.090	0.060	0.053	0.047
	50%	0.137	0.137	0.127	0.144	0.127	0.116	0.080	0.098	0.096	0.091	0.060	0.053	0.044

Table 10b
Results of water quality evaluation using T-P at the Yeongbon E measurement sites

Selected hydrological condition	Water quality (mg/L)											
	Hydrological condition					Average of the selected months						Average of the selected dry condition
	High flows	Moist condition	Mid-range flow	Dry condition	Low flows	6	7	8	10	11	12	0.094
Mid-range flow	0.130	0.101	0.097	0.097	0.096	0.071	0.131	0.127	0.097	0.073	0.063	

3.4. Discussion on the application of water quality evaluation methods

Analysis of the application of water quality evaluation methods at each observation point indicated that the results varied depending on the characteristics (water quality, flow rate, river geometry, and natural conditions) of the target site. The advantages and limitations of each method are discussed as follows.

The converted average and the arithmetic mean showed similar results, but variations in the results of the converted average were found to be smaller than those in the results of

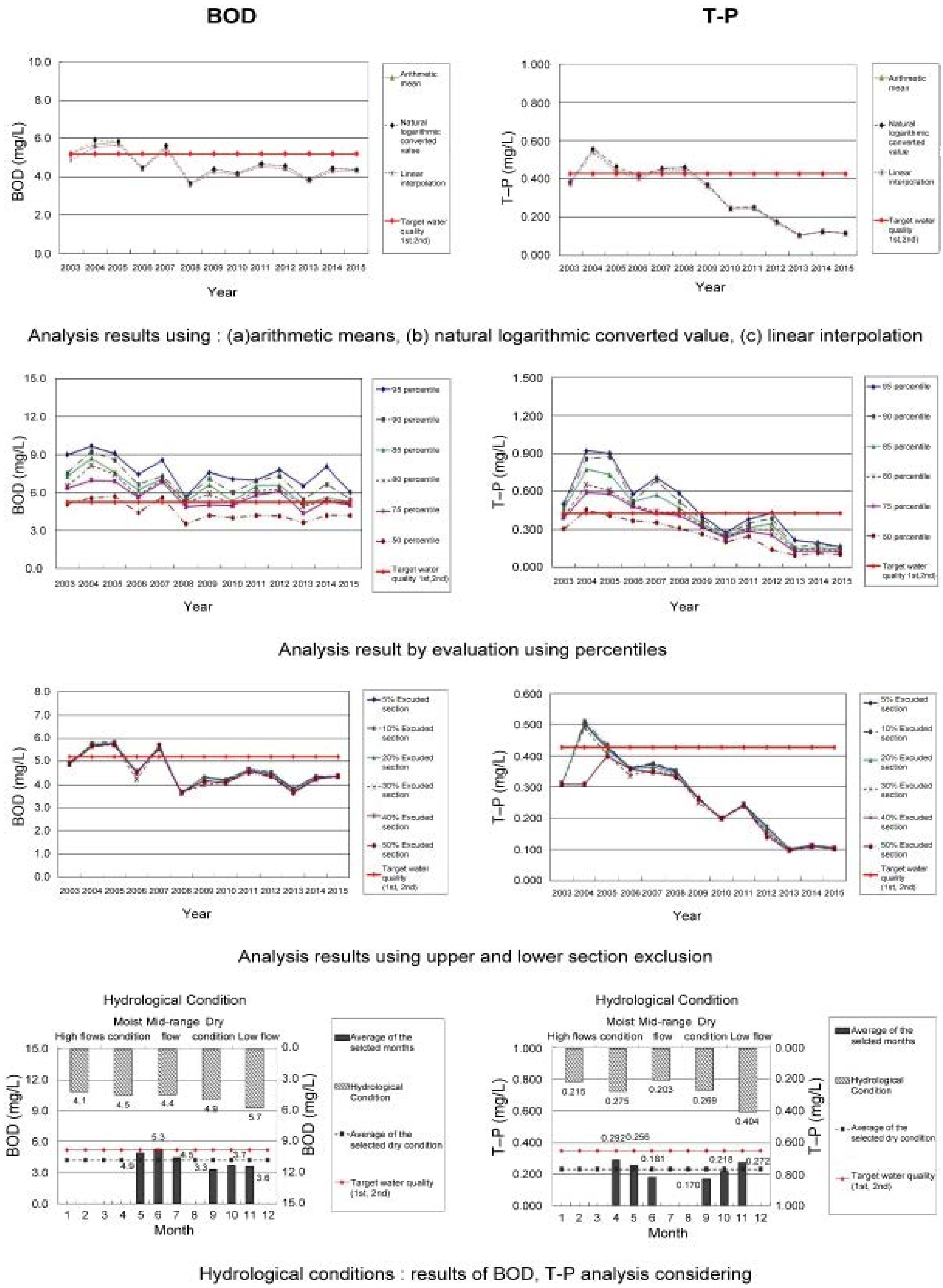

Fig. 5. Long-term variations in BOD, T-P, and flow rate at the Yeongbon D watershed. BOD: biochemical oxygen demand; T-P: total phosphorus.

