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Evaluation of Applicability of the ESTIMATOR Model for the Analysis of Nutrient Load Characteristics

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Abstract

It has been well-known that the Nonpoint Source (NPS) pollutions are the primary contributors to water quality degradation in the receiving water bodies as well as the Point Source (PS) pollutions. To develop an effective management practice for water quality improvement, pollutant loads must be first estimated. In many studies, the Numeric Integration (NI) method has been used because of its ease of application, irrespective of the total number of samples collected for each storm event. Thus, there have been needs for more accurate pollutant load estimation with a limited number of water quality samples. In this study, NI method and regression method using the USGS ESTIMATOR model were comparatively used to calculate the pollutant loads for the Wolgokri watershed, Gangwon Province. The NO_3-N, T-N, and T-P loads using NI method and ESTIMATOR model were 13.85 kg/ha, 45.92 kg/ha, and 1.887 kg/ha, and 11.93 kg/ha, 43.20 kg/ha, and 1.650 kg/ha, respectively. The estimated loads using ESTIMATOR model were lower than those using NI method by 86%, 94%, and 87%. These discrepancies in the estimated loads using a different load estimation method could be explained in that the total number of samples were not sufficient enough for NI method. Thus, ESTIMATOR model is recommended for the frequently stream discharge and less frequently measured water quality data.

Keywords : Pollutant loads, Numeric Integration, ESTIMATOR

I. Introduction

Various pollutants generated from the industrialization process have been causing water quality degradation in the receiving water bodies. The upstream areas of the Han River watershed play an important role in supplying the drinking water resources to the Seoul metropolitan area. However, the water quality of the main river and its tributaries has been deteriorated because of the Point Source (PS) and the NonPoint Source (NPS) pollution discharges into the stream (Choi et al., 1999; Choi, 2003). To improve the water quality of the river, many efforts have been made

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by the government to reduce pollutant loads from the PS pollution because it is relatively easy to be controled compared with the spatially diffused NPS pollution. As a result, the water quality in the Han River was improved to some degree, which was due to the fact that the contribution of the NPS pollution in water quality degradation was not negligible. Thus, the water quality of the Han River could not be improved by controlling only the PS pollution. The NPS pollution is a spatially and temporarily diffused and runoff-driven pollution (Choi, 1997; Magette et al., 1989). Therefore, the management technique for controlling the NPS pollution has been needed to improve the water quality of the stream (Choi, 1997). To develop efficient management techniques, it is imperative to estimate the time, place, and amount of pollutant loads are generated, which can be done by multiplying the representative pollutant concentration by discharge measured at a higher frequency. Flow can be measured at a much higher frequency because it is relatively easy and cheap compared with the water quality samplings and their analysis. Thus, a practical method is needed to estimate pollutant loads with frequently discharge and less frequently measured water quality data. The "Numeric Integration" (NI) method has been widely used for pollutant load estimation in many studies because of its ease of application (Cohn et al., 1989, 1992), NI method is efficient in evaluating pollutant loads, if the frequency of a water sampling is high enough and water quality samples are properly collected during the rainfall events (Haggard, et al., 2003). Roman-Mas et al. (1994) suggested that a sampling frequency sufficient to obtain 20 samples during one single storm period is necessary to obtain load estimates using NI method with an error less than a 5% of difference. Yaksich and Verhoff (1983) suggested 12 samples over the hydrograph. However, it was nearly impossible to collect 12~20 water samples for each rainfall event because of the cost for water sampling and analysis. Therefore, a better method than NI method for pollutant load estimation is needed. A regression analysis method such as the USGS regression model can be suggested for pollutant load calculation to estimate the "missing" concentration of the corresponding discharge observed at times when no water quality samples were taken (Haggard et al., 2003). Although the regression analysis method has advantages over NI method, very little efforts were made using the regression method for more accurate pollutant load estimation in Korea.

The objectives of this study are to: (1) analyze pollutant characteristics of the stream and (2) evaluate applicability of the USGS seven parameter regression model called ESTIMATOR for more accurate pollutant load estimation.

