Pollutant Flux Releases During Summer Monsoon Period based on Hydrological Modeling in Two Forested Watersheds, Soyang Lake

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Abstract

In this study, specific pollutant releases during the Asian monsoon season were estimated and the information was applied to the non-point pollutant sources management from two forested watersheds of the Soyang Lake. The two watersheds are part of the 2,703 km^2 Soyang Lake watershed in the northern region of the Han River. The outlets of the two watersheds were respectively analyzed for continuous water quality concentration and for discharge during various single rainfall events. Statistical power function methods are utilized to compare stream discharge and pollutant flux release during the study period. Based on the monitoring data during the study period, the specific load flux method using simulated discharge was conducted and validated in the two watersheds. The model predictions corresponded well with the measured and calculated pollutant releases. The modeling approach taken in this study was found to be applicable for the two forested watersheds.

Keywords: Rainy season, Pollutant flux release, Load rating curve, Hydrological modeling, Soyang Lake

1. Introduction

Since the pioneering research that involved estimating the sediment transport rate for predicting the life span of a dam in a river, various rating curves have been used to estimate pollutant release from a watershed.[1,2] The reason we need an empirical relationship is because most of the rivers have not been gauged or stream flow and suspended sediment flux data for these rivers is not readily available. Vogel et al.[3] reported that the amount of pollutant constituents including sediments from river flows depends on the form of the relationship between the effective river discharge and the pollutant flux as well as on the form of the frequency distribution of the river discharges based on over 300 journal articles. Cooper et al.[4] examined how opportunistic sampling in addition to weekly sampling of dissolved organic matter affected regression and ratio based on estimates of loading. Furthermore, Christiansen et al.[5] used a real time water quality monitoring and regression model to estimate the constituent concentration, loads, and yields in the Little Arkansas River in South Central Kansas. The study revealed that these indicators yielded errors greater than 25 percent. However, many of these studies have been carried out either in watersheds in

terms of sustainable urbanized effects on surface water quality[6-9] or on land use effects with an emphasis on the observation of stream flow.[10-12] Furthermore, the study of a large scale (>100 km^2) and non-impacted watershed for controlling a Non Point Source (NPS) has seldom been analyzed,[13] despite the long-term studies carried out in these fields. The process of determining the daily pollutants load that runs into a lake is both challenging and complex. Many lakes receive a high portion of their pollutant loading from non-point sources, which are highly variable and are difficult to quantify. Lakes manifest pollutant loading on a seasonal scale, not on a daily basis. The loading during the winter months may have little effect on summer algal densities. While non-point pollutant loads tend to flow out with extreme rainfall, forming a watershed, little information is available on how to control the flow effectively.

In this study, field monitoring in undisturbed watersheds are examined and an evaluation is performed of the characteristics of specific pollutant release generating flow discharge by using the hydrological modeling approach. The study consists of two stages. In the first stage, the hydrological processes for stream discharge were estimated by comparing the observed data. The second stage of this work was presented with a model validation to estimate the specific pollutant release based on the calculated flow discharge during the rainy season. Originally, this study was designed on the basis of the long-term rainfall phenomenon

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over 30 years in the two non-impacted watersheds of Soyang Lake.

2. Method and Tools

2.1. Watershed Description

The Soyang reservoir is an artificial dam located about 100 km to the east of Seoul. The reservoir is the deepest and largest reservoir in Korea; it was constructed on the North Han River in 1973 for flood control of down stream areas and water supply for Chunchon city including metropolitan cities. The hydraulic retention time is the longest (0.7 year) in Korea because the outflow rate is small, considering the reservoir's large volume (Table 1). The water depth varies from about 110 m on the outer part of the Dam to 30 m on the inner part and about 42 m on average. The Watershed of Soyang Lake has two main sub-watersheds: the Inbuk River (578 km^2 watershed area), of which part of the watershed is included in the north Kangwon province, Democratic People's Republic of Korea (North Korea), and the Naelin River (1,075 km^2 watershed area). The elevations above sea level ranged from 215 m to 1,348 m for the Inbuk River watershed and from 201 m to 1,567 m for the Naelin River watershed, which rapidly changed to steep slopes.

