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Performance evaluation of TMDLs in upstream Seomjin River Basin using LOAD ESTimator model

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ABSTRACT

In this study, target water quality achievements, water quality improvement, and causes of exceeding the target water quality were analyzed. Water quality and flow monitoring data of the unit basins of the Seomjin River obtained by implementing total maximum daily loads (TMDLs) given by the Korean Ministry of Environment were used and simulated in the LOAD ESTimator (LOADEST) model. Pollutant loads were simulated using regression equations of the LOADEST model. The simulation results exhibited appropriate ranges for statistical variates with the measured values, indicating that the LOADEST model can simulate pollutant loads and can effectively analyze water quality. While evaluating the target water quality in TMDLs using the measured loads and those predicted by the LOADEST model, biochemical oxygen demand did not exceed the target water quality (excess rate: 50%) at the target points; however, the total phosphorus exceeded permissible limits at some target points. The excess rate was higher in the simulated values than in the measured values and under high-flow conditions than under low-flow conditions. Further, TMDL management performance was quantitatively evaluated by applying the LOADEST model for continuous and efficient water quality management measures and to implement water quality management policies in the future.

Keywords: Total maximum daily loads; Pollutant loads; Regression model; LOAD ESTimator

1. Introduction

To improve water quality and recover the health of aquatic ecosystems, the Korean Government introduced and implemented various policies and systems. In the 2000s, the target water quality measurement stations were set at the downstream points of basins considering the water use and water quality of the system, and total maximum daily loads (TMDLs) to manage pollutant emissions in basins were implemented to obtain the target water quality. TMDLs were introduced in 2003 in the Yeongsan and Seomjin Rivers. Biochemical oxygen demand (BOD) and total phosphorus (T-P) were designated as target pollutants in the first (2005–2010) and second (2011–2015) phases, respectively [1]. The third phase was implemented from 2016 to 2020 for the same target pollutants.

To implement TMDLs, it is necessary to set target water quality, establish basic implementation plans, and evaluate their performance. Hence, the Ministry of Environment (ME) of South Korea regularly measures the flow rate and water quality at the outlet points of the TMDL unit basins >30 times annually at 8-d intervals. Based on these data, the

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ME has set the target water quality for the points. Changes in water quality at these points have been examined using average water quality over the past three years. If the average water quality exceeds the target water quality twice consecutively, TMDL implementation plans must be established. However, this water quality evaluation method has limitations in evaluating water quality improvement under the implementation of TMDLs, analyzing the causes of exceeding the target water quality, and establishing efficient load reduction measures. Because water quality is significantly affected by external factors, such as seasons, weather, and discharges from dams and reservoirs, these factors must be considered when evaluating the water quality changes.

Various techniques have been used to reasonably evaluate the target water quality achievements considering changes in external factors that affect water quality changes along with the implementation of TMDLs. Recently, the regression-based LOAD ESTimator (LOADEST) model developed by the United States Geological Survey is being utilized by various researchers [2]. In this model, regression equations are calculated through the statistical analysis of the measured flow rate and water quality data, and the flow rate data are calculated by substituting the data, which are obtained through a hydrological model or through actual measurement, into regression equations [3]. In recent years, various studies have been conducted using the LOADEST model in Korea. Park et al. [4] developed a LOADEST web-based tool to apply user-friendly models and provide input data collection, and subsequently, applied it to agricultural and urban basins to select those that require pollutant load reduction. Kim et al. [5] selected and constructed LOADEST-based optimal regression models using the flow rate and water quality data at the outlets of the TMDL unit basins. They developed multiple regression equations to estimate the regression model parameters and evaluated their applicability to unmeasured basins.

This study aimed to quantitatively evaluate the performance of the third phase of TMDLs from 2016 to 2020 in the upstream Seomjin River Basin and to propose continuous and efficient future water quality management measures. We applied the LOADEST regression models, and the measured water quality and flow rate data were analyzed. In addition, the success of the target water quality, improvement in water quality, and causes of exceeding the target water quality were analyzed.

2. Materials and methods

This study was conducted for the unit basins of Seombon A, Churyeong A, and Seombon B among the 15 TMDL unit basins of the Seomjin River (Fig. 1). These unit basins are located in the uppermost stream of the Seomjin River and include the administrative districts of Jinan, Sunchang, and Imsil counties, and Jeongeup City in Jeollabuk-do. Table 1 shows the area of each unit basin and the target water quality measurement points of the third phase of the TMDLs.

To evaluate the load variation characteristics of BOD and T-P in these unit basins during the third phase (2016–2020), multivariate log-linear model developed by Cohn et al. [6] was utilized, which is one of the 11 regression equations included in the LOADEST model. This regression equation requires seven coefficients, as shown in Eq. (1), and it is possible to evaluate the flow rate dependence, increasing or decreasing temporal trend, and seasonality of pollutant loads using the seven predicted coefficients.

$$\ln y = a_0 + a_1 \ln Q + a_2 \ln Q^2 + a_3 \sin\left(2\pi d\text{time}\right) + a_4 \cos\left(2\pi d\text{time}\right) + a_5 d\text{time} + a_6 d\text{time}^2 \quad (1)$$

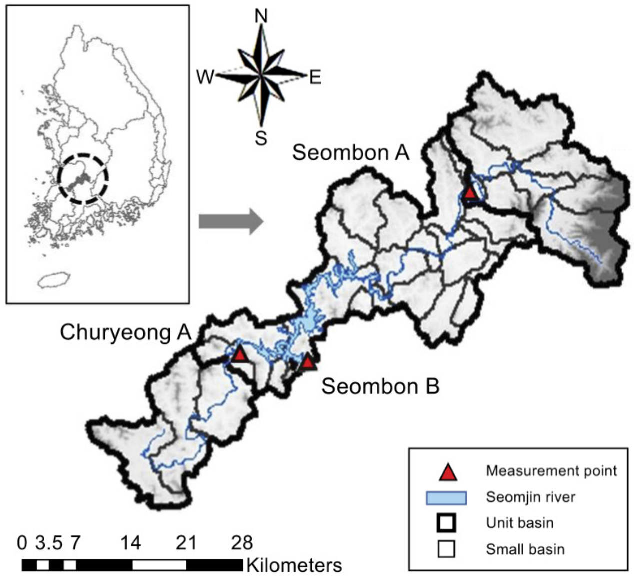

Fig. 1. Study area and locations of TMDL measurement points.

