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The effect of total maximum daily loads (TMDL) program on water quality improvement in the Geum River basin, Korea

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ABSTRACT

In this study, an analysis using nonparametric statistical methods was conducted to assess the effect of Korean total maximum daily load (TMDL) program on the improvement of water quality in the Geum River basin, Korea. The result of analyzing the trend of long-term BOD change from 2003 to 2012 by seasonal Mann–Kendall test showed that there was no significant change (GR-1, GS-1, MH-1) or a trend of increase (GR-2) in "water quality improvement plan area," whereas a trend of decrease was observed in "implementation plan area" (GR-3, GR-4, GR-5, GS-2, MS-2). The period of TMDL implementation was divided into four time sections, and the BOD in each time section was compared with the others using the Kruskal–Wallis test. Compared with pre-TMDL stage, the effect of water quality improvement did not appear in the early first stage but appeared first in the tributaries, Gap Stream (GS-2) and Miho Stream (MS-2) in the late first stage of TMDL. At the mainstream sites (GR-3, GR-4, GR-5), the effect of water quality improvement appeared only in the second stage. In conclusion, the TMDL program is considered to have contributed to improving water quality in the "implementation plan area" and strict management is considered necessary to achieve continuous improvement in water quality also in later stages of TMDL implementation.

Keywords: Korean TMDL; Kruskal–Wallis test; Nonparametric statistical method; Seasonal Mann–Kendall test; Trend of long-term BOD change

1. Introduction

To overcome the limitations of the water quality improvement policy relying only on the concentration regulation, Korea has been carrying out the total maximum daily loads (TMDL) program for four major river basins (the Nakdong River, the Geum River, the Youngsan Seomjin River, and the Han River) since 2004 [1]. This program allocates and controls the total amount of pollutants deemed acceptable to a body of water. Under TMDL program, watersheds are divided into unit watersheds so that each unit watershed achieves and maintains its own water quality target. During the first stage of TMDL implementation (2004–2010), BOD was selected as the target parameter and TP was additionally selected for the second stage (2011–2015).

Under Korean TMDL program, water quality management areas are categorized into the "implementation plan area" and the "water quality improvement

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plan area". The "implementation plan area" is the area where the current water quality is worse than water quality goal; therefore, the observance of load allocation is strictly required through annual performance assessment. The "water quality improvement plan area" is the area where the water quality is better than water quality goal; therefore, only the observance of the load allocation of the latest year is recommended.

The assessment on the Korean TMDL program has been partly carried out by some researches. Current status of water quality was compared with the water quality goal established for each unit watershed, and the performance result of the reduction plan was evaluated at the midpoint of first-stage TMDL [2]. The achievement of water quality goal in each unit watershed, observance of the allocated load, and correlation between the allocated load and the achievement of water quality goal during the first stage of TMDL in the Geum River basin was assessed [3]. They also investigated whether water quality goal was achieved depending on the conditions of flow rate in the Geum River [4]. However, these researches were mainly about the observance of the water quality goal and allocated load and no study to assess quantitatively water quality improvement effect of TMDL implementation by analyzing water quality trends with respect to time has been carried out. In order to evaluate the effect of the water quality management policy and operate the policy in an effective manner, it is necessary to analyze the changes in water quality during the management period. Therefore, it is necessary to analyze quantitatively the short-term and long-term water quality changes during TMDL period using a statistical method to assess water quality improvement effect due to implementation of TMDL program.

As the water quality data are generally not in normal distribution and the application of parametric statistical methods to data with non-normal distribution can lead erroneous conclusions, nonparametric statistical methods have been used to analyze water quality data in many studies. To establish the remediation priorities for TMDL, the water quality of the basins was compared using the normalized rank means [5]. The Mann–Kendall trend analysis was conducted to calculate the optimized sampling frequency [6]. To analyze the trend of water quality data, ANCOVA on rank transformed data and the seasonal Mann–Kendall test were used [7]. The Kruskal–Wallis test on the water quality data grouped in monthly basis was conducted to test the significance of the seasonal trend at the sampling site, and also the seasonal Kendall-τ analysis was conducted to analyze the trend of continuous change in water quality over a long period of time [8]. The Wilcoxon rank-sum test was conducted to examine whether there is any significant change in water quality after the improvement of nitrogen processing function in sewage treatment facilities [9]. In this study, nonparametric statistical methods were also applied to analyzing water quality change: The seasonal Mann–Kendall test and LOWESS to analyze the long-term and short-term trend of change in water quality and the Kruskal–Wallis test to compare the water quality groups classified by the TMDL periods.

To analyze the effect of TMDL program on water quality improvement, the Geum River basin was chosen for this study. Compared with the initial stage of the policy implementation, a rapid urbanization in the Geum River basin resulted in significant increase of pollutants during the later stages. However, there was an active effort to improve water quality in this area, which makes the area a suitable place for analyzing water quality improvement effect of the TMDL program. In addition, the water quality data from 2003 were accumulated in this area, so it is possible to analyze the short-term and long-term change in water quality and the effect of TMDL program depending on its implementation stages.

The purposes of this study were: (1) to identify the temporal trend in water quality from pre-TMDL to the present, (2) to analyze whether there was a statistically significant change in water quality in each stage of TMDL implementation, and (3) to assess the effect of the TMDL implementation on water quality improvement, at the major points of water quality sampling stations in the Geum River basin, Korea.

2. Materials and methods

2.1. Study area

The Geum River basin, the study area of this research, is located in the middle part of South Korea, and it is the third largest basin in Korea after the Han River and the Nakdong River. It has a total watershed area of 9,912.15 km^2 and total length of 397.79 km.

In the upper region of the Geum River basin (upstream of Daecheong Dam), the water quality is relatively good, but Gap Stream penetrating Daejeon City and Miho Stream crossing Cheongju City meet the mainstream at the middle region of the basin and the water quality deteriorates due to the inflow of Gap Stream as the river flows downstream, Miho Stream and other tributaries containing various pollutants generated in medium and small cities, such as Gongju and Buyeo and other farming areas.