Table 1. Hydrological characteristics and land use in watershed of Soyang reservoir

Surface area (km^2)	70
Shape	Dendritic
Circulation type	Warm monomitic
Trophic state	Meso-eutrophic
Water capacity (m^3)	2.9×10^9
Yearly average inflow (m^3/s)	55.50
Designed flood level (EL. m)	198.0
Maximum depth (m)	110
Mean depth (m)	42
Length of dam (m)	530.0
Hydraulic residence time (yr)	0.7
Length of main axis (km)	60
Drainage area (km)	2,703
Forest and mountainous area (km^2)	2,411
Agricultural area (km^2)	144.2
Paddy area in drainage basin (km^2)	141.4
Urban area (km^2)	6.4

The two watersheds consist of over 60% of the total watershed area. The water quality conditions in the lake maintain an oligotrophic to mesotrophic state. The water blooms with cyanobacteria, mainly *Anabaena spp.*, which has also been annually reported in some tributaries of the lake.[14,15]

2.2. Methods

Data obtained during the rainy season over the past 2 years, from 2004 to 2005, for a rating curve with a long term water quality were analyzed when available. The annual mean precipitations of the Inbuk River watershed and the Naelin River watershed were 1,083 and 1,118 mm, respectively, and over

80% of the annual mean rainfalls in the two main watersheds of the Soyang River were concentrated in heavy showers that occurred several times during the rainy season from May to September. This rainfall phenomenon results in a deposit of pollutive components during dry seasons.

The higher rainfall that occurs from May to September will mobilize the build-up of contaminants, creating a larger discharge. The basic water quality parameters such as Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), SS, Total Nitrogen (T-N), and Total Phosphorus (T-P) were chosen for the derivation of the flux rating curve, because they are major indicators for the estimation of organic, turbid, and nutritive conditions, respectively. The samplings in the two watersheds are concentrated in single rainfall events, because the samples in the period tend to be sufficient to characterize the seasonal pollutant load. A limited number of samples are also monitored during low discharge periods to allow the pollutant load with a baseflow. This method assumes that river flows vary significantly and that concentrations increase with flow during storm run-off events. Based on the observed data, experimental relations such as the pollutant regression curve are applied. The most commonly used basic pollutant rating curve is the power function:[16]

$$C = aQ^b \tag{1}$$

where C is the concentration (mg/L), Q is the discharge (m^3/s), and a and b are the regression coefficients. Large scale watershed models for NPS lack a variable source area hydrology routine for stream flow, and are unable to identify spatially dynamic runoff. In this regard, hydrological efforts to evaluate stream discharge will be described in the next session.

An important issue for the water resource manager is the determination of a specific pollution flux on a daily basis. If continuous concentration and flow measurements could be made for the entire study period, the mass flux could be estimated by multiplying by the appropriate unit conversion. For these comparisons, load (kg/day) L, which is integrated over the study period and given as a day of observations, is defined by the following Eq. (2);

$$L = \int_{t=1}^{Day} C_t \cdot Q_t \cdot F dt \tag{2}$$

where C is the concentration (mg/L), Q is the discharge (m^3/s), and F is the conversion factor. In order to summarize the specific load, Eq. (3) uses a byproduct of load estimates, normalizing them to the monitored watershed area, A (km^2). The specific pollutant flux which is a modified power function equation was used as follows:

$$\frac{Q}{A} = \frac{L}{A} \tag{3}$$

In Eq. (3), Q is not provided as a continuous measurement

due to various reasons including cost restrictions. In order to capture the seasonal variation of a specific pollutant release during the rainy period, continuous samples of single rainfall events in two watersheds of the Soyang Lake were corrected and validated considering the antecedent rainfall, the rainfall intensity, and the term of the sampling periods. In order to assess the difference in efficiency between the observed and the predicted rating curve, the Root Mean Square Error (RMSE) method was used according to the following formula:

$$RMSE = \sqrt{\frac{1}{n}\sum\left(\frac{measured - calculated}{measured}\right)^2} \quad (4)$$

where n: the number of observations.

2.3. Hydrological Modeling for Stream Flow

In an ungauged watershed, the first step for estimating NPS is to generate stream discharge. The TOPMODEL selected for this study is a rainfall-runoff model in which distributed predictions of watershed responses are made based on the hydrological similarity of any point in a watershed. TOPMODEL is a topographically based hydrological model which reproduces the hydrological behavior of watersheds in a semi-distributed way.[17-19] Since a detailed explanation of TOPMODEL has been reported elsewhere, only a brief description will be provided as follows: The simplicity of TOPMODEL is in the topographic index, the $\ln(\alpha / \tan\beta)$ index, as an index of hydrological similarity derived from the digital elevation models as shown in Fig. 1, where α is the cumulative drainage though a point, and the hydraulic gradient of the saturated zone can be approximated by the local surface topographic slope, $\tan\beta$,