Table 1
Characteristics of the three unit basins: Seombon A, Churyeong A, and Seombon B

Unit basin	Administrative district	Area (km²)	No. of small basins	3rd phase (2016–2020) Target water quality (mg/L)	
				BOD_5	T-P
Seombon A	Jeollabuk-do Jinan County	232.2	9	1.1	0.021
Churyeong A	Jeollabuk-do Sunchang County	152.3	3	1.1	0.018
Seombon B	Jeollabuk-do Imsil County, Jeongeup City, Jinan County	379.3	22	1.0	0.016

BOD_5 – Biochemical oxygen demand

where y is the pollutant load, ln$Q$ is the log value of the flow rate minus the center of these values, dtime is the value obtained by converting the time of the year into a decimal value between 0 and 1 minus the center of these values, and $a_0 - a_6$ are the regression coefficients. The details of the method for calculating the center are presented by Cohn et al. [6]. To develop the regression equation, the flow rate, and water quality data measured at the TMDL measurement points located at the outlet of each unit basin at 8-d intervals from 2016 to 2020 were used.

The primary load estimation method used within LOADEST is adjusted maximum likelihood estimation (AMLE). AMLE has negligible BIAS when the calibration dataset is censored [7]. When the calibration dataset is uncensored, the AMLE method converges to the maximum likelihood estimation. If the residuals do not adhere to the assumption of normality, load estimates from the least absolute deviation method should be considered in lieu of AMLE.

To evaluate the suitability of the developed model, the Nash–Sutcliffe efficiency (NSE), percent BIAS (PBIAS), and root mean square error-observation standard deviation ratio (RSR) were used along with the coefficient of determination (R^2). The corresponding equations of NSE, PBIAS, and RSR are presented in Eqs. (2)–(4). The monthly data-based four-step criteria proposed by Moriasi et al. [8] were applied as criteria for evaluating the suitability of each statistical variate (Table 2).

$$\mathrm{NSE} = 1 - \frac{\sum\left(Q_{\mathrm{obs}} - Q_{\mathrm{cal}}\right)^2}{\sum\left(Q_{\mathrm{obs}} - \overline{Q_{\mathrm{obs}}}\right)^2} \tag{2}$$

$$\mathrm{PBIAS} = 1 - \frac{\sum\left(Q_{\mathrm{obs}} - Q_{\mathrm{cal}}\right)^2 \times 100}{\sum Q_{\mathrm{obs}}} \tag{3}$$

$$\mathrm{RSR} = \frac{\mathrm{RMSB}}{\mathrm{STDEV}} = 1 - \frac{\sqrt{\sum\left(Q_{\mathrm{obs}} - Q_{\mathrm{cal}}\right)^2}}{\sqrt{\sum\left(Q_{\mathrm{obs}} - \overline{Q_{\mathrm{obs}}}\right)^2}} \tag{4}$$

where Q_{obs} is the measurement data, Q_{ca} is the predicted data, and $\overline{Q_{\mathrm{obs}}}$ is the average of the measurement data.

3. Results and discussion

3.1. Flow rate and water quality characteristics

Based on the data measured at the outlets of the Seombon A, Churyeong A, and Seombon B unit basins, the water quality statuses and flow rates were analyzed from 2016 to 2020.

As shown in Table 3, during 2016–2020, the largest annual average flow rate (13.926 m^3/s) was observed at Seombon B in 2020. The maximum flow rate was 61.268 m^3/s at Seombon B (2020), and the minimum flow rate was 0.483 m^3/s in Churyeong A (2017).

The BOD concentration was not significantly different in the three-unit basins as it ranged from 0.5 to 1.7 mg/L at Seombon A, from 0.5 to 1.4 mg/L at Churyeong A, and from 0.5 to 1.9 mg/L at Seombon B. The average concentration from 2016 to 2020 was also similar as it was 1.0 mg/L at Seombon A, 0.9 mg/L at Churyeong A, and 0.9 mg/L at Seombon B. The T-P concentration ranged from 0.009 to 0.095 mg/L at Seombon A, 0.005 to 0.043 mg/L at Churyeong A, and 0.005 to 0.069 mg/L at Seombon B, thus, demonstrating almost high concentrations at Seombon A. The average concentration from 2016 to 2020 was also the highest (0.028 mg/L) at Seombon A among the three-unit basins. In particular, the T-P concentration tended to increase mainly during summer when the flow rate increased (Fig. 2).

3.2. Development of regression models for pollutant loads

Regression models for BOD and T-P loads in the three-unit basins were constructed using Eq. (9) of the LOADEST model, and the statistical variations between the simulated and measured values are shown in Table 4. All BOD load models for the three-unit basins were evaluated to be very good, while the T-P load models for only Churyeong A and Seombon B were evaluated to be very good. The T-P load model for Seombon A was evaluated to be unsatisfactory for NSE and RSR because of the difference between the observed and calculated values; however, it was evaluated to be very good for PBIAS. The R^2 values of the developed models ranged from 0.83 to 0.95. The BOD and T-P load regression models developed in this study for the three-unit basins reflected the measured values relatively well and were suitable for continuously simulating pollutant loads and identifying their tendencies.