2.2. Monitoring sites and data

To analyze the water quality data, the data measured by the Korean Ministry of Environment in 8-d interval from 2003 to 2012 were used and among them, BOD concentration, the target parameter of TMDL program, was analyzed. The Geum River basin is composed of 22 TMDL unit watersheds, and there are water quality monitoring stations at the end of each unit watershed. A total of nine sites, such as two sites in the upstream area of Daecheong Dam, three sites in the downstream area of Daecheong Dam, and among the tributaries, two sites in Miho Stream and two sites in Gap Stream, were selected as the monitoring sites (Fig. 1).

GR-1 and GR-2 are sites for the "water quality improvement plan area" located in the upstream area of Daecheong Dam in the mainstream of the Geum River. GR-3 is the site for a unit watershed where the Gap Stream flows in and the "implementation plan area" begins, and GR-4 is the site for a mainstream watershed where Miho Stream flows in. GR-5 is the site for a mainstream watershed where Nonsan Stream flows in, located on the downstream boundary of the "implementation plan area." Among the major tributaries that flowed in the Geum River, Gap Stream, and Miho Stream were selected for analysis. Among sites for the unit watersheds of Gap Stream, GS-1 at the end of upstream "water quality improvement plan area" and GS-2 at the end of "implementation plan area" were selected and among sites for Miho Stream unit watersheds, MS-1 at the end of upstream "water quality improvement plan area" and MS-2 at the end of "implementation plan area" were selected for analysis.

2.3. Statistical analysis

To study the trend of long-time change in BOD concentration from pre-TMDL implementation to the present, the monotonic trend was assumed and the seasonal Mann–Kendall analysis was conducted. The LOWESS(LOcally WEighted Scatter plot Smoother) analysis was conducted at the same time to study the trend of short-time change in water quality. To analyze the change in water quality by TMDL implementation stage, BOD concentration of each section was compared with the others after the period of TMDL implementation was divided into four time sections. For this, the Kruskal–Wallis test, a nonparametric statistical method, was used and Mann–Whitney test that applied Bonferroni correction was conducted for *post hoc* analysis. The analysis period was divided into four time sections: The pre-TMDL stage (2003–2005), the early first-stage TMDL (2006–2008), the late first-stage TMDL (2009–2010), and the second-stage TMDL (2011–2012). "The pre-TMDL stage" refers to the stage before the start of fist-stage TMDL, which is assumed to have started in 2003 when water quality monitoring began. "The first-stage TMDL" means period between the start and the end of the first-stage TMDL. The first-stage TMDL was assumed to have started in 2006 because it was the year when the practical implementation plan of TMDL was established and its result started to be reflected though the TMDL was reported to have started in 2004. The first-stage TMDL was divided into two time sections ("the early first-stage TMDL" and "the late first-stage TMDL") because most of development plans and load reduction plans were concentrated in 2009–2010 [2]. "The second-stage TMDL" refers to period between the start of the second-stage TMDL and present (2012).

2.3.1. Seasonal Mann–Kendall test and LOWESS

The seasonal Mann–Kendall test is a method to analyze the trend of change in water quality in consideration of the seasonal factors, and it has been much used in the past researches for such analysis [9–16]. The seasonal Mann–Kendall test is nonparametric statistical method in which the Mann–Kendall static is calculated for each user-defined season and trend is calculated as the weighted average of seasonal estimates [14]. In addition, this method has an advantage that even though there are some missing values in observed values, their influence is not so great. Slope estimates for magnitude of trend are the median slope of all ranked seasonal regression slopes [12,17].

This study conducted the seasonal Mann–Kendall test for each monitoring site using the monthly BOD median data during the period of 2003–2012 and analyzed the magnitude of trend by deriving the seasonal Kendall slope estimator. For the seasonal Mann–Kendall test, however, at least 30 data are necessary if a season is divided into months [18]. In addition, as this test basically assumes the monotonic trend during the study period, it cannot easily find the changing trend within the specific period of time. Therefore, to find the trend of short-term change as well as the trend of long-term change in water quality, this study also suggested the result of applying the LOWESS analysis [19,20].

2.3.2. Kruskal–Wallis test

The Kruskal–Wallis test [21] was used to check if there is any change in water quality in each stage of

TMDL implementation during the entire period. This test is a nonparametric statistical method that analyzes the differences between three or more independent groups [12], and the researches to compare the water quality of the groups in different periods or in different locations were carried out in the past [8,22–24].

However, the Kruskal–Wallis test can only analyze whether or not there are differences between the independent groups. The multiple comparisons among groups are conducted through *post hoc* analysis. In general, *post hoc* analysis is conducted with the Mann–Whitney test after pairing each group. The significance is determined using p value calculated through Bonferroni-type correction [25]. Mann–Whitney test, which is a nonparametric statistical method to analyze the differences between the two groups, compares the mean rank of the groups [12,26].

3. Results and discussion

3.1. Trend analysis for the entire period

For each monitoring site, the analysis of the trend in BOD concentration change for 10 years from 2003 to 2012 was conducted using the seasonal Mann–Kendall test and its result was presented in Fig. 2 and Table 1. In addition, to analyze the short-term change in water quality, LOWESS analysis was also conducted at the same time (Fig. 2).

The result of the seasonal Mann–Kendall test for the upper reaches of the Geum River showed no significant trend in GR-1 (Fig. 2(a), Table 1) but showed an the increase of BOD in GR-2. However, it is difficult to conclude that the water quality deteriorated because GR-2 maintained a low concentration close to 1.0 mg/L, the water quality goal (Fig. 2(b), Table 1). GR-3, GR-4, and GR-5, which are the sites located in the mainstream of Daecheong Dam downstream, all displayed the trend of a decrease in BOD. The result of the LOWESS analysis showed that the BOD increased in GR-3 and GR-4 in the initial stage but began to decrease beginning in 2006 (Fig. 1(c)–(e), Table 1).