$$q_i = T_0 \tan\beta_i e^{-S_i/m} \quad (5)$$

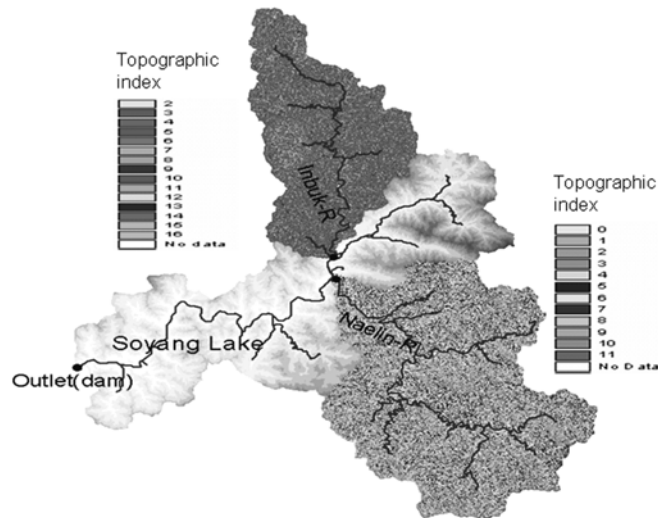where T_0 represents the local value of the saturated transmissivity of the soil. β_i is the slope angle, S_i is the local storage deficit, and m is the change in transmissivity with depth. The local deficit is defined as:

$$S_i = \overline{S} + m[A - \ln(\alpha / \tan\beta)_i] \quad (6)$$

where $\overline{S}$ is the average storage deficit and A is the local average area of $\ln(\alpha / \tan\beta)$.

The vertical drainage q_v from the unsaturated store at any point i is controlled by the local saturated zone deficit S_i, which depends on the depth of the local water table:

$$q_v = \frac{S_{UZ}}{S_i t_d} \quad (7)$$

Where S_{UZ} is the storage in the unsaturated zone and t_d is a time delay constant. The evaporation for the TOPMODEL description is allowed at the full potential rate for water draining freely in the unsaturated zone and for predicted areas of surface saturation. When the gravity drainage zone is exhausted, actual evapotranspiration E_a as a function of potential evaporation E_p may continue to deplete the root zone store at the rate Ea given by:

$$E_a = E_P\left(1 - \frac{S_{rz}}{S_{r\max}}\right) \quad (8)$$

where S_{rz} and $S_{r\max}$ are the root zone storage deficit and the maximum allowable storage deficit, respectively. The watershed flux of water entering the water table, Q_v is calculated by summing the q_v of each topographic index class:

$$Q_V = \sum_i q_V A_i \quad (9)$$

The output from the saturated store is represented by the baseflow term, Q_b which can be calculated using a subsurface storage deficit-discharge function of the form:

$$Q_b = Q_0 e^{-\overline{S}/m} \quad (10)$$

where $Q_0 = Ae^{-\overline{\lambda}}$ is the discharge in the case when $\overline{S}$ is zero.

3. Results and Discussion

The single event rainfall amount for two watersheds ranged from 24 mm to 198 mm. The fitted relationships between specific discharge and pollutant flux releases using Eq. 3 are summarized in Table 2. Most of the regressions for the two watersheds during the rainy season that are given in Table 2 have positive values. This may be due to the discharge through the wash off process in which rainfall results in pollutant deposition during the light rainy season from January to May or October to

Fig. 1. Spatial distribution of topographic index in two catchments.

December. In certain cases, the regression values were high during the consistently short sampling period term in the cases of the 2nd and 3rd rainfall events or the same monthly data in the cases of the 3rd and 4th rainfall events in the Inbuk River watershed.[20] It has been reported in a number of studies that runoff quality during the initial storm of the season has higher pollutant concentrations than in later rainfall events. Lee et al.[21] defined this phenomenon as seasonal first flush. Also, their study reported that peak pollutant concentrations tend to precede peak runoff flow rates and thus result in the runoff of a greater pollutant release during early storm stages. However, in this study, a seasonal first flush phenomenon of specific pollutant fluxes in two watersheds did not occur for selected indicators. This phenomenon of pollutant release is important in the management of the pollutant load from the diffused watershed. As a higher pollutant mass load is delivered during the rainy season, controlling the entire pollutant load during the rainy season will be more effective than trying to treat the pollutant mass of all storms throughout the season. Because the months of July and August usually have the greatest rainfall, the bulk of the discharge in the two river watersheds is expected to occur during the rainy season. Conversely, the long dry period from April or May to October allows contaminants to build up in these areas.

The watershed-scale hydrological model for pollutant flux release could assist environmental managers to focus their limited discharge data set. In order to estimate and validate pollutant load flux release, two single rainfall events were selected for the Inbuk River and the Naelin River respectively. Fig. 2 illustrates the observed pollutant flux using Eq. (3) versus the calculated pollutant flux from the predicted discharge using distributed TOPMODEL in two rivers and demonstrates the close relationship of over 80% of all the selected parameters. This modeling approach allows seasonal pollutant fluxes to be produced effectively, when the discharges in the insufficient rating curve areas are generated well. Fentie et al.[22] reported that the relative differences between total suspended sediment loads using rating curves varied depending on the scale of the watershed areas. However, further data sets are required to confirm the significant relationship between them. The magnitude of RMSE values depends on the variances between a true discharge and pollutant fluxes distribution. The values of five indicators including discharge were 0.14 for the Inbuk River and 1.58 for the Naelin River, which implies lower RMSEs. The calculated results indicate that the pollutant releases that control discharge at the large scale non-urbanized forest area are well captured by the hydrological-link model. This approach can also simulate the trend as well as the variability in the daily or monthly pollutant release at any point of outlet of the two watersheds during the rainy season.