Figs. 3 and 4 show the comparison results of the loads simulated by the regression models and the measured loads. For the BOD, the simulated values reflected the measured values in the three-unit basins. In the case of T-P, the simulated values reflected the measured values at Churyeong A and Seombon B, except for Seombon A. At Seombon A, the flow rate increased to 13.112 m^3/s on June 29, 2017 because of heavy rainfall, and the T-P concentration (0.341 mg/L) was more than ten times higher than the average concentration from 2016 to 2020. When this singular value was excluded, T-P at Seombon A also

Table 2
Performance ratings based on the monthly data statistics [8]

Performance rating		NSE			PBIAS (%)			RSR	
Very good	>0.75	NSE	≤1.0		PBIAS	±<10	>0.00	RSR	≤0.5
Good	>0.65	NSE	≤0.75	±≤10	PBIAS	±<15	>0.50	RSR	≤0.6
Satisfactory	>0.50	NSE	≤0.65	±≤15	PBIAS	±<25	>0.60	RSR	≤0.7
Unsatisfactory		NSE	≤0.50		PBIAS	±>25		RSR	>0.70

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

Year	Item	Seombon A			Churyeong A			Seombon B		
		BOD (mg/L)	T-P (mg/L)	Flow rate (m^3/s)	BOD (mg/L)	T-P (mg/L)	Flow rate (m^3/s)	BOD (mg/L)	T-P (mg/L)	Flow rate (m^3/s)
2016	Min.	0.5	0.007	0.415	0.4	0.002	0.493	0.3	0.002	0.563
	Max.	2.0	0.105	23.353	1.8	0.054	24.047	1.9	0.043	1.641
	Ave.	1.0	0.030	3.595	0.9	0.023	3.938	1.0	0.017	0.990
2017	Min.	0.5	0.007	0.290	0.5	0.003	0.230	0.5	0.005	0.399
	Max.	2.2	0.341	21.168	1.6	0.042	19.869	2.6	0.029	3.061
	Ave.	1.0	0.032	3.581	0.9	0.016	2.312	0.9	0.014	1.059
2018	Min.	0.5	0.011	0.413	0.5	0.005	0.403	0.5	0.008	0.358
	Max.	3.4	0.061	21.695	1.7	0.046	23.399	2.2	0.054	2.699
	Ave.	1.1	0.027	4.143	1.0	0.020	3.300	1.1	0.020	1.692
2019	Min.	0.6	0.006	0.624	0.4	0.003	0.344	0.5	0.006	1.324
	Max.	2.8	0.061	19.011	1.7	0.050	26.961	1.8	0.049	4.541
	Ave.	1.1	0.028	2.504	1.0	0.024	2.970	0.9	0.020	2.078
2020	Min.	0.4	0.005	0.482	0.4	0.004	0.260	0.4	0.005	1.581
	Max.	1.7	0.133	18.973	1.4	0.039	30.603	1.4	0.079	194.766
	Ave.	0.8	0.024	3.452	0.7	0.016	3.507	0.8	0.018	14.098
2016~2020	Min.	0.4	0.005	0.290	0.4	0.002	0.230	0.3	0.002	0.358
	Max.	3.4	0.341	23.353	1.8	0.054	30.603	2.6	0.079	194.766
	Ave.	1.0	0.028	3.470	0.9	0.020	3.183	0.9	0.018	4.102
Standard deviation		0.445	0.028	4.595	0.299	0.011	4.969	0.365	0.028	17.502

exhibited reproducibility similar to that of the other points. In addition, the load values simulated by the LOADEST regression models showed a tendency to be slightly underestimated compared to the measured values, and this tendency was reported by Morse et al. [9].

3.3. Analysis of the trends of pollutant loads

Table 5 shows the regression coefficients of the LOADEST model, which were suitable for identifying load fluctuations in the Seombon A, Churyeong A, and Seombon B unit basins located in the upstream area of the Seomjin River.

The regression coefficient that represents dependence on the flow rate (a_1) was found to have statistically significant positive values in all unit basins. This indicated that the load increases as the flow rate increases. In addition, the regression coefficient of T-P tended to be slightly higher than that of BOD at the same point, indicating that the T-P load increased more as the flow rate increased. As shown in Table 6, the pollutant loads by non-point sources are significantly larger (73.2%–92.9% for BOD and 83.8%–94.3% for T-P) than point sources in these unit basins, and the contribution rate of non-point sources to pollutant loads is higher for T-P than for BOD. It appears that T-P exhibited a relatively higher load increase tendency with the increase in flow rate because of the difference in the contribution rate of non-point sources to pollutant loads.

The regression coefficient, a_5, which represents a load increase or decrease tendency over time, showed a statistically significant tendency to decrease in all unit basins for BOD, and Seombon B exhibited the largest tendency to decrease among the three-unit basins. A statistically significant decreasing tendency was observed for T-P at Seombon A; however, a statistically significant increasing or decreasing tendency was not observed at Churyeong A and Seombon B. As described above, T-P has been managed since it was designated as a target pollutant in the second phase of TMDLs; however, the load reduction effect of the management is still insignificant compared to BOD, which has been managed since the first phase of TMDLs.

3.4. Status of achieving the target water quality and analysis of the causes of exceedance

In this study, the success of achieving the target water quality in TMDLs and the causes of exceeding the target water quality were analyzed using the water quality, flow rate data, measured loads, and loads predicted by the LOADEST model for each unit basin.

