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Analysis of the Pollution Load Contribution Rate of Inflowing Tributaries for the Sustainable Management of the Seomjin River (Seombon D)

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Abstract: The total maximum daily load (TMDL) system divides the watershed into unit basins for implementation and evaluates water quality by assessing whether targets have been achieved based on investigated data through continuous monitoring. River water quality is influenced by the amount and type of pollutants entering the river, making continuous monitoring, along with analysis and evaluation, essential for the ongoing development of policies and systems aimed at improving water quality. In this study, basic data for water quality management were gathered by analyzing the pollution contributions of the main river (the Seomjin River) and its tributaries, identifying major pollutant sources, and conducting trend analyses. The delivery pollution load of the Seombon D unit basin, one of the main watersheds of the Seomjin River in South Korea, shows a rapid increasing trend (BOD, 1.2–2.4, 2020), which is different from the trend in the B unit watershed of the Boseong River, also a tributary. The rapid increase is presumed to be due to the characteristics of Seombon D, including the inflow of pollution sources of Seombon C, an upstream point. The D unit basin of Seombon is located in the middle of the unit watersheds that divide the main stream of the Seomjin River in Korea into A, B, C, D, E, and F. This increase is thought to be due to the inflow of pollutants specific to Seombon D's characteristics and the influence of the upstream Seombon C unit basin. In the pollution load contribution rate analysis of Seombon D, it was found that the contribution rate from Seombon C, the upstream area (BOD, 38.42–120.08%), was higher than that of the Boseong B unit basin tributary. The self-purification capacity of Seombon D is believed to have contributed to the improvement in its water quality. It is essential to manage the upstream Seombon C unit basin to sustainably improve the water quality of the Seombon D unit basin. Therefore, managing Seombon C is deemed necessary to further enhance the water quality of Seombon D.

Keywords: Seommjin River; delivery pollution load; contribution ratio; TMDLs (total maximum daily loads)

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1. Introduction

Currently, water environment management is effectively addressed through a water quality management system focused on unit basins. One of the key systems being implemented for this purpose is the total maximum daily load (TMDL) system, which divides the watershed into unit basins. Extensive implementation of TMDL programs in the U.S. has substantially improved water quality and has been established as an effective river basin pollution management approach. Applying TMDL to the field of water quality control has become a major trend in international river governance and basin management [1].

TMDL plays a significant role in advancing sustainable water resource management, contributing to the protection of aquatic ecosystems, public health preservation, and the ecological equilibrium of water bodies [2].

Korea operates a total maximum daily load (TMDL) system with the goal of improving water quality by appropriately managing water resources and pollution sources. Currently, the system is in its fourth phase. The TMDL system evaluates water quality based on data collected through continuous monitoring to determine whether the set goals are being achieved.

Korea's total maximum daily load (TMDL) system for water quality management is implemented across the four major river basins: the Han River, Nakdong River, Geum River, and Yeongsan–Seomjin River. Initially launched in 2003 for three river basins (Nakdong, Geum, and Yeongsan–Seomjin), the system was expanded to include the Han River basin in 2010. Since then, it has been mandatory across all four major river basins. Im et al. [3] analyzed the effects of the total maximum daily load (TMDL) system on water quality and aquatic ecosystem health in the Jinwi River basin from 2012 to 2019. Their findings indicated that water quality improved following the implementation of the TMDL system, and this trend was attributed to the execution of reduction plans under the system.

In South Korea, the results of the performance evaluation of the total maximum daily load (TMDL) system indicate that river water quality has improved. Management items have expanded from BOD (biochemical oxygen demand) to T-P (total phosphorus), and after 2030, the application of TOC (total organic carbon) is currently under review.

After completing the first phase of the Han River water system and the third phase of the three major river systems (the Nakdong, Geum, Yeongsan, and Seomjin Rivers), evaluation results indicated that both BOD and T-P in the four major river systems were discharged at levels lower than the pollution loads allocated during the planning stage (BOD: 23.0% less, T-P: 25.6% less) [4].

The performance evaluation of the total maximum daily load (TMDL) system assesses the achievement of target water quality for each divided unit basin.

The short-term performance evaluation focuses on assessing the attainment of the annual allocated load and reduction plans outlined in the implementation plan, as well as monitoring discharge facilities. In contrast, the long-term performance evaluation determines whether the target water quality has been achieved by analyzing long-term water quality variation data and investigating the causes of any failures to meet the target. This analysis aims to propose institutional and technical improvements for the next phase of the total maximum daily load (TMDL) system [5]. Therefore, the Ministry of Environment has installed and is operating monitoring networks to evaluate whether each sub-watershed is achieving its targets.

By utilizing data from the monitoring network, the analysis of pollutant load, river water quality and flow rate trends, and their impact on the river provided important information for water quality management policies [6]. Due to the significance of the total maximum daily load (TMDL) system, many studies have been conducted.

Kal et al. [7] stated that water quality management measures require substantial resources and time, necessitating a process to evaluate their feasibility before implementation. To this end, in the Seohwa Stream watershed located upstream of Daecheong Lake in Korea, the SWAT (Soil and Water Assessment Tool) model was utilized to apply water quality improvement measures. The effectiveness of these measures was then assessed using load duration curves.

Choi et al. [8] calculated the delivery pollution load by developing and utilizing flow duration curves and delivery pollution load correlation using actual monitoring data. Lee et al. [9] analyzed the characteristics of pollutant loads during dry seasons and the contribution rates to the main stream of the Namhan River to identify critical rivers requiring focused management and major pollution sources. Park evaluated the contribution rates of the Soyang Lake watershed by estimating the delivery pollution load from drainage areas and assessing flow duration change and seasonal changes on the Soyang Lake watershed [10].