II. Methodology

1. Study Watershed

In this study, the Wolgokri watershed located in the upstream areas of the Han River, Chuncheon, Gangwon Province, was selected with 3.41 km^2 in size and 12.56 km in length for the entire reach segments. The population density of the area was only 50 people/km^2 with 65 household, a nursery, and a jade mine, and no big

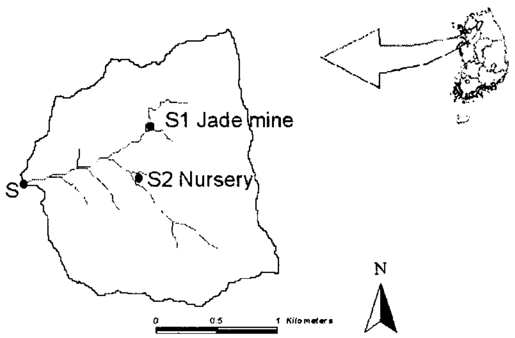

Fig. 1 Location of the Wolgokri watershed

pollutant discharging industry facilities were established (Fig. 1).

2. Analysis of Precipitation

Precipitation information from April 2004 to March 2005 for the Wolgokri watershed was obtained from the Korea Meteorological Administration to analyze the relationship between precipitation and amounts of stream discharge and to evaluate watershed hydrologic responses to the precipitation.

3. Stream Discharge Measurement and Water Quality Analysis

The flow measurement equipment, Orphimedes, was installed to measure the height of water table for discharge estimation at the outlet of the Wolgokri watershed (S in Fig. 1) from April 2004 to March 2005. The water table were measured for every 5 minutes during the rainfall events and every 30 minutes during the dry days.

A total of 8 water quality samples were collected at the same point where the water table were measured during the same period. 3~4 water samples for each rainfall event and one sample at least every two weeks during the dry days were collected, and were analyzed for NO_3−N, T−N, and T−P based on the method specified in the "Standard Method for Water Quality Analysis" by the Ministry of Environment. The Flow Weighted Mean Concentrations (FWMC) were calculated to analyze the pollutant characteristics in the stream.

4. Pollutant Load Estimation

1) NI Method

NI method is only satisfactory if the sampling frequency is relatively high as the order of 100 samples or more per year, and sufficiently frequent that all major runoff events are well-sampled (Haggard, et al., 2003). NI method estimates the pollutant load by dividing the entire period by the number of samples and multiplying the discharge by representative water quality sample concentration for each flow section. Eq. 1 shows NI method for load estimation.

$$Load = \sum_{i=1}^{n} C_i q_i t_i \quad \cdots\cdots (1)$$

Where C_i is the concentration in the ith sample, q_i is the corresponding discharge, and t_i is the time interval represented by the ith sample given by 1/2 $(t_{i+1}-t_{i-1})$.

Fig. 2 shows the discharge in time steps and characteristics of the concentrations for the Wolgokri watershed in June 2004. The concentration of NO_3−N, T−N, and T−P is representative value for each time interval, specified as I, II, and III, and the loads were estimated as the sum of discharge for each interval which was multiplied by representative concentration. But if

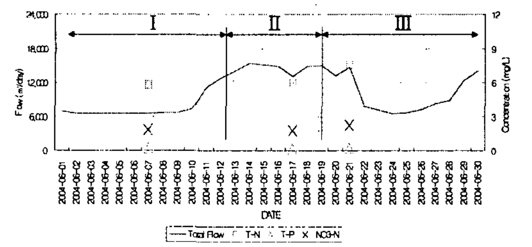

Fig. 2 Stream flow and representative water quality data for June 2004

water samples were not taken sufficiently, the pollutant loads could be differently estimated from the true value, because the true concentration collected before and after precipitation occurrence would differ from the representative concentrations in the intervals collected in the rainy event (Shin et al., 2005). However, the pollutant loads by NI method were simply estimated using the measured concentrations and daily flow because it could not infer the "missing" daily concentrations in Fig. 2.

Thus, the pollutant loads using NI method could be either overestimated or underestimated compared with the true values. If the water quality samples were not taken frequently enough, a better method is needed for more accurate load estimation rather than using NI method with less frequently measured water quality data.