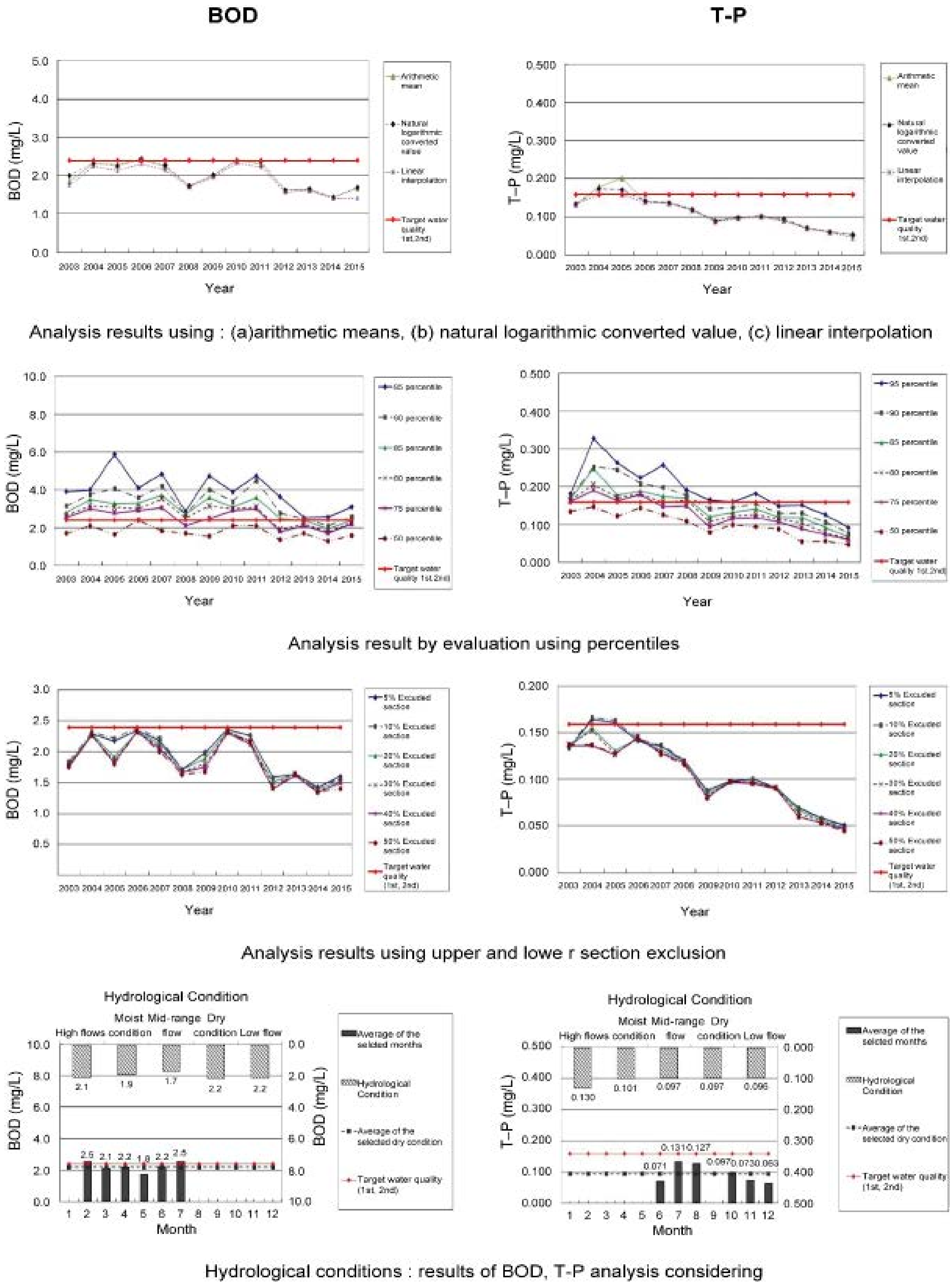

Fig. 6. Long-term variations in BOD, T-P, and flow rate at the Yeongbon E watershed. BOD: biochemical oxygen demand; T-P: total phosphorus.

the arithmetic mean. The arithmetic mean had advantages as a generalized and widely used method, but could not account for the influence of the flow rate and outflow. Additionally, it exhibited low reliability for the results that reflected the outliers of water quality.

The linear interpolation method, which takes the upper and middle values of the measured values, exhibited the validity of measured water quality and had advantages as a generalized method similar to the arithmetic mean. However, it could not account for the flow rate and showed relatively good water quality evaluation when there were outliers in water quality data and a high degree of variance.

Evaluation by percentiles, a water quality evaluation method by ranking, can evaluate water quality without considering the outliers of water quality, facilitates calculation, and makes it easy to identify deviations. However, it may exhibit fluctuations in water quality under external influences (rainfall and effluent from basic environmental facilities). Thus, such fluctuations need to be considered. In addition, significant differences in the results caused by the evaluation criteria and water quality distribution must be considered.

Exclusion of water quality in the upper and lower sections can exclude the influence of singular values and can be easily applied to points with little influence of the flow rate and small fluctuations in water quality. In addition, it is possible to identify the water quality trend in a stable manner as the upper and lower extreme values are excluded from the evaluation results. This method is significantly affected by the variance in water quality, and its limitation is the problem with the criteria for evaluation (exclusion sections).

Water quality evaluation by flow condition can identify water quality changes and employ various evaluation methods. In addition, it can be utilized as data for setting the target water quality. However, it requires long-term monitoring data and reliable data. The complexity of the calculation process, difficulty in securing justification, and possible lack of representativeness due to the limited data must also be considered.