For GS-1 in the upper reaches of Gap Stream, a tributary flowing into the downstream of the dam, the result of the LOWESS analysis showed that the BOD increased after a slight decrease in the initial stage, but the result of the seasonal Mann–Kendall test showed no significant trend (Fig. 1(f), Table 1). In GS-2, the site located in the downstream of Gap Stream, the BOD decreased overall (Fig. 1(g), Table 1). At the MS-1 site located upstream of Miho Stream, there was no significant change in BOD but there was a trend of decrease in MS-2 located downstream of Miho Stream (Fig. 1(h) and (i)).

The result of the seasonal Mann–Kendall test indicated that there is a site showing an increasing trend in the upstream area of the Daecheong dam but according to the trend slope, it showed no greater trend of BOD change than other sites in the downstream area of Daecheong Dam. The BOD downstream of Daecheong dam showed a decreasing trend at all monitoring sites in the Geum River mainstream. Among them, GR-4 exhibited the greatest decrease in BOD as the result of trend slope estimation. Among the monitoring sites in the tributaries, only the GS-2 and MS-2 sites showed a trend of decrease in BOD, the greatest trend of decrease among all monitoring sites (Table 1).

As a result of comparing long-term changes in water quality in "water quality improvement plan areas," such as GR-1, GR-2, GS-1, and MS-1, with those in "implementation plan areas," such as GR-3, GR-4, GR-5, GS-2, and MS-2, only the "implementation plan areas" showed a decrease in BOD.

3.2. Comparison of water quality among TMDL implementation stages

The period of TMDL implementation was divided into four time sections, and the BOD concentration in each section was compared with the other sections.

The distribution of BOD concentration is shown in Fig. 3 in the Box-Whisker plot for four different time sections at all monitoring sites. The median of symmetric data should be located in the middle portion of the box and the length of the upper and lower whiskers should be almost the same [27]. Most of the data shown in Fig. 3, however, show asymmetric forms for the whole period. The width of the distribution was revealed to have decreased after the implementation of TMDL at all monitoring sites. It is considered that this result was found because the control of the pollutants was stably performed at all monitoring sites by the implementation of the TMDL program.

The result of the normality test via a Kolmogorov–Smirnov test for the four different time sections at each monitoring site showed that none of the monitoring sites satisfied normality. Therefore, for comparison of BOD concentrations in the four time sections, the Kruskal–Wallis test was also conducted. The results are shown in Table 2 along with the number of data and mean rank in the four time sections. The analysis result showed that there was a significant difference in BOD concentrations in at least two of the groups for all sites except the GR-1 site. For all sites except the GR-1 site where there was no significant difference among the groups as a result of the Kruskal–Wallis analysis, the Mann–Whitney test was conducted by pairing the groups in each time section, and a significance test was

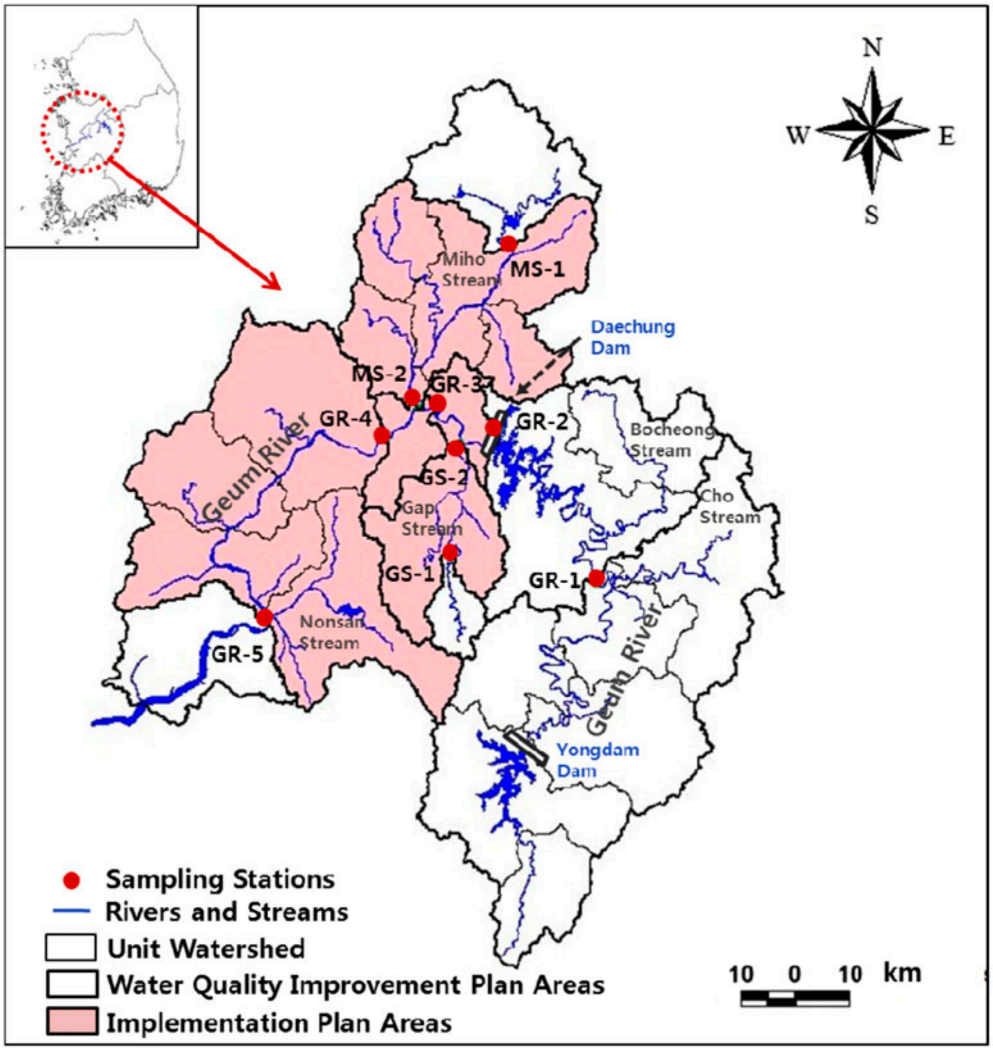

Fig. 1. Study area and monitoring sites in Geum River basin (GR-1: Geumbon E; GR-2: Geumbon F; GR-3: Geumbon G; GR-4: Geumbon H; GR-5: Geumbon K; GS-1: Youdeung A; GS-2: Gapcheon A; MS-1: Miho A; MS-2: Miho C).

conducted using Bonferroni-adjusted *p*-value (Table 3). The major result of analysis was presented in Fig. 4 in comparison with the result of the seasonal Mann–Kendall test.