2) The USGS Seven Parameter Model, ESTIMATOR

Because of the defects in NI method in many cases, Cohn et al. (1992) has developed a regression based model called ESTIMATOR to evaluate the pollutant loads using the relationship between discharge and measured water samples. Concentration in the stream has temporal inertia, which, at a given spot in the day is related to the concentration of the day before in the same place, more weakly related to the concentration two days ago, and more strongly related to the flux of an hour before (Cohn et al., 1992). ESTIMATOR model also called USGS Seven Parameter Model infers the missing daily concentrations. Eq 2 shows ESTIMATOR model.

$$\ln[C] = \beta_o + \beta_1 \ln\left(\frac{Q}{\tilde{Q}}\right) + \beta_2 \ln\left(\frac{Q}{\tilde{Q}}\right)^2 + \beta_3 \ln[T - \tilde{T}] + \beta_4 \ln[T - \tilde{T}]^2 + \beta_5 \sin[2\pi T] + \beta_6 \cos[2\pi T] + \varepsilon \quad \cdots\cdots (2)$$

Where ln[ ] means the natural logarithm of the parameter, C is pollutant concentration, Q is discharge, and T is time measured in years. The errors denoted by ε are assumed to be independent and normally distributed with a mean value of 0 and variance σ^2. β_0 through β_6 are the seven parameters which must be estimated by regression, and $\tilde{Q}$ and $\tilde{T}$ are "centering variables", which simplify the mathematics, but have no effect on the load estimate. ESTIMATOR model analyzes the relationship among *ln[C]*, *ln[Q]*, *ln[Q²]*, time, *time²*, and the seasonal effect to make the regression equation and total loads at daily time steps with discharge and less frequently sampled water quality data, as an input to the model. It calculates the model seven parameter coefficients, daily and monthly pollutant loads using the input data. ESTIMATOR model has advantages over NI method in that it infers the "missing" daily concentrations from the relationship between measured daily flow and measured water quality data.

3) Pollutant Load Estimation using NI Method and ESTIMATOR

As described above, ESTIMATOR model has advantages over NI method in estimating the pollutant loads. Both NI method and ESTIMATOR model were utilized in this study to evaluate load estimation. The pollutant loads using ESTIMATOR model were compared with those calculated using NI method, applicability was then evaluated.

Ⅲ. Result and Discussion

1. Stream Flow Characteristics of the Wolgokri Watershed

From April 2004 to March 2005, a precipitation of 1,365.9 mm occurred, which was higher than the average precipitation in Korea. The yearly stream discharge for the Wolgokri watershed is 3,322,192 m^3, and the stream discharge from June 2004 to September 2004 was 2,500,000 m^3, which was 75% of the total stream discharge of the year. The stream discharge ratio obtained by dividing the total stream discharge by the monthly stream discharge for July was approximately 44.4%. This was because of the torrential rainfall event of 532.3 mm. Table 1 shows the monthly rainfall, stream flow, and stream flow ratio for the watershed under investigation, representing the hydrologic characteristics of the Wolgokri watershed is primarily affected by the dry days.

2. Pollutant Characteristics of the Wolgokri Watershed

The maximum, minimum, and FWMC values for NO_3-N, T-N, and T-P for the Wolgokri watershed were calculated and shown in Table 2. As the nature of the NPS pollution is runoff-driven, the FWMC values for NO_3-N, T-N, and T-P were highly affected by the rainfall intensity rather than the total amount of rainfall occurred in a day. The maximum daily precipitation of 142.5 mm occurred on July 12, 2004. However, the maximum values for NO_3-N and T-N were contributed by a rainfall event of 60.5 mm occurred on August 17, 2004. This was because of a much higher rainfall of 41.5 mm/h on August 17, 2004. The maximum concentration value for

Table 1 Monthly rainfall, stream flow, and stream flow ratio of the Wolgokri watershed

Month	Precipitation (mm)	Stream discharge (m^3)	Stream discharge ratio (%)
Apr. 2004	59.7	45,639	1.4
May 2004	135.0	73,044	2.2
June 2004	105.7	267,663	8.2
July 2004	532.3	1,457,272	44.4
Aug. 2004	215.6	503,953	15.4
Sep. 2004	193.6	326,817	10.0
Oct. 2004	1.8	307,170	9.4
Nov. 2004	43.0	66,342	2.0
Dec. 2004	27.2	58,983	1.8
Jan. 2005	3.7	45,533	1.4
Feb. 2005	30.8	65,318	1.8
Mar. 2005	17.5	104,458	2.0
Total	1,365.9	3,322,192	100

Table 2 Selected statistics of NO_3-N, T-N, and T-P concentrations in the Wolgokri watershed