Mingyu Huang monitored the major characteristics of pollutants entering Erhai Lake, focusing on total nitrogen (TN), total phosphorus (TP), ammonia nitrogen (NH_3-N), and chemical oxygen demand (CODCR). This analysis aimed to clarify the water quality and quantity of Erhai Lake and to estimate the impact of these pollutants on its overall water quality [11].

Simeonov monitored the water quality of several rivers in Greece, including the Aliakmon, Axios, Loudias, Strymon, and Gallikos, using a variety of parameters such as pH (potential hydrogen), electrical conductivity (EC), dissolved oxygen (DO), total suspended solids (TSSs), nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), orthophosphate (PO_4^{3-}), chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), dissolved organic nitrogen (TON), and hydrolyzable total phosphorus (TP). The data were analyzed to reduce variation and provide useful information for water quality evaluation and management [12].

Surface water quality is a highly sensitive issue. Anthropogenic influences—such as urban, industrial, and agricultural activities, along with increased water consumption—combined with natural processes like changes in surface water recharge, precipitation, and soil water quality, significantly affect groundwater quality and its suitability for drinking, industrial, agricultural, recreational, or other purposes [13].

River water quality is influenced by the amount and type of pollutants entering the river.

The water quality of rivers is determined by the amount and types of pollutants entering the river, so monitoring, along with subsequent analysis and evaluation, is necessary to continuously develop policies and systems for improving water quality.

For effective water quality management, it is essential to assess the contribution of pollution to the main river's water quality, identify major pollution sources, and analyze trends. Additionally, understanding the pollution load characteristics and analyzing the contribution rates at target points in the inflow rivers that are the source of the main river environment is crucial.

In this study, we aim to analyze recent data from the target site to investigate the pollution sources of the Boseong River, which is an upstream tributary of the target site, and the pollution sources of the upstream unit watershed at the Seombon C site, focusing on the Seombon D site that is subject to water quality pollution. This analysis will help characterize the trends in pollution sources and contribution rates at the target site. Through this, we aim to secure rational foundational data for establishing water quality policies and improvement measures in accordance with the performance of the total maximum daily load (TMDL) system.

2. Research Content and Unit Watershed Status

2.1. Study Area

The Seomjin River watershed was divided into unit basins for the performance of the total maximum daily load (TMDL) system, including the main stem of the Seomjin River and its tributaries, such as the Yocheon A, Yocheon B, Osu A, and Boseong A and B unit basins. Each location was named using abbreviations from the main stem of the Seomjin River, such as Seombon A point, Seombon B point, and Osu A point.

In this study, the Seombon D unit basin, which exhibits high variability in pollution sources due to the inflow of the Boseong River, was selected as the target area. The study aimed to evaluate the contribution rate of pollutants by assessing the impact of the pollution load from the Boseong B unit basin, an inflow tributary. Figure 1 shows the TMDL estimation for the Seombon D and Boseong B unit basins.