The analysis result revealed that there was no statistically significant change in BOD at any of the monitoring sites in the early first stage of TMDL compared with the pre-TMDL stage (Fig. 4(a), Table 3). The BOD at GR-2 in the late first stage of TMDL increased compared with the pre-TMDL stage because the BOD increased during the process of moving on to the late first-stage from the early first-stage TMDL (Fig. 4(b), Table 3). At other mainstream sites, there was no BOD change in the late first stage of TMDL compared with the pre-TMDL stage (Fig. 4(b), Table 3). While GS-1 showed a trend of BOD increase compared with the pre-TMDL stage and MS-1 showed no BOD change, GS-2 at the end of Gap Stream and MS-2 at the end of Miho Stream showed the trend of a BOD decrease in the late first stage. In spite of the decrease in BOD from Miho Stream and Gap Stream, which are the tributaries that greatly influence the water quality of Daecheong Dam downstream, there was no significant change in BOD at GR-3, the site after the inflow of Gap Stream, GR-4, the site after the inflow of Miho Stream, and GR-5 located downstream of these.

Among the sites located in Daecheong Dam upstream in the second-stage TMDL, GR-1 showed no significant BOD change from the pre-TMDL stage but GR-2 showed an increased concentration (Table 3, Fig. 4(c)). As there was no BOD change between in the late first stage and in the second-stage TMDL at

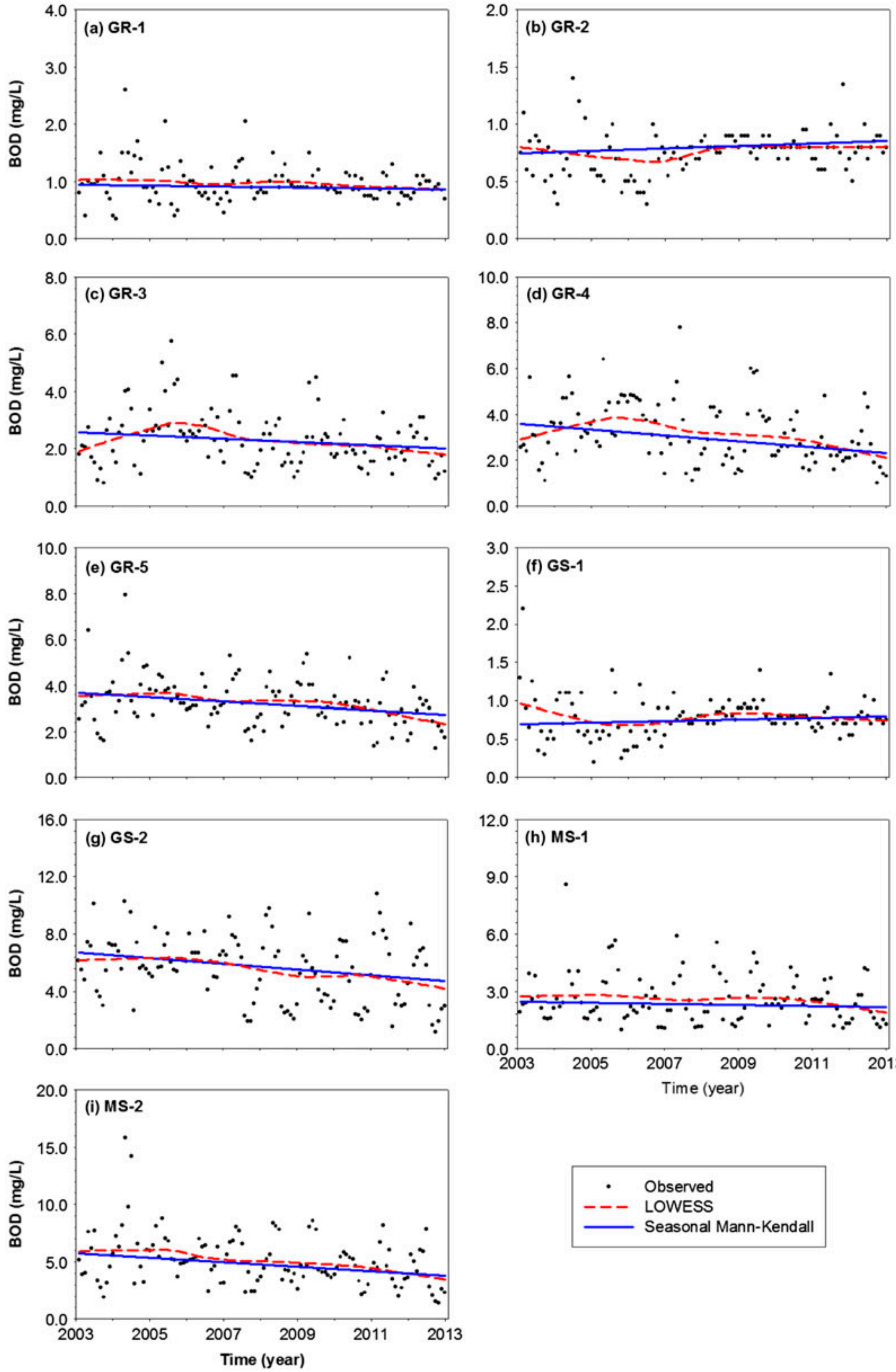

Fig. 2. Temporal trend of BOD monthly median in each site with seasonal Mann–Kendall line and LOWESS line (2003–2012).