As for changes in water quality at points where the target water quality in TMDLs was set, the average water quality was calculated using Eqs. (5)–(7) in accordance with the relevant laws [11] and changes in water quality during the fourth phase of TMDLs are presented in Tables 6 and 7.

$$\text{Average water quality} = e^{\left(\text{converted average water quality} + \frac{\text{converted variance}}{2}\right)} \quad (5)$$

$$\text{Converted average water quality} = \frac{\ln\begin{pmatrix}\text{measured}\\ \text{water quality}\end{pmatrix} + \ln\begin{pmatrix}\text{measured}\\ \text{water quality}\end{pmatrix} + \cdots}{\text{Number of measurements}} \quad (6)$$

$$\text{Converted variance} = \frac{\ln\left(\text{measured water quality}\right) - \begin{pmatrix}\text{converted average}\\ \text{water quality}\end{pmatrix}^2 + \cdots}{\text{Number of measurements} - 1} \quad (7)$$

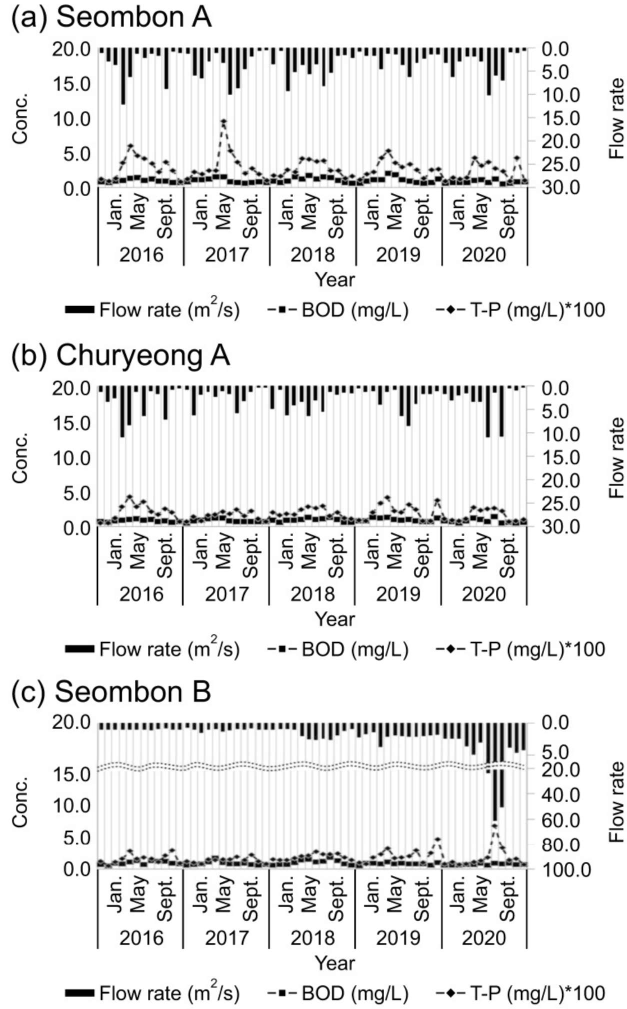

Fig. 2. Monthly variations in water quality (BOD and T-P) and flow rate in the study areas.

As shown in Table 6, the BOD satisfied the target water quality of the third phase in all three unit basins (Seombon A, Churyeong A, and Seombon B) over the last five years. However, T-P exceeded the target water quality in all unit basins (Table 7).

Meanwhile, the target water quality excess rate during the third phase (2016–2020) was analyzed based on the BOD and T-P measurement data and the data predicted based on the LOADEST model, as shown in Tables 8 and 9. As shown in Table 10, the three-year average water quality for BOD satisfied the target water quality in all of the unit basins; however, the excess rates of the total measurement data were 28.2%, 16.9%, and, 30.6% for Seombon A, Churyeong A, and Seombon B, respectively. The excess rates analyzed based on the LOADEST model prediction results were also similar: 33.8%, 18.9%, and 33.0% for Seombon A, Churyeong A, and Seombon B, respectively. In the case of T-P, the third-year average water quality exceeded the target water quality in all unit basins. The excess rates of the total measurement data were 54.9%, 49.8%, and 45.9% for Seombon A, Churyeong A, and Seombon B, respectively. The excess rates analyzed based on the LOADEST model prediction results were 58.2%, 53.7%, and 56.0% for Seombon A, Churyeong A, and Seombon B, respectively (Tables 8 and 9).

In this study, the excess rate under the flow rate condition was analyzed to determine the causes of the target water quality being exceeded. To this end, flow rate sections with a 10% range were set from high to low flow rates based on the measured flow rate, and the target water quality excess rate was analyzed for each flow rate section using the measured loads and the loads predicted by the LOADEST model.

At Seombon A, both the measured and simulated values of BOD exhibited a high excess rate of 42.9% in the 80%–90% section. The excess rates in the 60%–70% section were 28.6% and 47.6% for the measured and simulated values, respectively, and it was found that the excess rate of the simulated values was high in the high flow rate (10%–30%) sections. For the entire section, the number of points, which exceeded permissible limits for the simulated values (72) was higher

Table 4
Evaluation according to the general performance ratings of recommended statistics

Measurement point	Item	R^2	NSE		PBIAS (%)		RSR	
Seombon A		0.91	0.84	Very good	1.54	Very good	0.45	Very good
Churyeong A	BOD	0.95	0.92	Very good	0.53	Very good	0.29	Very good
Seombon B		0.86	0.91	Very good	2.12	Very good	0.35	Very good
Seombon A		0.90	0.49	Unsatisfactory	7.63	Very good	1.14	Unsatisfactory
Churyeong A	T-P	0.89	0.88	Very good	–4.75	Very good	0.34	Very good
Seombon B		0.83	0.92	Very good	0.01	Very good	0.27	Very good