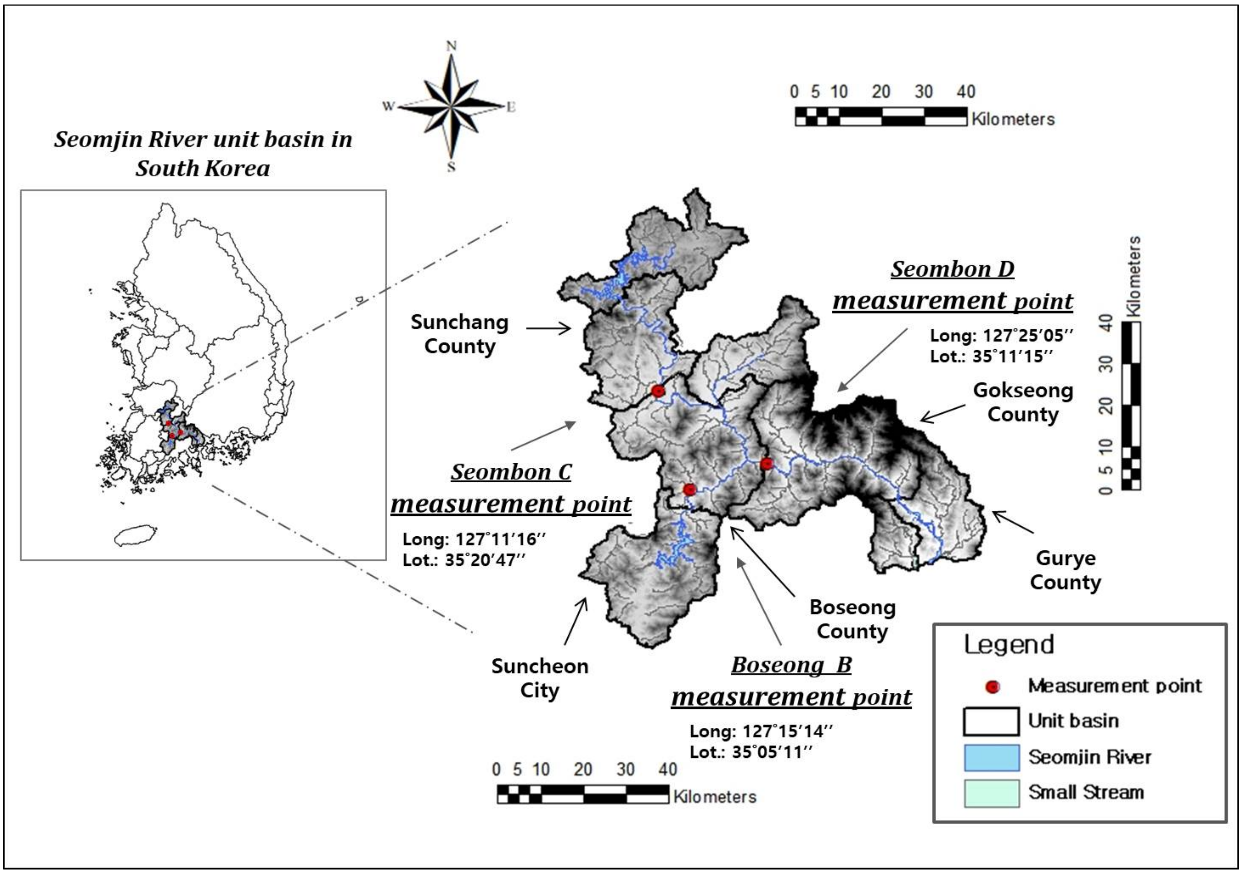

Figure 1. Study area and point in the Seombon D unit basin.

2.2. Research Analysis Method

The water quality analysis items were BOD (biochemical oxygen demand) and T-P (total phosphorus), and to evaluate the impact of incoming flow tributaries, the correlation between observational data was analyzed using SPSS (Ver. 17). Monitoring was conducted on-site every 8 days, and experimental analyses were performed for BOD_5 over 5 days, along with molecular orthometric analysis for T-P.

During the analysis period (2019–2023), the diagram of the delivery pollution load curve was drawn and analyzed to assess the inflow load. The water quality and pollution load data of Seombon D and Boseong B unit basin were used to estimate the pollution load and evaluate the contribution rate.

The delivery pollution load refers to the pollutants generated in the watershed that are discharged and transported to the target water quality point. The generation of pollutants is influenced by natural conditions and anthropogenic activities. Pollutants generated in this manner are delivered to the target water body through natural processes or artificial treatment. The delivery pollution load represents the amount of pollutants that reaches the target watershed [14].

The delivery pollution load can be estimated using a watershed model through an integrated method or by calculating the delivery pollution load rate. This rate is the ratio of pollutants discharged from the source that reach a specific point in the water body, and the delivery pollution load to the river can be estimated according to Equation (1) [15].

$$\text{DEL Load}_t = \text{DIS Load}_t \times \text{DR}_t \quad (1)$$

here, DEL Load_t (delivered pollution load) refers to the delivered pollution load (kg/day) under condition t. DIS Load_t (discharged pollution load) refers to the discharged pollution load (kg/day) under condition t. DR_t (delivery Ratio) refers to the delivery ratio under condition t.

In this study, the cumulative effluent load curve was used to analyze the delivered pollution load input. If the curve is convex above the 1:1 line, it indicates a higher than average delivered pollution load input; if it is concave below the 1:1 line, it indicates a lower than average delivered pollution load input. Figure 2 shows an example of the cumulative effluent load curve.

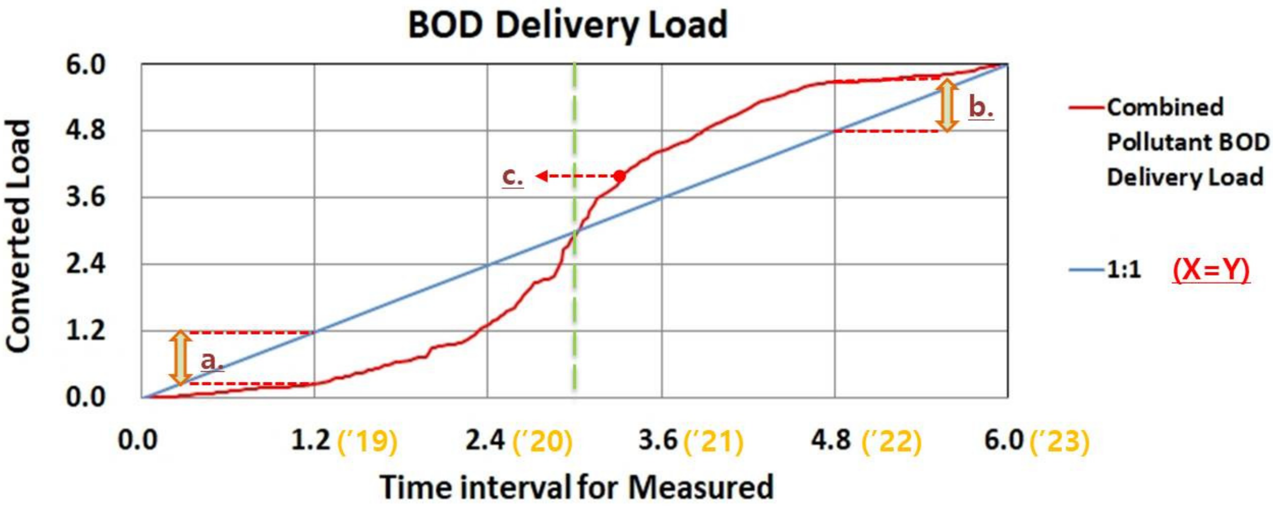

Figure 2. Example of Variation in Pollutant Delivery Load and Delivery Ratio. (**a**) The part below the corresponding line is the smaller than average inflow load. (**b**) The part above the corresponding line is the larger than average inflow load. (**c**) The change in the amount of inflow load. The dotted green lines indicate the midpoint of the study period. The yellow numbers indicate the years of the study period.