Table 1
Seasonal Mann–Kendall test result for BOD data in Geum River during 2003–2012

Site	Range	Z	p	Decision	Trend slope (mg L^{-1} $year^{-1}$)	TMDL watershed classification*
GR-1	0.35–2.60	−1.305	0.194	NOT	−0.008	W.P.A.
GR-2	0.30–2.10	2.322	0.020	UP	0.011	W.P.A.
GR-3	0.80–5.75	−2.307	0.021	DOWN	−0.057	I.P.A
GR-4	1.00–7.80	−4.099	0.000	DOWN	−0.129	I.P.A
GR-5	1.25–7.95	−3.320	0.001	DOWN	−0.096	I.P.A
GS-1	0.20–2.20	1.368	0.174	NOT	0.010	W.P.A.
GS-2	1.15–10.80	−3.156	0.002	DOWN	−0.203	I.P.A
MS-1	1.00–8.60	−1.338	0.184	NOT	−0.029	W.P.A.
MS-2	1.40–15.85	−4.152	0.000	DOWN	−0.200	I.P.A

*I.P.A., Implementation plan area.
W.P.A., Water quality improvement plan area.

GS-2 in the downstream of Gap Stream and MS-2 in the downstream of Miho Stream, the same result as that of the late first stage was reflected. Among the mainstream sites, GR-3, GR-4, and GR-5 downstream of Daecheong Dam were all analyzed to have decreased in BOD compared with the pre-TMDL stage.

As compared to the pre-TMDL stage, water quality was improved at the second-stage TMDL in all of monitored "implementation plan area" but not in the "water quality improvement area". Water quality improvement did not appear in the early first-stage TMDL but it first appeared in the tributaries Gap Stream (GS-2) and Miho Stream (MS-2) in the late first-stage TMDL. Furthermore, it is considered that water quality improvement appeared in the second stage at mainstream sites. The comparison of BOD between the pre-TMDL stage and the second-stage TMDL showed the same result as the trend revealed in the seasonal Mann–Kendall test, which shows us that the comparison of water quality between the groups adequately reflect the overall trend (Fig. 3(c) and (d)).

3.3. Analysis of the effect of the TMDL implementation on water quality improvement

The fact that the BOD concentration in the downstream "implementation plan area" decreased though there was no BOD change or BOD increase in upstream sites (GR-2, GS-1, and MS-1) suggests that the water quality in that area has been improved. So it is considered that the TMDL program had an effect on the improvement of BOD concentration in the "implementation plan area."

On the other hand, the "water quality improvement plan area" showed no BOD change or BOD increase compared with the pre-TMDL because the management was not sufficiently carried out by evaluating only the observance of the load allocation of the final year in "water quality improvement plan area." There was a significant increase in BOD at GR-2 because pollution sources increased and load reduction plans were not sufficiently fulfilled in unit watersheds between GR-1 and GR-2 during the first stage of TMDL [3]. However, water quality at GR-2 is not considered to have deteriorated after TMDL implementation because the average BOD concentration of the last three years of 2010–2012 is still less than the water quality goal (1.0 mg/L) corresponding to a Grade I water quality standard.

Using the annual discharge load data for unit watersheds from 2003 to 2010 of NIER (National Institute of Environmental Research) [28], the accumulated BOD discharge load from upstream watersheds at each site was calculated after the analysis period was divided into three time sections: Pre-TMDL stage (2003–2005), the early first-stage TMDL (2006–2008), and the late first-stage TMDL (2009–2010). Fig. 5 shows the results. It was found that at GR-1, GR-2, GS-1, and MS-1 in the "water quality improvement plan area," the discharge load slightly decreased or partly increased in the early and late first-stage TMDL compared to other monitoring sites (Fig. 5(a), (b), (f), and (h)). On the other hand, it was shown that the discharge load at GR-3, GR-4, GR-5, GS-2, and MS-2 in the "implementation plan area" decreased in the early or late first-stage (Fig. 5(c), (d), (e), (g), and (i)).

The estimation of daily average precipitation in the Geum River basin showed that the precipitation decreased in the early first stage compared with the pre-TMDL stage and maintained a similar level in the late first stage but increased again in the second stage (Fig. 6). Therefore, it is considered that one of