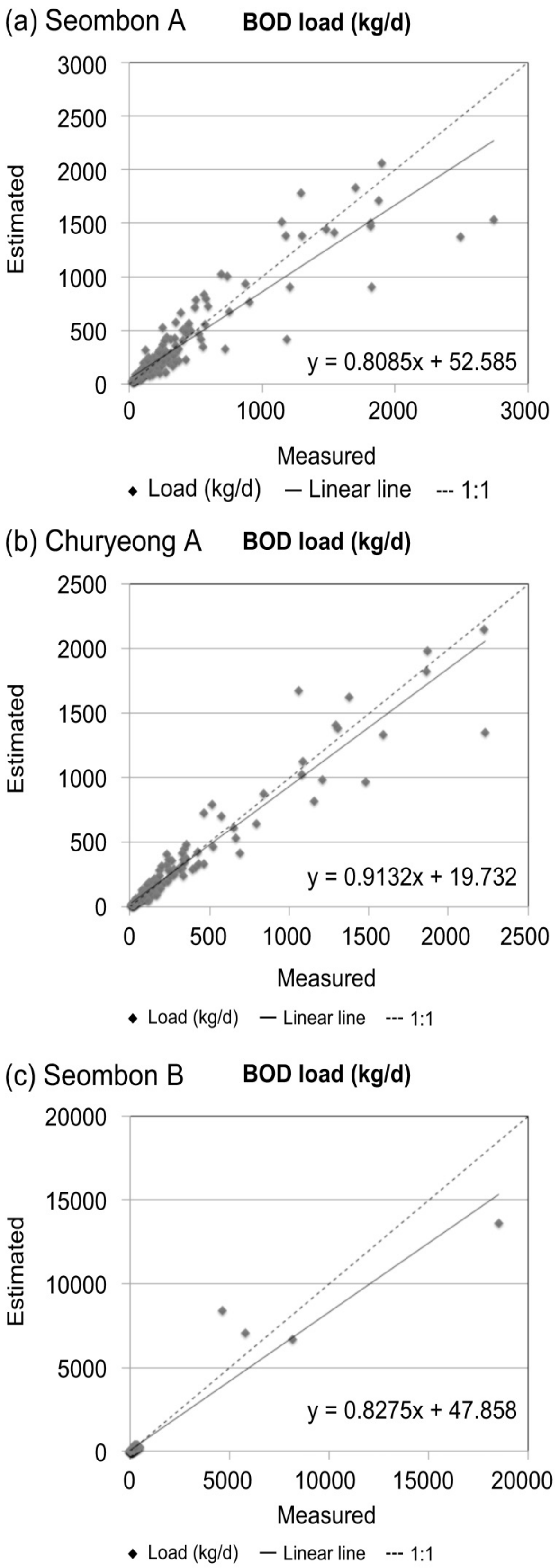

Fig. 3. Comparison of the measured BOD loads and the loads estimated by LOADEST.

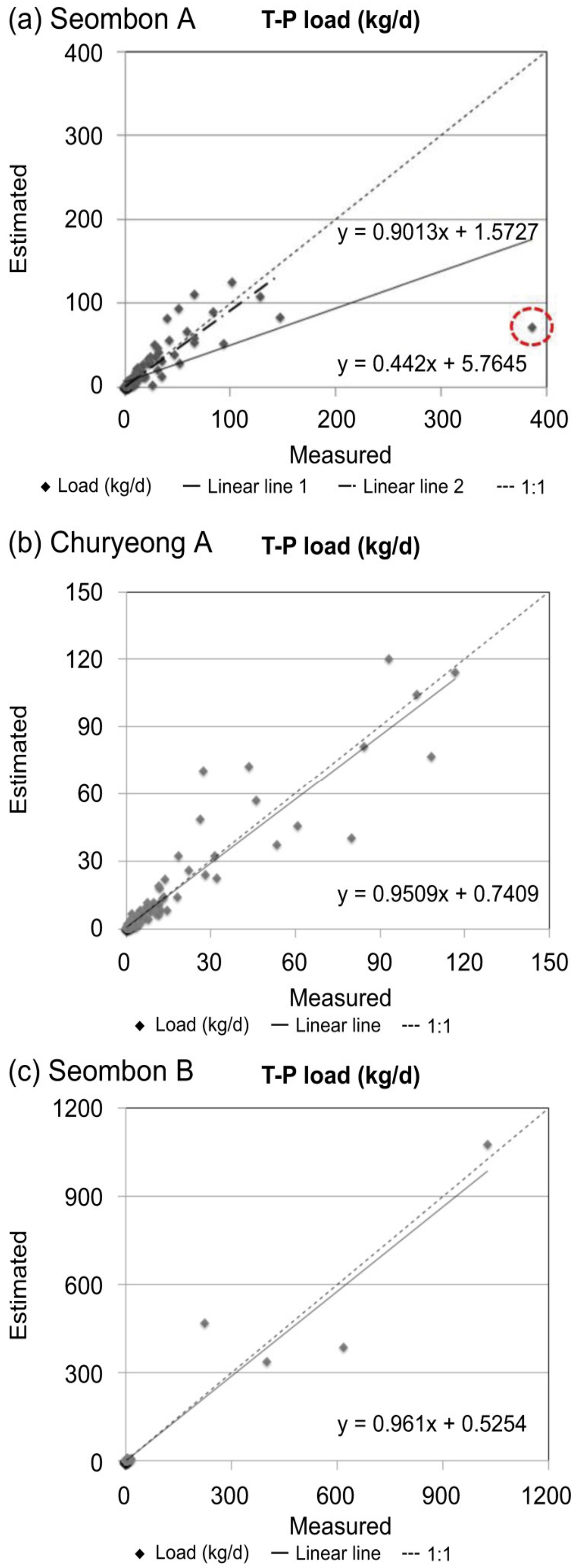

Fig. 4. Comparison of the measured T-P loads and the loads estimated by LOADEST.