4. Conclusions

In the present study, we evaluated the achievement of the water quality goal in the light of implementation of water quality improvement policies. Various water quality evaluation methods were studied considering the characteristics of river water quality and their advantages and limitations. As a result of applying the current water quality evaluation methods, such as the annual average, average transformation, and statistical methods considering the flow velocity, it is challenging to apply various evaluation methods using the flow rate and pollutant concentration because of the target watershed characteristics. Therefore, in this study, a reliable method was selected and analyzed.

- When the advantages and limitations of the evaluation methods were analyzed, it was found that the arithmetic mean and the linear interpolation method could easily calculate results as generalized and commonly used methods. However, these methods could not consider the influence of the flow rate. Evaluation by percentiles and exclusion of water quality in the upper and lower sections enabled stable evaluation by excluding outliers (singular values). However, these methods could not reflect the influence of the flow rate. Water quality evaluation by flow condition enabled evaluation by reflecting the flow rate, but it required long-term monitoring data; moreover, the calculation process was complex and securing justification was difficult.
- By examining the applicability of the water quality evaluation methods, the application of the linear interpolation method, arithmetic mean, and converted average was found to be appropriate for Yeongbon C where the flow rate was controlled by weirs. The evaluation by percentiles was observed to be reasonable for Yeongbon D where significant changes in water quality occurred due to the influence of the flow rate. For Yeongbon E, a point where the influence of the flow rate on water quality was small due to the influence of the estuary barrage, evaluation by percentiles was found to be suitable.

As the target study sites were points influenced by the low fluctuation range (deviation) and flow rate due to an improvement in water quality. It was considered reasonable to apply linear interpolation and evaluation by percentiles.