2.3. Unit Watershed Status and Observation Data

The total area of the unit watershed of Seomjin River's Seombon D is 650.287 km^2, while the unit watershed of the Seomjin River between Suncheon County and Gokseong County, from the boundary of Gokseong County to the boundary of Suncheon City, is 580.659 km^2. The unit watershed of Seombon D contains 40 sub-watersheds, and the unit watershed of Bosung B has 31 sub-watersheds [16]. Total load estimation is conducted at the end of each unit watershed, with the flow rate and water quality measured simultaneously at approximately 8-day intervals.

Table 1 shows the status of Seombon D. Figure 3 presents data from the total maximum daily load (TMDL) monitoring network from 2019 to 2023 at approximately 8-day intervals, while Table 2 and Figure 4 display the estimated load based on flow rate, BOD, and T-P data.

Table 1. Characteristics of study area.

Tributary	Administrative District		No. of Sub-Basin	No. of TMDL Basin	Area (km²)	4th Phase (′21~′25) Target Water Quality (mg/L)	
						BOD_5	T-P
Boseong B	Jeollanam-do	Boseong county	10	1	580.659	1.3	0.030
		Suncheon city	14				
		Whasun county	7				
Seombon D	Jeollanam-do	Gurye county	2	1	650.287	1.3	0.051
		Suncheon city	1				
	Jeollabuk-do	Gokseong county	31				
		Namwon city	5				
		Sunchang county	1				

Fourth master plan for quantity regulation of water pollution in Seomjin River, Jeollanam-do (′21).

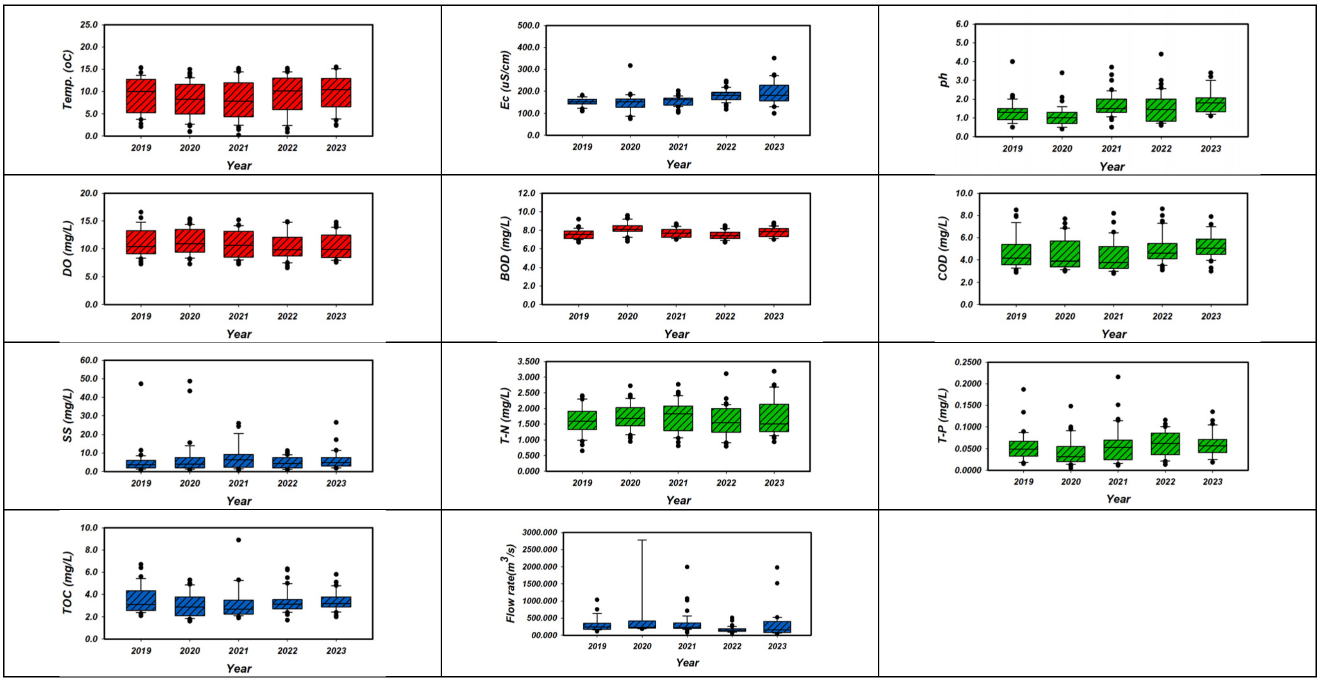

Figure 3. Measurement data of flow rate and water quality in Seombon D from 2019 to 2023.

Table 2. Annual average of delivery loads of pollutants (biological oxygen demand [BOD], total phosphorus [T-P] at the measurement points.

Unit Basin Items / Year	Seombon C		Boseong B		Seombon D	
	BOD (kg/d)	T-P (kg/d) × 100	BOD (kg/d)	T-P (kg/d) × 100	BOD (kg/d)	T-P (kg/d) × 100
2019	1495.643	6588.429	462.354	1307.040	3771.816	16,474.785
2020	2148.450	12,161.283	424.111	1247.631	7272.512	41,819.189
2021	2419.246	9020.088	522.045	1188.294	5816.151	24,154.060
2022	1560.933	3203.116	384.716	607.671	2088.283	9705.173
2023	2359.616	6017.444	408.888	774.867	4374.065	19,058.79