Table 5
Coefficient values of the calculated LOADEST model

Measured point	Item	a_0	a_1	a_2	a_3	a_4	a_5	a_6
Seombon A		5.3959**	0.9178**	0.0151	–0.1233**	0.2907**	–0.0366*	–0.0315**
Churyeong A	BOD	5.1546**	0.9528**	0.0027	–0.1525**	0.2453**	–0.0239*	–0.0363**
Seombon B		5.9630**	1.0070**	–0.0046	0.0119	0.2042**	–0.0563*	–0.0275*
Seombon A		1.6915**	1.1298**	0.0526*	0.0799*	0.5649**	–0.0365*	–0.0330*
Churyeong A	T-P	1.2197**	1.1577**	0.0424*	0.0402	0.5266**	–0.0057	–0.0482*
Seombon B		1.9686**	1.1017**	0.0609**	0.1606**	0.2876**	0.0135	–0.0555**

**Highly significant; *Significant

Table 6
Effluent waste loads of study area in 2017

Unit basin	BOD (kg/d)			T-P (kg/d)		
	Point source	Non-point source	Total	Point source	Non-point source	Total
Seombon A	143.14 (7.1%)	1,862.77 (92.9%)	2,005.91	7.682 (5.7%)	127.472 (94.3%)	135.154
Churyeong A	187.05 (26.8%)	511.84 (73.2%)	698.89	7.926 (16.2%)	41.021 (83.8%)	48.947
Seombon B	315.59 (12.8%)	2,144.58 (87.2%)	2,460.17	16.175 (8.7%)	170.406 (91.3%)	186.581
Total	645.78 (12.5%)	4,519.19 (87.5%)	5,164.97	31.783 (8.6%)	370.682 (91.4%)	370.682

4th Master Plan for Quantity Regulation of Water Pollution in Jeollabuk-do Seomjin River (2021) [10].

Table 7
BOD target water quality calculated at the measurement point

Measurement point	Target water quality (3rd)	Annual arithmetic mean					TMDL evaluation water quality		
		‘16	‘17	‘18	‘19	‘20	‘16~’18	‘17~’19	‘18~’20
Seombon A	1.1	1.0	1.0	1.1	1.1	0.8	1.0	1.1	1.0
Churyeong A	1.1	0.9	0.9	1.0	1.0	0.7	0.9	0.9	0.9
Seombon B	1.0	1.0	0.9	1.1	0.9	0.8	1.0	0.9	0.9

Table 8
Number of points that exceeded the target water quality and excess rate of target BOD in target water quality

Measurement point	Item	Number of measurements	Number of points that exceeded the target water quality	Excess rate
Seombon A	Measured	213	60	28.2%
	Estimated		72	33.8%
Churyeong A	Measured	201	34	16.9%
	Estimated		38	18.9%
Seombon B	Measured	209	64	30.6%
	Estimated		69	33.0%

Table 9
Number and excess rate of target T-P in target water quality

Measurement point	Item	Number of measurements	Number of points that exceeded the target water quality	Excess rate
Seombon A	Measured	213	117	54.9%
	Estimated		124	58.2%
Churyeong A	Measured	201	100	49.8%
	Estimated		108	53.7%
Seombon B	Measured	209	96	45.9%
	Estimated		117	56.0%

Table 10
T-P target water quality calculated at the measurement point

Measurement point	Target water quality (3rd)	Annual arithmetic mean					TMDL evaluation water quality		
		'16	'17	'18	'19	'20	'16~'18	'17~'19	'18~'20
Seombon A	0.021	0.030	0.032	0.027	0.031	0.026	0.029	0.029	0.028
Churyeong A	0.018	0.023	0.016	0.020	0.023	0.016	0.020	0.020	0.020
Seombon B	0.016	0.017	0.014	0.020	0.021	0.018	0.017	0.018	0.019

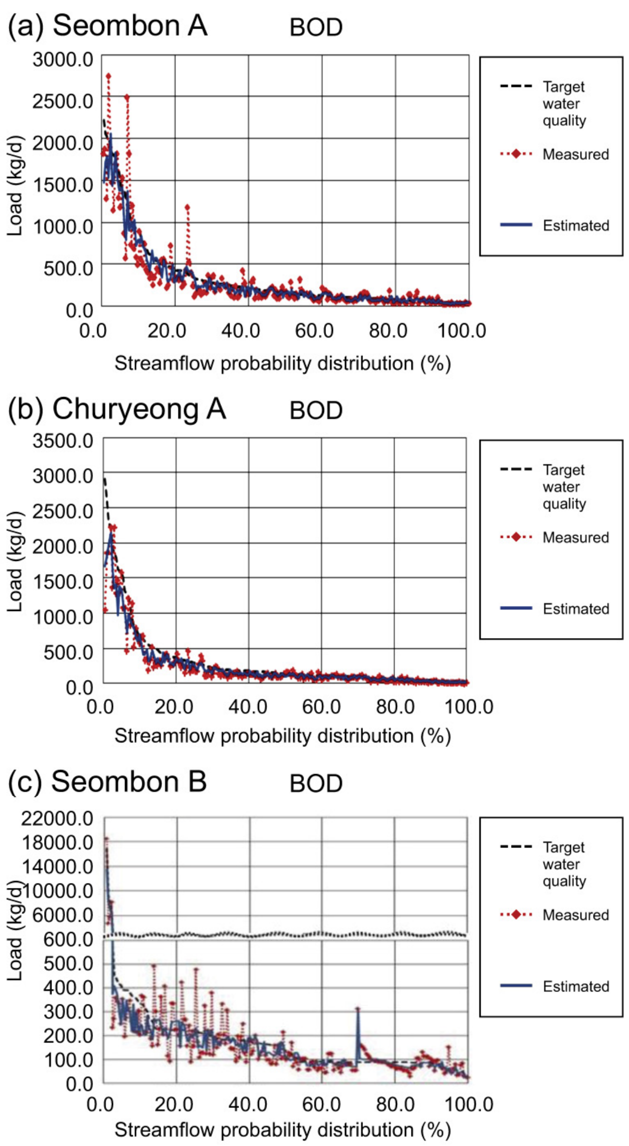

Fig. 5. Comparison of characteristics in BOD load by flow section.