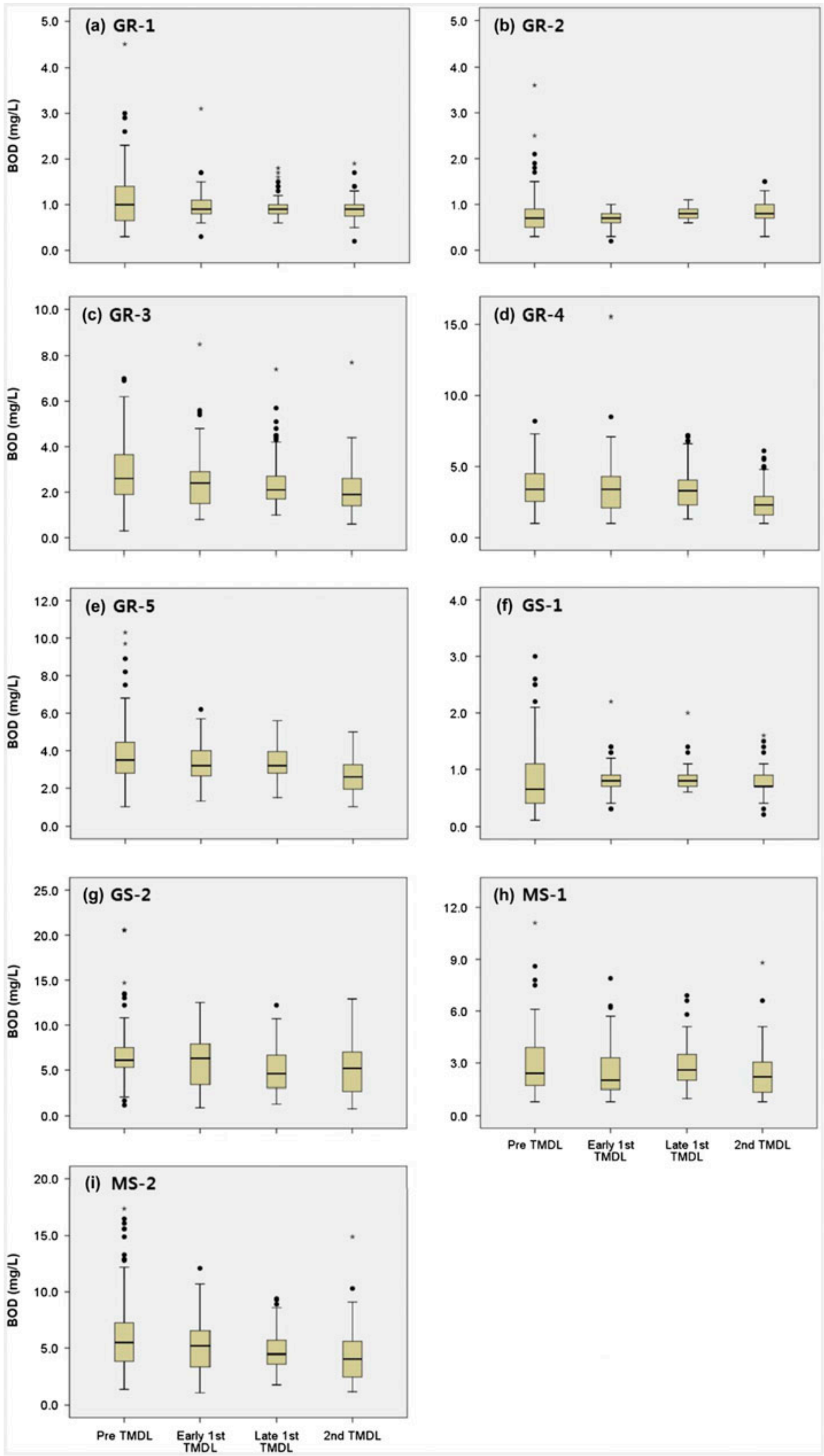

Fig. 3. Box-Whisker plots for BOD at each TMDL stage in the Geum River (● and *denote outliers with 1.5IQR and 3IQR, respectively).

Table 2
Kruskal–Wallis test result for comparison of BOD concentrations among TMDL implementation stages

Site	Pre-TMDL		Early 1st stage TMDL		Late 1st stage TMDL		2nd stage TMDL		Kruskal–Wallis test (*p*-value)
	N	Mean Rank	*N*	Mean Rank	*N*	Mean Rank	*N*	Mean Rank	
GR-1	119	212.87	107	194.15	83	198.19	83	174.37	0.122*
GR-2	119	176.06	107	172.64	83	237.73	87	223.56	0.000
GR-3	119	235.02	107	198.01	83	199.80	94	166.69	0.000
GR-4	119	226.23	107	207.44	83	207.97	87	140.55	0.000
GR-5	119	232.76	107	205.61	83	209.46	87	132.43	0.000
GS-1	118	173.24	107	195.14	83	230.52	83	194.95	0.005
GS-2	118	231.51	107	212.14	83	173.65	94	176.31	0.000
MS-1	119	211.18	107	179.50	83	219.02	83	174.85	0.013
MS-2	119	235.36	107	211.40	83	189.67	94	159.95	0.000

*The difference is not significant ($p > 0.05$).

Table 3
Mann–Whitney test result for evaluation of pairwise BOD difference among TMDL implementation stages

Site	Mann–Whitney test result (*p*-value[a])					
	Pre→Early 1st	Pre→Late 1st	Pre→2nd	Early 1st →Late 1st	Early 1st →2nd	Late 1st →2nd
GR-1	N.T.[b]	N.T.	N.T.	N.T.	N.T.	N.T.
GR-2	5.862	0.002 ↑[c]	0.017 ↑	0.000 ↑	0.011 ↑	2.370
GR-3	0.097	0.144	0.000 ↓	5.809	0.370	0.198
GR-4	1.645	1.400	0.000 ↓	5.669	0.001 ↓	0.000 ↓
GR-5	0.275	0.608	0.000 ↓	5.101	0.000 ↓	0.000 ↓
GS-1	0.581	0.011 ↑	0.447	0.089	4.806	0.062
GS-2	1.668	0.001 ↓	0.008 ↓	0.180	0.234	4.592
MS-1	0.278	4.413	0.158	0.069	4.636	0.012↓
MS-2	0.659	0.022 ↓	0.000 ↓	1.052	0.011 ↓	0.281

[a]The *p*-values from Mann–Whitney test are Bonferroni-adjusted *p*-values.
[b]N.T., means not tested.
[c]Up and down arrows indicate significant increases and decreases, respectively.