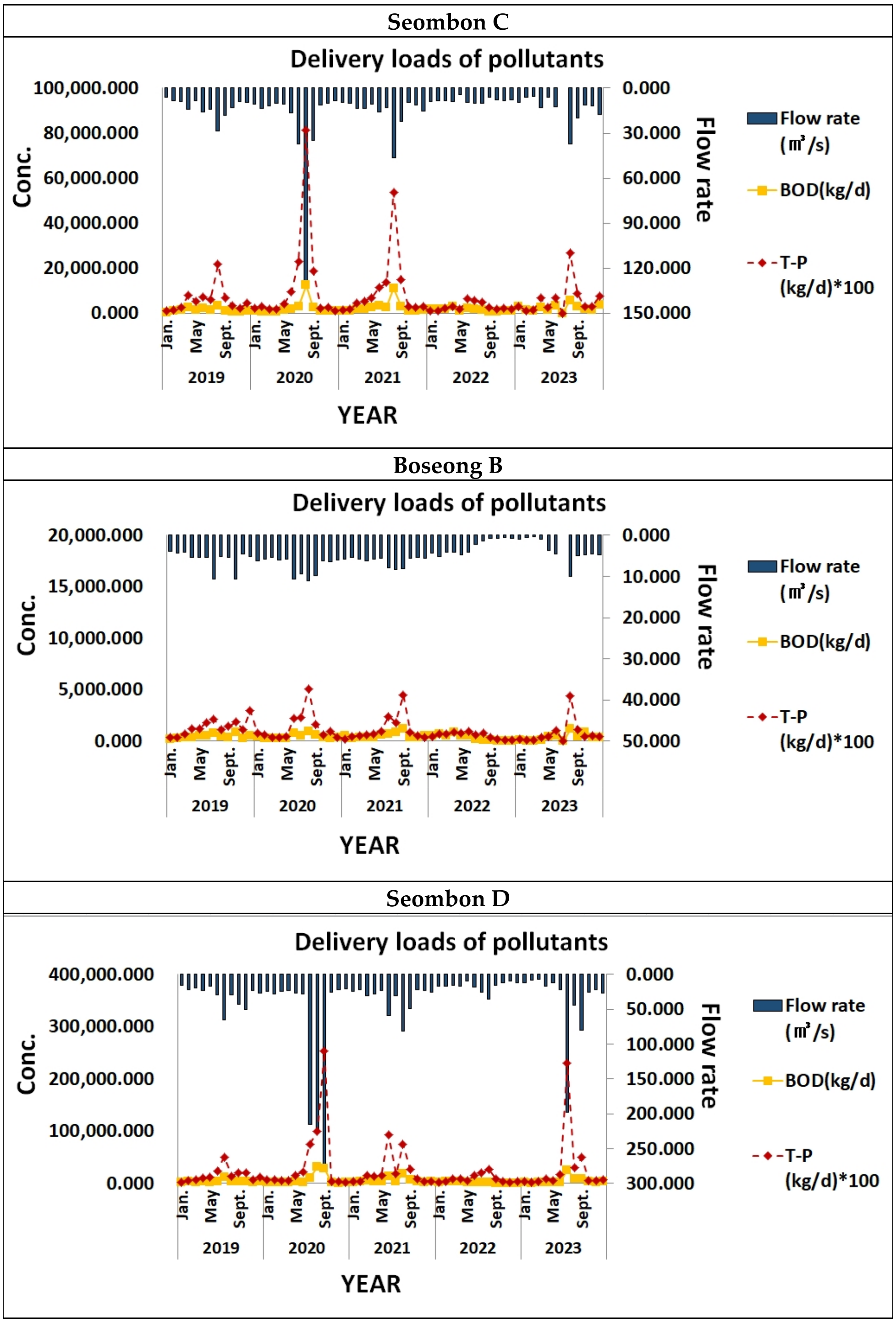

Figure 4. Annual average of delivery loads of pollutants biological oxygen demand [BOD], total phosphorus [T-P] at the measurement points from 2019 to 2023.

3. Results and Discussion

3.1. Status Analysis

The analysis of flow rate, BOD, and T-P changes in the study area from 2019 to 2023 revealed that the BOD at Seombon D exhibited a decreasing trend from 2019 to 2020, followed by an increase and another decrease. In contrast, the BOD at Boseong B displayed an increasing trend after 2020, suggesting that Seombon D was not significantly affected by the inflow concentration from Boseong B. T-P increased from 2020 to 2022 but then decreased after 2022, while the flow rate showed a declining trend after 2020. It was determined that the T-P and flow rate at Seombon D were affected by the inflow from Boseong B. The causes of the increase or decrease in BOD and T-P are related to the monitoring schedule. Since the monitoring is conducted at 8-day intervals, it is presumed to be affected by rainfall events and short-term development projects within the sub-watershed.

Figure 5 shows the annual averages of flow rate, BOD, and T-P based on the observational data.