- The application of water quality evaluation by flow condition to the target sites made it possible to identify water quality changes and presented a new evaluation method by evaluating water quality using the observation data (flow rate). When the water quality evaluation methods were applied, different evaluation results were derived depending on the characteristics of the evaluation method and the achievement of the goal was also evaluated differently. It was confirmed that applying a water quality evaluation method suitable for each evaluation (target) site through a multifaceted examination of factors that affected water quality (target site, flow rate, pollution sources, and river geometry) could evaluate water quality more accurately than applying the same single water quality evaluation method.
- In this study, the applicability of TMDLs, tributary and stream evaluation, and target water quality achievement points in terms of water quality evaluation was confirmed. Further research is required on scientific water quality evaluation methods that can consider the limitations of various water quality evaluation methods examined in this study and the characteristics of the evaluation (target) site.

Acknowledgments

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Supplementary information

S1. Analysis of water quality fluctuations

An SK test, an extension of Mann–Kendall test, is a non-parametric statistical method that analyzes trends using correlation between measurements and independently performs a Kendall test for each season, before deriving a Kendall estimate through the weighted sum of each result to exclude seasonality (Mann, 1945; Kendall, 1975; Hirsch et al., 1982). The SK test divides the data by month and season and then calculates and tests the sum of Kendall's *S* statistic [Eq. (S1)]. The Mann–Kendall statistic for each season is:

$$\mathcal{S}_g = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\mathcal{S}_{\text{gn}}\left(X_{\text{jg}} - X_{\text{ig}}\right) \quad \text{(S1)}$$

where S_{gn} (season) = 1, 2, …, p [10].

The seasonal Kendall statistic is:

$$\dot{\mathcal{S}} = \sum_{g=1}^{p}\mathcal{S}_g \quad \text{(S2)}$$

As shown in Eq. (S2), when the sample is large ($n > 10$) (Helsel and Hirsch [9]), and it approaches a normal distribution with μ_{SK} (mean) and Var(S^*) (variance), then: $\mu_{\text{SK}} = 0$,

$$\mathcal{V}_{\text{ar}}\left(\mathcal{S}^*\right) = \sum_i \mathcal{V}_{\text{ar}}\left(\mathcal{S}^*\right) = \frac{\sum_i\left[n_i\left(n_i - 1\right)\left(2n_i + 5\right)\right]}{18} \quad \text{(S3)}$$

As shown in Eq. (S3), if multiple data represent the same value, then they are placed into groups and substituted as shown below. If the mean is 0 and $n > 10$, then the standardized *z*-statistic using Var(S^*) is:

$$\mathcal{V}_{\text{ar}}\left(\mathcal{S}^*\right) = \sum_i \mathcal{V}_{\text{ar}}\left(\mathcal{S}^*\right) = \sum_i\left[n_i\left(n_i - 1\right)\left(2n_i + 5\right)\right] - \sum_{t_i} t_i(t_i - 1)\left(2t_i + 5\right)\Big] / 18$$

$$\mathcal{Z}_{\mathcal{SK}} = \begin{cases} \dfrac{\mathcal{S}^* - 1}{\sqrt{\mathcal{V}\text{ar}\left(\mathcal{S}^*\right)_{\mathcal{SK}}}} & \mathcal{S}_{\mathcal{K}} > 0 \\ 0 & \mathcal{S}_{\mathcal{K}} = 0 \\ \dfrac{\mathcal{S}^* + 1}{\sqrt{\mathcal{V}\text{ar}\left(\mathcal{S}^*\right)_{\mathcal{SK}}}} & \mathcal{S}_{\mathcal{K}} < 0 \end{cases} \quad \text{(S4)}$$

where, n_i = number of data in the *i*th season and t_i = number of tied groups (if $|Z_{\text{sk}}| > Z_{\alpha/2}$, then the null hypothesis is rejected). The null hypothesis H_0 is a slope of $\tilde{b}_i = 0$ (no trend); after obtaining the *z*-statistic and *p*-value, the significance was verified and the presence or absence of a water quality trend was determined.