the reasons there was no BOD decrease despite the decrease in accumulated discharge load in GR-3, GR-4, and GR-5 in the early or late first stage is that the river flow decreased compared with the pre-TMDL stage. Accordingly, if the river flow conditions had been similar to those in the pre-TMDL stage, the BOD might have decreased in the early or late first stage. Unlike the mainstream, the tributaries, Gap Stream and Miho Stream showed the effect of BOD decrease in the late first stage. In Gap Stream, the amount of change in flow is relatively small because of its comparatively small watershed area, so it showed the effect of BOD decrease in the early first stage when the accumulated discharge load decreased. On the other hand, in Miho Stream, the amount of change in flow is greater than in Gap Stream because of its comparatively large watershed area even though it is a tributary. Furthermore, the average chlorophyll a concentration at the early first stage at the end of Miho Stream was highest among the four stages (13.9 mg/m^3 in pre-TMDL, 27.8 mg/m^3 in early first stage, 22.0 mg/m^3 in late first stage and 10.5 mg/m^3 in second stage). Therefore, it was considered that there was no change in BOD of the early first stage despite a decrease in accumulated discharge load at the end of Miho Stream because of the impact of autochthonous organic matter with river flow decrease on BOD. While the accumulated discharge load at the end of Miho Stream increased in late first stage, the discharge loads from midstream and downstream watersheds, which gave greater impact on BOD at the end of Miho Stream than the upstream watershed, maintained a level similar to that in the early first stage. So the effect of water quality improvement

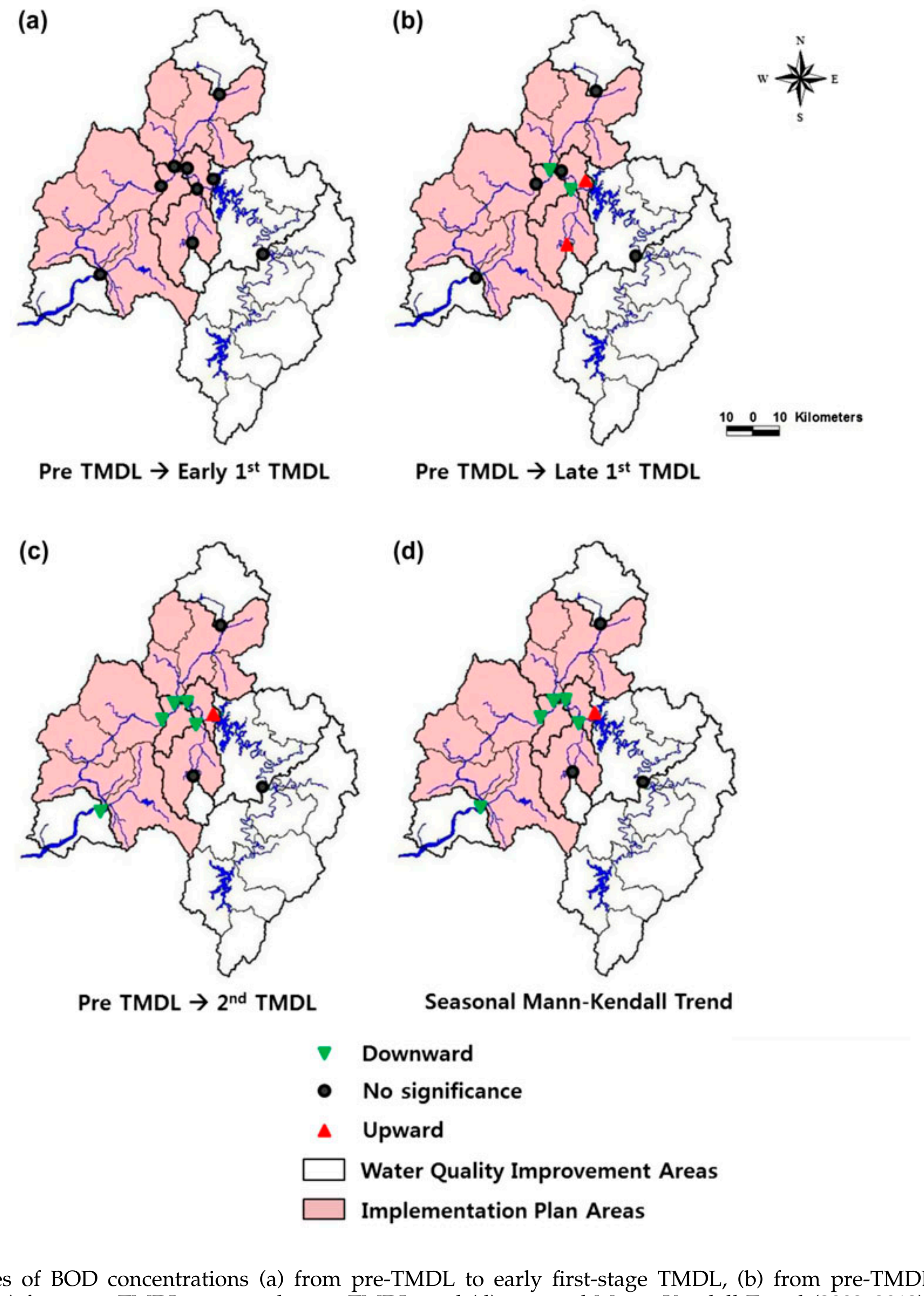

Fig. 4. Changes of BOD concentrations (a) from pre-TMDL to early first-stage TMDL, (b) from pre-TMDL to late first-stage TMDL, (c) from pre-TMDL to second-stage TMDL, and (d) seasonal Mann–Kendall Trend (2003–2012).

appeared in the late first stage when discharge load from the midstream and downstream watershed and flow conditions were similar to but the growth of algae was less than the early first stage.