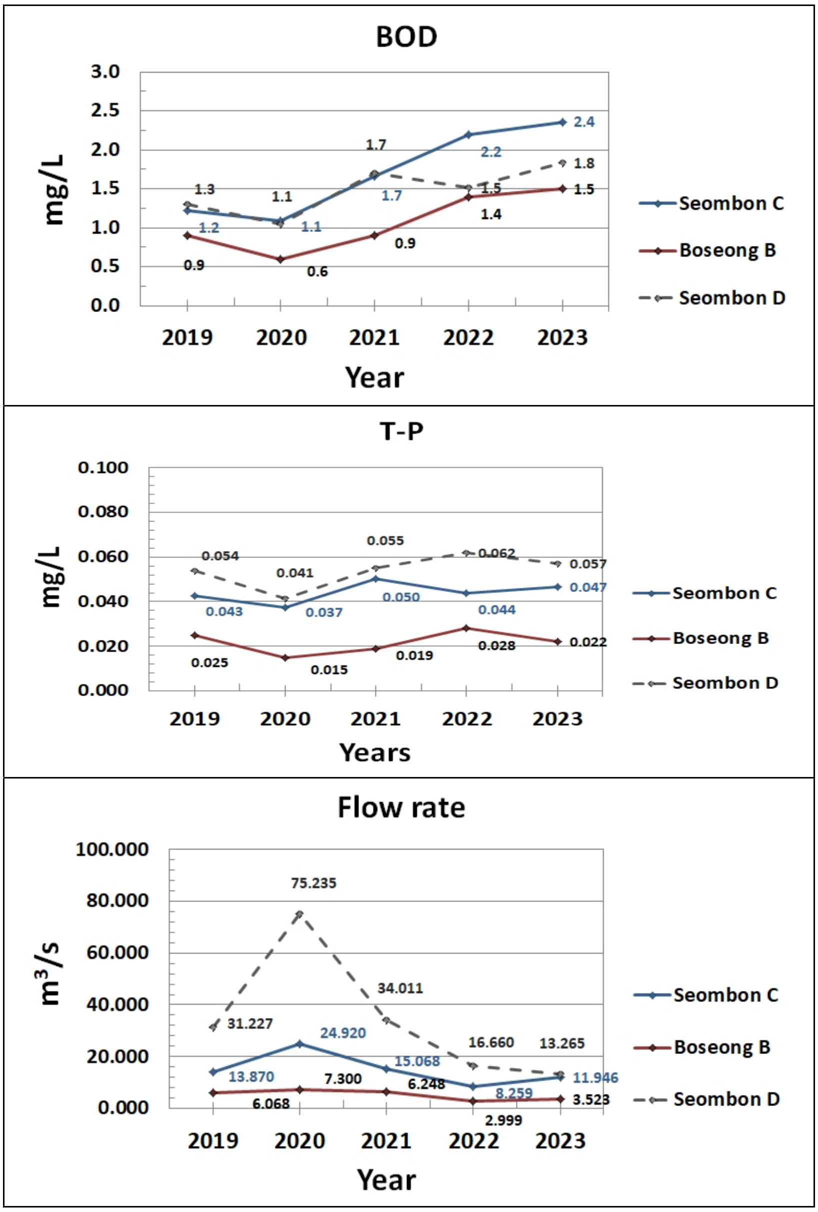

Figure 5. Annual average graph of flow rate, BOD, and T-P, which are observation data at the study area.

3.2. Statistical Analysis

To analyze the characteristics of water quality in the study area, the statistical program SPSS (Ver. 17) was used to examine the correlation between ten water quality parameters, including BOD, T-P, and flow rate for total maximum daily load (TMDL) management.

The normality of the data was assessed using the Kolmogorov–Smirnov test, which indicated that the data did not follow a normal distribution, as the significance probability (P) was less than 0.05 ($P < 0.05$). The skewness and kurtosis were evaluated using an absolute value of 2, but both exceeded the significance level. Correlation analysis was performed using the Spearman method. The analysis revealed that the BOD at the target point was high, with COD at 0.358 and SSs (suspended solids) at 0.332, both significant at the 0.01 level, as shown in the annotation (**). Additionally, T-P showed a strong correlation with TOC (0.777), SSs (0.762), and a negative correlation with DO (−0.735). BOD and T-P are highly correlated with organic matter, while their strong correlation with SS is likely influenced by rainfall. Furthermore, the negative correlation between T-P and DO may reflect the seasonality of temperature fluctuations.(Tables 3 and 4)

Table 3. Normal distribution of measured data in Seombon D.

Item	Kolmogorov–Smirnova	Descriptive Statistics		Standard Error
Temp. (°C)	0.000	Skewness	−0.235	0.173
		Kurtosis	−1.135	0.344
EC (uS/cm)	0.000	Skewness	1.255	0.173
		Kurtosis	4.587	0.344
pH	0.005	Skewness	0.474	0.173
		Kurtosis	0.024	0.344
DO (mg/L)	0.000	Skewness	0.336	0.173
		Kurtosis	−1.070	0.344
BOD (mg/L)	0.000	Skewness	1.279	0.173
		Kurtosis	2.273	0.344
COD (mg/L)	0.000	Skewness	1.379	0.173
		Kurtosis	3.093	0.344
SS (mg/L)	0.000	Skewness	7.179	0.173
		Kurtosis	62.775	0.344
T-N (mg/L)	0.030	Skewness	0.364	0.173
		Kurtosis	−0.133	0.344
T-P (mg/L)	0.001	Skewness	1.371	0.173
		Kurtosis	3.422	0.344
TOC (mg/L)	0.000	Kurtosis	1.388	0.173
		Skewness	2.932	0.344
Flow rate (m^3/s)	0.000	Kurtosis	5.736	0.173
		Skewness	40.307	0.344

Table 4. Matrix correlation of analysis items to Seombon D.

Items	Temp. (°C)	pH	EC (uS/cm)	DO (mg/L)	BOD (mg/L)	COD (mg/L)	SS (mg/L)	T-N (mg/L)	T-P (mg/L)	TOC (mg/L)	Flow Rate (m^3/s)
Temp. (°C)	1.000										
pH	−0.220 **	1.000									
EC (uS/cm)	−0.368 **	0.146 *	1.000								
DO (mg/L)	−0.818 **	0.408 **	0.370 **	1.000							
BOD (mg/L)	−0.006	−0.046	0.037	−0.065	1.000						
COD (mg/L)	0.576 **	−0.193 **	−0.074	−0.580 **	0.358 **	1.000					
SS (mg/L)	0.557 **	−0.351 **	−0.343 **	−0.662 **	0.332 **	0.719 **	1.000				
T-N (mg/L)	−0.613 **	−0.062	0.170 *	0.401 **	−0.002	−0.160 *	−0.087	1.000			
T-P (mg/L)	0.742 **	−0.376 **	−0.214 **	−0.735 **	0.243 **	0.809 **	0.762 **	−0.228 **	1.000		