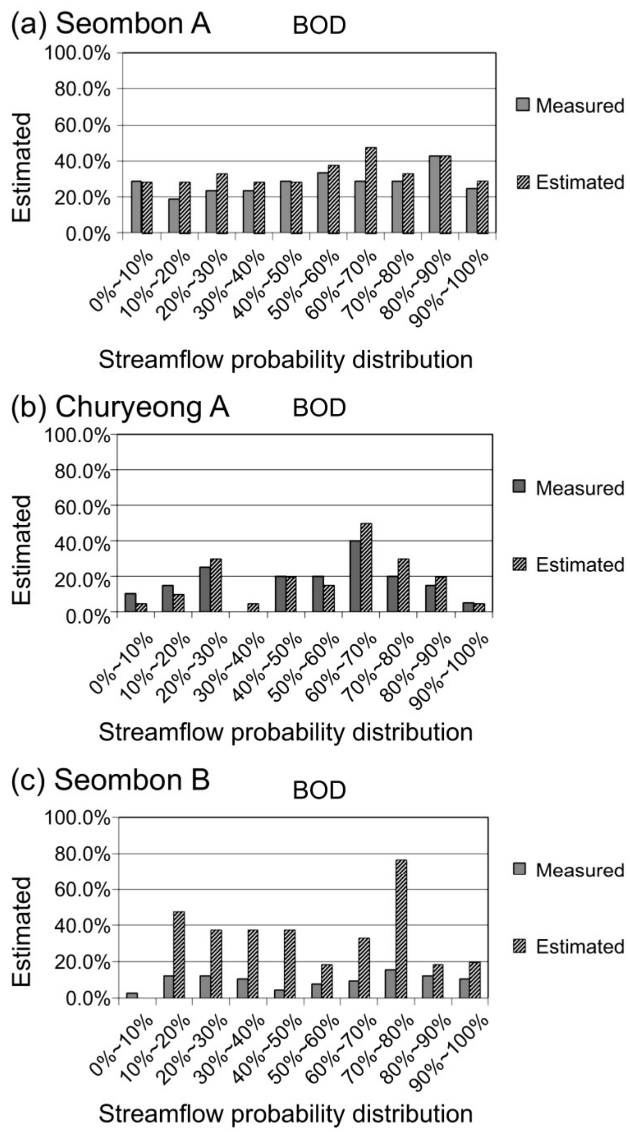

Fig. 6. Exceeding of the BOD frequency by flow rate section.

than that for the measured values (60). At Churyeong A, the number of points, which exceeded permissible limits for the simulated and measured values were 34 and 38, respectively, for the entire section. The measured values exhibited high excess rates in the high flow rate (0%–20%) sections, whereas the simulated values showed high excess rates in the low flow rate (60%–90%) sections. At Seombon B, the number of points, which exceeded permissible limits, was 64 for the measured values and 69 for the simulated values among the 209 measurements. In particular, there was a significant difference in excess rate in the 10%–20% section (12.5% for the measured values and 47.6% for the simulated

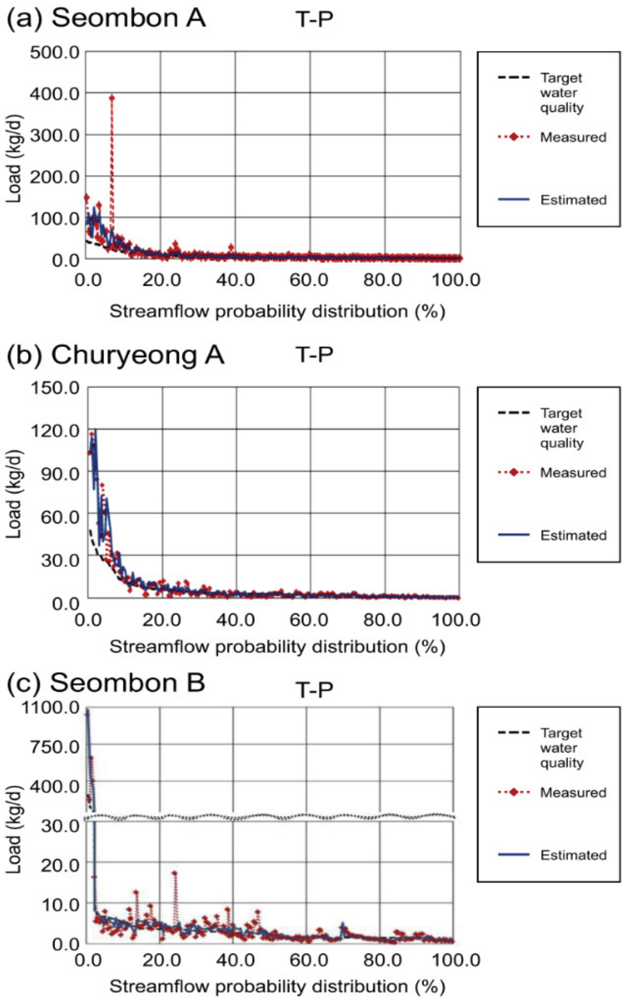

Fig. 7. Comparison of characteristics in T-P load by flow section.

values) and the 70%–80% section (15.6% for the measured values and 76.2% for the simulated values) (Figs. 5 and 6)

At Seombon A, the measured and simulated values of T-P exhibited high excess rates of 95.2% and 100% in the 0%–10% section and 81.0% and 95.2% in the 10%–20% section, respectively. For the entire section, the measured and simulated values exceeded the target water quality 117 and 124 times, respectively, among the 213 measurements. At Churyeong A, the measured and simulated values showed high excess rates of 95.0% and 100% in the 0%–10% section, respectively. The simulated values showed high excess rates in the high flow rate (0%–50%) sections, whereas the measured values exhibited high excess rates in the low flow rate (50%–70% and 80%–90%) sections.