(unit: mg/L)

Statistics \ Pollutants	NO_3-N	T-N	T-P
Maximum concentration	4.97	16.56	1.280
Minimum concentration	0.15	1.35	0.002
FWMC	1.41	4.70	0.187

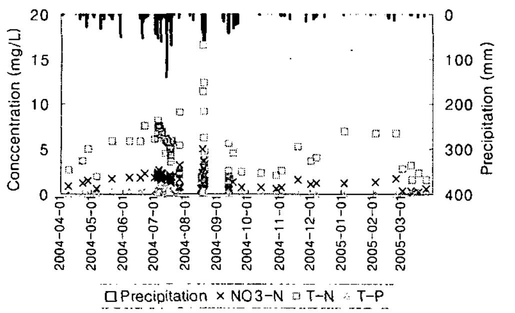

Fig. 3 Characteristics of the NO_3-N, T-N and T-P of concentrations with respect to precipitation and time

T−P occurred on July 12, 2004. Fig. 3 shows characteristics of NO_3−N, T−N and T−P concentration values with respect to precipitation and time.

The FWMC for NO_3−N, T−N, and T−P were 1.41 mg/L, 4.70 mg/L, and 0.187 mg/L, respectively, where the FWMC for T−N was more than three times greater than that for NO_3−N, indicating that the organic N content of T−N was very high. This was because the organic matters from the paddy and farm fields were washed into the stream with direct runoff during the rainy days. Another possibility for a greater amount of the organic N content in the stream during the dry season is a direct incharge of algae inhabiting in the stream bed.

3. Pollutant Load Estimation using NI Method and ESTIMATOR

The annual pollutant loads of NO_3−N, T−N, and T−P estimated using NI method for the Wolgokri watershed were 13.85 kg/ha, 45.92 kg/ha, and 1.887 kg/ha, respectively. NO_3−N, T−N, and T−P loads contributed by the rainfall occurred from May to September were 84%, 82%, and 86% of total loads. This indicates that the pollutant load characteristics for the Wolgokri watershed were largely affected by the torrential rainfall.

ESTIMATOR model was used to estimate the pollutant loads for the Wolgokri watershed, and to determine the relationship between concentration and daily flow based on the days when the samples were taken and analyzed. The seven parameter coefficients ($\beta_0 \sim \beta_6$ centering variables), $\tilde{Q}$, and $\tilde{T}$ in Eq. 2 for log−transformed NO_3−N, T−N, and T−P were estimated in Table 3.

The estimated log−transformed concentrations of the pollutants had to be accordingly back−transformed, then multiplied by the mean discharge (Cohn et al., 1992). However, when these back−transformed values were used to calculate the average daily loads or the total annual loads, the results were biased to be low (Ferguson, 1986; Koch and Smillie, 1986; Cohn et al., 1989, 1992). In order to avoid such a bias,

Table 3 Coefficients of ESTIMATOR Model

	β_0	β_1	β_2	β_3	β_4	β_5	β_6	$\tilde{Q}$	$\tilde{T}$
$ln\|NO_3$-N|	-0.2764	-0.0411	0.0359	-0.0190	-0.0060	0.6719	-0.0975	2.315	0.889
ln|T-N|	1.2216	-0.0114	0.020	-0.0152	-0.0161	0.0760	0.0579	2.315	0.889
ln|T-P|	-2.6510	-0.0346	-0.0318	0.0184	-0.0007	1.0025	0.1125	2.315	0.889

a value needed to be added to each estimated log-concentration before it was back-transformed, and ESTIMATOR model revised the bias with a minimum variance unbiased estimator (MVUE) proposed by Cohn et al. (1989).

Fig. 4 illustrates the values of the measured T-N concentration and back-transformed T-N concentration from April 2004 to March 2005. Although there are biases in the back-transformed T-N concentration in Fig. 4, the seasonal patterns in the estimated T-N concentration can be noticed. The bias corrected daily concentration values were multiplied by the daily flow to obtain the daily pollutant loads in ESTIMATOR model. In July, 2004, 38 water quality samples were taken, and the variations in the measured T-N concentration values were reflected in the estimated daily T-N concentration in July 2004 using ESTIMATOR model.