Table 4. *Cont.*

Items	Temp. (°C)	pH	EC (uS/cm)	DO (mg/L)	BOD (mg/L)	COD (mg/L)	SS (mg/L)	T-N (mg/L)	T-P (mg/L)	TOC (mg/L)	Flow Rate (m^3/s)
TOC (mg/L)	0.600 **	−0.272 **	−0.141 *	−0.576 **	0.296 **	0.898 **	0.672 **	−0.174 *	0.777 **	1.000	
Flow rate (m^3/s)	0.318 **	−0.206 **	−0.534 **	−0.356 **	−0.125	0.031	0.438 **	0.054	0.209 **	0.104	1.000

** Correlation is significant at the 0.01 level (two-tailed). * Correlation is significant at the 0.05 level (two-tailed).

3.3. Analysis of Cumulative Effluent Load

The cumulative effluent load curve was used to analyze the delivery pollution load during the monitoring period from 2019 to 2023. The X-axis is marked from 0.0 to 6.0, dividing the five-year period from 2019 to 2023 by month.

The characteristics of the delivery pollution load at the target point and the incoming flow tributary, Boseong B, were analyzed.

The observed data were calculated as a delivery pollution load and evaluated. The cumulative effluent load curve can be used to determine the periods of pollutant concentration and inflection points, while the delivery load can be assessed according to the shape of the graph. For Boseong B, the BOD was found to be nearly consistent with the average (1:1) curve, while T-P was analyzed to be higher than average during periods excluding the initial range of 0.0 to 1.2 (2019) and the later period (2022). The inflow type was analyzed to show no sudden increases or decreases. The BOD at Seombon D point in 2020 sharply increased to 1.2–2.4, indicating an upward trend, and T-P exhibited a similar pattern to BOD. This is attributed to the increase in BOD and T-P during the period from 2020 to 2021, which is believed to be influenced by the upstream unit, Seombon C.

Figure 6 shows the cumulative effluent load curve.

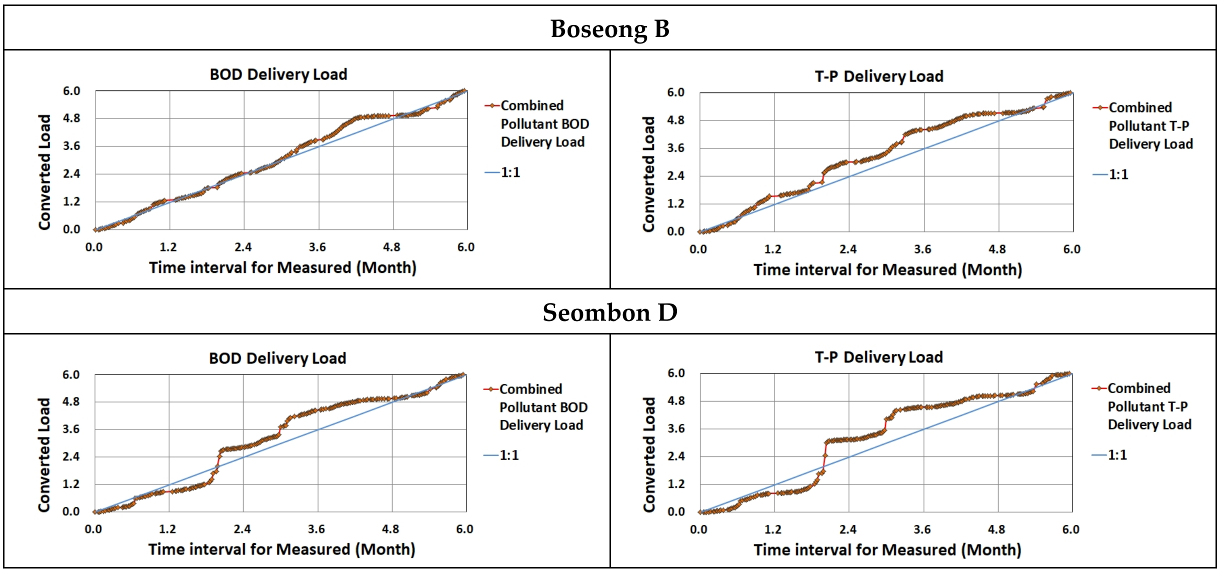

Figure 6. Variation in Pollutant Delivery Load and Delivery Ratio in Seombon D.

3.4. Contribution Rate Analysis

The analysis of the contribution rate at Seombon D revealed that the BOD contribution from Boseong B increased after 2020. Although the BOD concentration at Seombon D decreased to 1.5 mg/L in 2022, which made it less influenced by the contribution rate, the contribution from Boseong B was found to significantly impact the water quality at Seombon D. T-P levels were also influenced by fluctuations in the contribution rate from Boseong B. Additionally, the pollution load at Seombon D was significantly affected by

Seombon C, the upstream unit basin. In 2023, the contribution rate of the BOD load at Seombon C was 120.08%, suggesting that self-purification at Seombon D improved the downstream water quality. Table 5 and Figure 7 present the calculated load and the corresponding contribution rates.

Table 5. Analysis of contribution ratio of Boseong B unit watershed delivery pollutant loads to Seomjin D unit watershed.