At Seombon B, the measured and simulated values exceeded the target water quality by 96 and 117 times, respectively, of the 209 measurements. The overall excess rate was higher for the simulated value than for the measured value. In particular, there was a difference in the excess rate in the 30%–40% section between the measured value (66.7%) and simulated value (95.2%), and the overall excess rate of the simulated value was higher than that of the measured value.

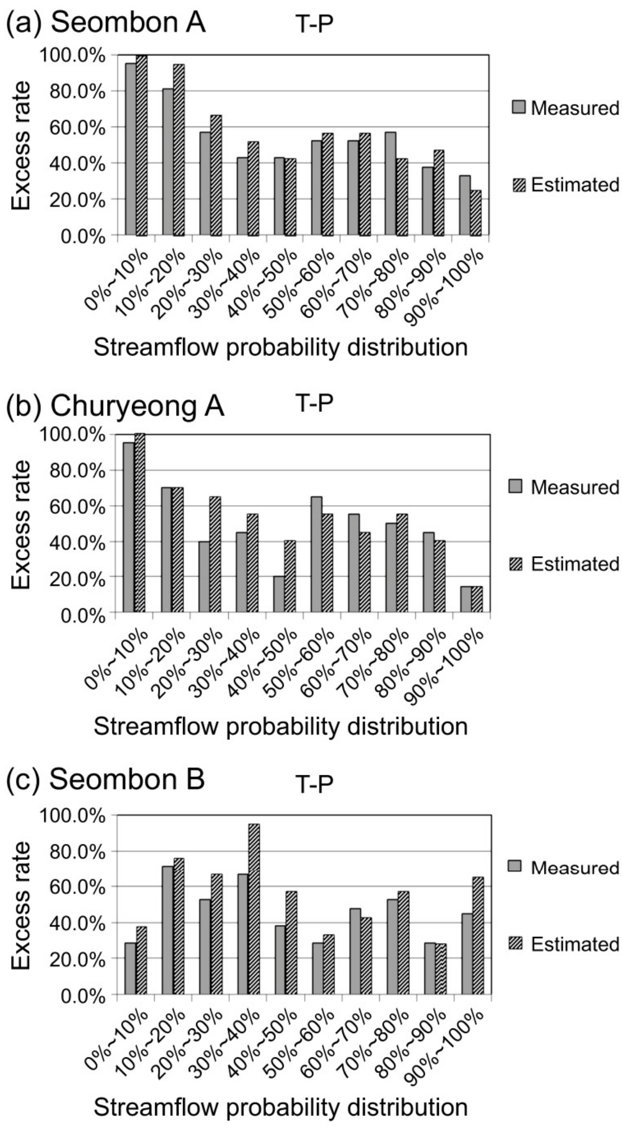

Fig. 8. Exceeding of the T-P frequency by flow rate section.

At the target points, the simulated values were significantly different from the measured values, and the excess rate was high for T-P and in high flow rate sections (Figs. 7 and 8).

4. Conclusion

In this study, the performance of the third phase of the implementation of TMDLs by the South Korean ME was evaluated for the unit basins of Seombon A, Churyeong A, and Seombon B located in the upstream area of the Seomjin River based on the water quality and flow rate measurement data and the simulated results from the LOAD ESTimator (LOADEST) regression models. In addition, the causes of exceeding the target water quality were analyzed to present efficient water quality management measures in the future. The results of this study can be summarized as follows:

- Pollutant loads were simulated by applying loads to the target basins based on the measurement data and the regression equation [Eq. (9)] of the LOADEST model. The simulation results exhibited appropriate ranges for statistical variates with the measured values, indicating that the LOADEST model can simulate pollutant loads by effectively reflecting the measured values. However, for points where the measurement data significantly changed within a short period of time, such as Seombon A, ratings for statistical variates were lowered because of the difference between the measured and simulated values. Further, the characteristics of the measurement data must be analyzed first for application to the LOADEST model.
- Water quality (BOD and T-P) was simulated using the LOADEST model. This model could evaluate the factors influencing water quality and their tendencies by analyzing the regression coefficient that represents dependence on the flow rate (β_1), seasonal regression coefficients (β_3 and β_4), and time regression coefficients (β_5 and β_6) through the simulation of measurement data. Hence, LOADEST model can be used as a tool for water quality analysis.
- When the target water quality excess rate was analyzed at the three target points using the measured values and the values simulated by the LOADEST model, the excess rate of BOD was <50% in all unit basins, indicating that the target water quality of the third phase of TMDLs was satisfied. However, T-P could not satisfy the target water quality because the excess rate exceeded 50% in all unit basins.

The overall excess rate was higher for the simulated value compared to the measured value. This may be attributed to the increase in non-point sources that flow into rivers during rainfall, flow rate fluctuations, and characteristics of the LOADEST model regression equation that reflect specific measurement data (outliers).

- When the characteristics of exceeding the target water quality were analyzed through the application of the LOADEST model, the excess rates of the measured and simulated values were found to be high for T-P and in high flow rate sections. T-P exhibited high excess rates because the reduction effect was insignificant as it was included as a target pollutant in the second phase of TMDLs (2011–2015), unlike BOD. Continuous management measures (non-point sources) are required to achieve the target water quality regarding T-P.
- The simulation results exhibited appropriate ranges for statistical variables, indicating that the LOADEST model is applicable for the simulation of pollutant loads. The LOADEST model, which is capable of analyzing the factors influencing data and their tendencies using various parameters, is expected to contribute to the implementation and establishment of water quality management policies when used to analyze long-term monitoring data.

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