When estimating the pollutant loads using NI method, only the pollutant concentration values from the water samples were used for the entire period. However, ESTIMATOR model first estimated the daily pollutant concentration based on the daily flow and less frequently measured

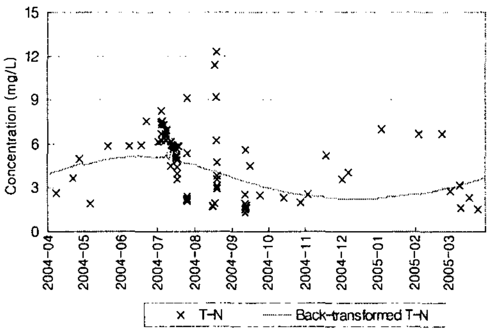

Fig. 4 Values of the measured T-N concentration and back-transformed concentration from ESTIMATOR model

Table 4 Comparison of the pollutant loads estimated by using NI and ESTIMATOR model

(unit: kg/ha)

Month	NI method			ESTIMATOR model		
	NO_3-N	T-N	T-P	NO_3-N	T-N	T-P
Apr-04	0.16	0.50	0.074	0.18	0.93	0.028
May-04	0.33	1.07	0.050	0.95	4.26	0.159
June-04	1.60	5.28	0.201	1.73	5.29	0.258
July-04	7.29	23.07	0.579	5.81	18.95	0.798
Aug-04	2.03	6.70	0.762	1.02	4.04	0.166
Sep-04	0.77	2.73	0.097	0.56	3.16	0.105
Oct-04	0.61	2.04	0.066	0.64	3.08	0.073
Nov-04	0.26	0.86	0.007	0.26	0.61	0.014
Dec-04	0.24	0.79	0.008	0.22	0.54	0.007
Jan-05	0.16	0.93	0.004	0.16	0.42	0.005
Feb-05	0.29	1.28	0.004	0.29	0.66	0.010
Mar-05	0.11	0.67	0.035	0.11	1.26	0.027
Total	13.85	45.92	1.887	11.93	43.20	1.650

concentration values as the true values. Thus, ESTIMATOR model was used to evaluate the "missing" concentration in the dry season.

The estimated loads of NO_3-N, T-N, and T-P using ESTIMATOR model were 11.93 kg/ha, and 43.20 kg/ha, 1.65 kg/ha, respectively. which were lower than those estimated by using NI method by 86%, 94%, and 87%, respectively (Table 4), proving that NI method overestimated the pollutant loads. The total number of water samples collected were not sufficient enough for NI method to be estimated, as suggested by Roman-mas et al. (1994).

Ⅳ. Summary

In this study, the stream flow, pollutant concentration, and pollutant load characteristics were analyzed for the Wolgokri watershed. The

Numeric Integration (NI) method and the USGS Seven Parameter(ESTIMATOR) model were utilized comparatively to estimate the pollutant loads using the measured flow and water quality data. The results obtained from the study were summarized as follows:

1. The yearly stream discharge from the Wolgokri watershed from April 2004 to March 2005 was 3,322,192 m^3 and that from June to September was 2,500,000 m^3, which is 75% of the yearly stream discharge.

2. Concentration values of NO_3−N, T−N, and T−P were in the range of 0.15~4.97 mg/L, 1.3 5~16.56 mg/L, and 0.002~1.280 mg/L and the Flow Weighted Mean Concentrations (FWMC) values were 1.41 mg/L, 4.70 mg/L, and 0.187 mg/L, respectively. The FWMC value of T−N was over three times greater than that of NO_3−N, indicating that a significant amount of organic N were introduced from the watershed. Also, a direct incharge of algae inhabiting in the stream was also responsible for the discrepancy.

3. The NO_3−N, T−N, and T−P loads using NI method and ESTIMATOR model were 13.85 kg/ha, 45.92 kg/ha, 1.887 kg/ha, and 11.93 kg/ha, 43.20 kg/ha, 1.650 kg/ha, respectively. The loads estimated by ESTIMATOR model are smaller than those by NI method. It was assessed that the selected NPS pollutant loads by ESTIMATOR are equally or better reliable considering that ESTIMATOR reflects missing water quality based on the relationship between flow rate and concentration. However, it was also suggested that more in−depth research is necessary to validate the applicability of ESTIMATOR model by comparing its predicted values with the measured values through long−term monitoring and analysis.

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