Year	Unit Basin	Flow Rate (m^3/sec)	BOD (mg/L)	Delivery Pollutant Loads (kg/d)	Contribution Ratio (%)	T-P (mg/L)	Delivery Pollutant Loads (kg/d)	Contribution Ratio (%)
2019	Seombon D	31.227	1.3	3507.417		0.054	145.693	
	Boseong B	6.068	0.9	471.848	13.45%	0.025	13.107	9.00%
	Seombon C	13.87	1.2	1438.042	41.00%	0.043	51.530	35.37%
	Total				54.45%			44.37%
2020	Seombon D	75.235	1.1	7150.334		0.041	266.512	
	Boseong B	7.3	0.6	378.432	5.29%	0.015	9.461	3.55%
	Seombon C	24.92	1.1	2368.397	33.12%	0.037	79.664	29.89%
	Total				38.42%			33.44%
2021	Seombon D	34.011	1.7	4995.536		0.055	161.620	
	Boseong B	6.248	0.9	485.844	9.73%	0.019	10.257	6.35%
	Seombon C	15.068	1.7	2213.188	44.30%	0.05	65.094	40.28%
	Total				54.03%			46.62%
2022	Seombon D	16.66	1.5	2159.136		0.062	89.244	
	Boseong B	2.999	1.4	362.759	16.80%	0.028	7.255	8.13%
	Seombon C	8.259	2.2	1569.871	72.71%	0.044	31.397	35.18%
	Total				89.51%			43.31%
2023	Seombon D	13.265	1.8	2062.973		0.057	65.327	
	Boseong B	3.523	1.5	456.581	22.13%	0.022	6.697	10.25%
	Seombon C	11.946	2.4	2477.123	120.08%	0.047	48.510	74.26%
	Total				142.21%			84.51%

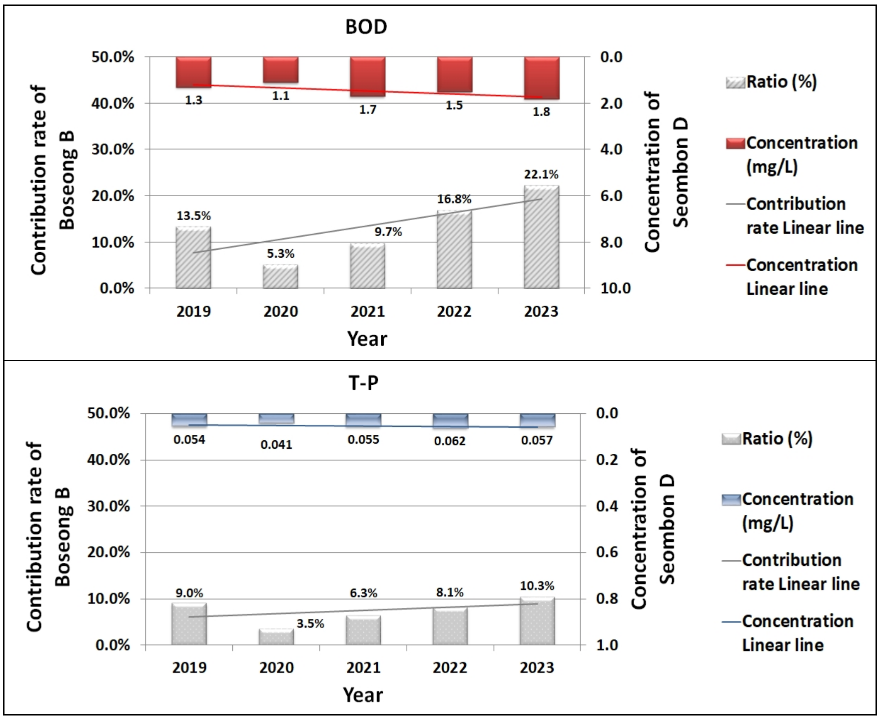

Figure 7. Boseong B unit watershed delivery pollutant loads to Seomjin D unit watershed.

4. Conclusions

The correlation analysis of the observational data revealed that BOD at Seombon D exhibited a strong correlation with COD (0.358) and SSs (0.332). In contrast, T-P demonstrated a robust correlation with TOC (0.777), SSs (0.762), and a negative correlation with DO (−0.735). BOD was found to be partly influenced by inflow from rainfall, while T-P's strong correlation with SSs and its inverse relationship with DO indicate that inflow during the summer rainfall season has a significant impact.

The analysis of the cumulative effluent load curve indicated that the delivery pollution load at Seombon D unit basin increased sharply in two stages, differing from the trend observed in the tributary Boseong B unit basin. This variation is attributed to the characteristics of the Seombon D unit basin and the influence of inflow from the upstream point, Seombon C unit basin. The sharp increase of 1.2 to 2.4 in 2020 is believed to have resulted from inflow during the rainfall season. The delivery pollution load varies according to the characteristics of each point, necessitating a tailored management plan. The analysis suggests that management measures, such as retention basins, are required at unit watershed Seom bon D unit basin to address the inflow of pollutants.

The BOD and T-P contribution rates from Boseong B changed during the target period (2019–2023), as did the concentration of Seombon D. The concentration at Seombon D was found to be influenced by fluctuations in the contribution rate from Boseong B. Analysis of the delivery pollution load contribution rate at Seombon D revealed that the contribution from upstream Seombon C was higher than that from Boseong B. The water quality at Seombon D improved due to its self-purification capacity. The analysis results indicate that the water quality of Seombon D improved as a result of this self-purification. To further enhance the water quality of the Seombon D unit basin, it is necessary to manage the Seombon C unit basin effectively. For this purpose, it is necessary to establish tailored countermeasures, including precise assessments of pollution sources at key locations.

The results of this study will be used as a rational foundation for establishing water quality policies and improvement measures of the total maximum daily load (TMDL) system by analyzing the characteristics of pollution sources in key sub-watersheds among the various sub-watersheds delineated under the system.

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