In conclusion, the discharge load in the Geum River basin decreased through the implementation of the TMDL program and the effects of water quality improvement in the mainstream area, while they did not appear in a period of less river flow, did appear in the period of similar river flow. The water quality could more greatly deteriorate in decreased river flow conditions but the TMDL program is considered to have played a role of maintaining water quality. The water quality improvement effect was observed at the

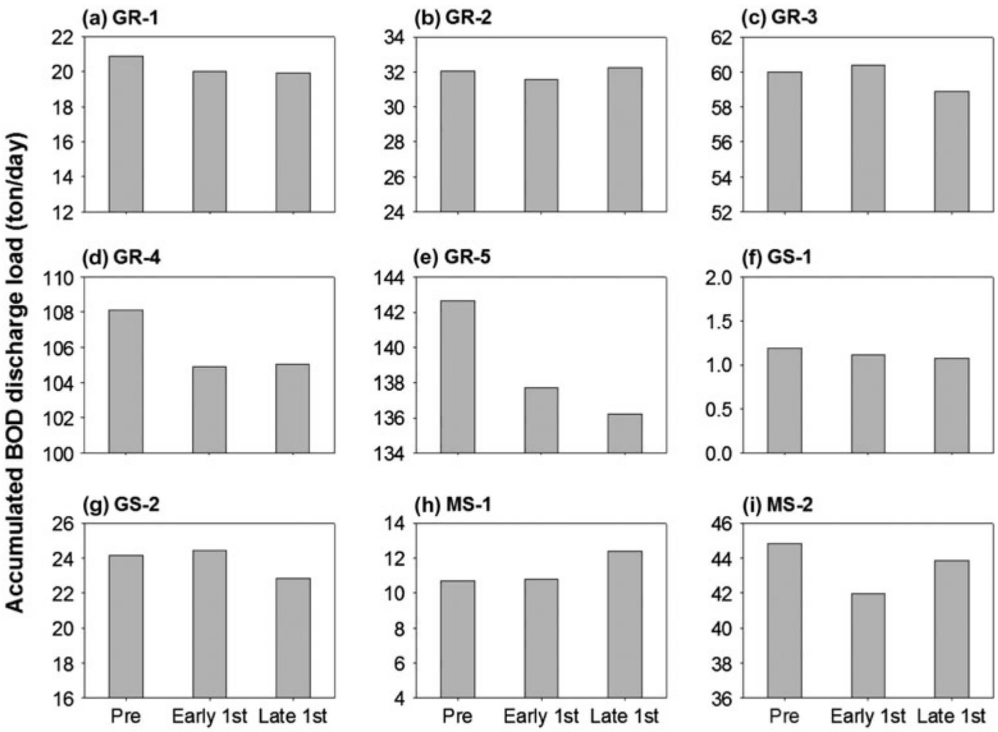

Fig. 5. Comparison of accumulated BOD discharge loads (ton/d) from upstream watershed at each monitoring site among three TMDL periods (pre-TMDL stage, Early first-stage TMDL, and Late first-stage TMDL).

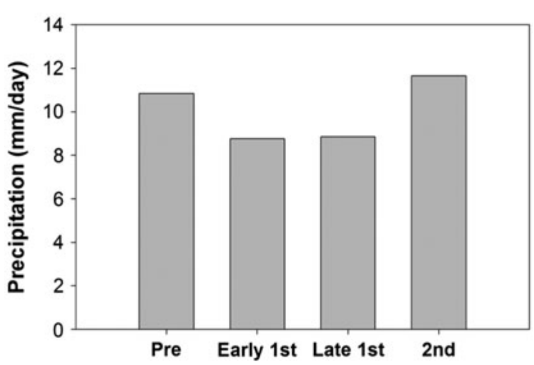

Fig. 6. Average daily precipitation (mm/d) in Geum River basin for four TMDL periods (pre-TMDL stage, Early first-stage TMDL, Late first-stage TMDL, and Second-stage TMDL).

end of the basin that includes the "implementation plan area" but at the end of the basin composed of only the "water quality improvement plan area," it was comparatively weak. As the "water quality improvement plan area" meets the water quality goals, the need for improving water quality is not urgent. However, as the discharge load in the upstream area can ultimately influence the downstream area, the discharge load in the "water quality improvement plan area" needs to be adequately controlled.

4. Conclusions

To assess the effect of the Korean TMDL program on the improvement of water quality in the Geum River basin, this study conducted an analysis using a nonparametric statistical method. The trends of long-term BOD change were analyzed, and the BOD in different time sections was compared for major monitoring sites in the Geum River basin. Using the results, the effect of the TMDL program on water quality improvement was assessed.

The result of analyzing the trend of long-term BOD changes from 2003 to 2012 showed that there was no significant change (GR-1, GS-1, and MS-1) or trend of increase (GR-2) in the "water quality improvement plan area" but there was a trend of decrease in the "implementation plan area" (GR-3, GR-4, GR-5, GS-2, and MS-2).

The period of TMDL implementation was divided into four time sections, including the pre-TMDL stage, the early first-stage TMDL, the late first-stage TMDL, and the second-stage TMDL, and the BOD in each time section was compared with the others. Compared to the pre-TMDL stage, the effect of water quality improvement did not appear in the early first stage but appeared first in the tributaries Gap Stream (GS-2) and Miho Stream (MS-2) in the late first-stage TMDL. At the mainstream sites (GR-3, GR-4, and GR-5), the effect of water quality improvement appeared only in the second stage.

As the BOD in the "implementation plan area" in the downstream decreased despite there being no BOD change or BOD increase at the upstream sites (GR-2, GS-1, MS-1), the TMDL program was considered to have effect on the improvement of BOD concentration in the "implementation plan area." However, there was either no change or a slight increase of BOD in the "water quality improvement plan area" compared to pre-TMDL levels, which may be because the management was not sufficient compared to the "implementation plan area" where the assessment on the implementation has been annually conducted.

The result of analyzing the cause of the improvement using the accumulated discharge load data from the upstream of each site and the average precipitation showed that the discharge load in the "implementation plan area" decreased by the implementation of TMDL program and the effect of TMDL on water quality improvement in the mainstream areas appeared well in the period with the similar river flow conditions as the pre-TMDL stage. Though there was no concentration decrease in the period of decreased river flow compared with the pre-TMDL stage, the TMDL program is considered to have played the role of restraining the concentration increase.

In conclusion, the TMDL program is considered to have played the role of improving the water quality in the "implementation plan area" and strict management is considered necessary to achieve a continuous improvement in water quality also in future TMDL implementation periods. The "water quality improvement plan area" is already meeting the water quality goal, but considering its effect on the downstream areas, management should be undertaken at the least to prevent water quality from further deteriorating.

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