4. Conclusions

The rainfall phenomenon is an important factor in the control of pollutant load from diffuse areas. The procedure demonstrated in this study is a frame approach for simulating specific pollutant flux releases in two forested watersheds where detailed river flow data is not available during the rainy season. Extensive water sampling data in two forested watersheds was collected to derive specific pollutant flux regression curves during various rainfall events. For simulating a specific pollutant release, a conceptual model was applied in the large forested watersheds. The results of this study indicate that the relationship between discharge and specific pollutant load have a high regression coefficient. The flows during the rainy season provide most of the pollutant fluxes in this study, providing evidence of the important link between discharge and pollutant load. The five pollutant load rating curves for this study were developed using continuous sampling data during the heavy rainfall season. The simulation results indicate that the proposed approach can be used to predict both the discharge and pollutant release from the forested watershed, while the values of RMSE's are 0.14 for the Inbuk River watershed and 1.58 for the Naelin River watershed, respectively. This approach allows the estimation of other pollutive indicators following the same procedure. Concerning the treatment of pollutant loads from diffused watersheds, there is no agreement about at which level the contaminated waters should be removed. This result, considering the long term rainfall phenomenon, suggests that treating pollutant fluxes from a

Table 2. Correlation coefficients with pollutant rating coefficient a and exponent b for indicators in Inbuk River, 2004 and Naelin River, 2005

Water-sheds	Indi-cators	1st (from May 28 to 29) (A.R.3mm:T.E.R. 31mm)			2nd (from June 19 to 21) (A.R.2mm: T.E.R.60mm)			3rd (from July 4 to 5) (A.R.0mm: T.E.R. 54mm)			4th (from July 12 to 14) (A.R.5mm: T.E.R.135mm)			5th (from Aug. 16 to 19) (A.R.3mm: T.E.R. 198mm)		
		a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2
Inbuk River	BOD	1E-04	1.1058	0.7206	3E-05	1.5338	0.5195	8E-05	0.8607	0.5417	3E-07	1.8041	0.8678	8E-04	0.9230	0.8282
	COD	2E-04	1.4223	0.7631	4E-04	1.3683	0.9254	1E-04	1.1672	0.9224	5E-05	1.4759	0.9001	4E-04	1.2961	0.9516
	SS	9E-09	2.8788	0.8680	9E-04	1.5407	0.6121	1E-04	1.7215	0.5945	6E-08	2.3573	0.5752	1E-05	1.2548	0.7777
	TN	7E-04	1.0710	0.9526	7E-04	1.0922	0.9744	8E-04	1.0565	0.9573	1E-04	1.2045	0.7208	2E-04	0.7433	0.9359
	TP	1E-06	2.3935	0.8961	1E-04	1.5578	0.5501	9E-05	1.7588	0.7863	8E-08	2.3556	0.6399	7E-04	1.3463	0.8551
		1st (from May 18 to 19) (A.R.9mm: T.E.R. 24mm)			2nd (from June 27 to 28) (A.R.41mm: T.E.R. 85mm)			3rd (from July 28 to 30) (A.R.20mm: T.E.R. 87mm)			4th (from Aug. 18 to 20) (A.R.0mm: T.E.R. 55mm)			5th (from Sep. 13 to 15) (A.R.38mm: T.E.R. 32mm)		
		a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2
Naelin River	BOD	1E-04	1.2740	0.9470	5E-04	0.9186	0.8395	3E-04	1.2045	0.6960	3E-08	2.1272	0.4901	2E-04	0.6113	0.7092
	COD	4E-04	0.8895	0.8787	4E-04	1.0270	0.9406	3E-05	1.5227	0.9770	8E-05	1.3967	0.5682	5E-04	0.5535	0.4076
	SS	7E-04	0.9440	0.4541	2E-04	1.3089	0.8562	6E-06	1.7901	0.9632	5E-07	2.0125	0.1926	3E-04	0.6555	0.1057
	TN	6E-04	1.1765	0.9458	8E-04	1.1276	0.9970	1E-04	1.0692	0.9894	9E-03	0.8631	0.7919	7E-04	0.7368	0.8797
	TP	6E-04	0.9834	0.8986	6E-04	1.0712	0.8159	5E-04	1.3300	0.9448	1E-04	1.5633	0.2166	8E+0	0.3838	0.0974

A. R. : Antecedent Rainfall, T. R.: Total Event Rainfall, Unit of indicators: kg km^-2day^-1
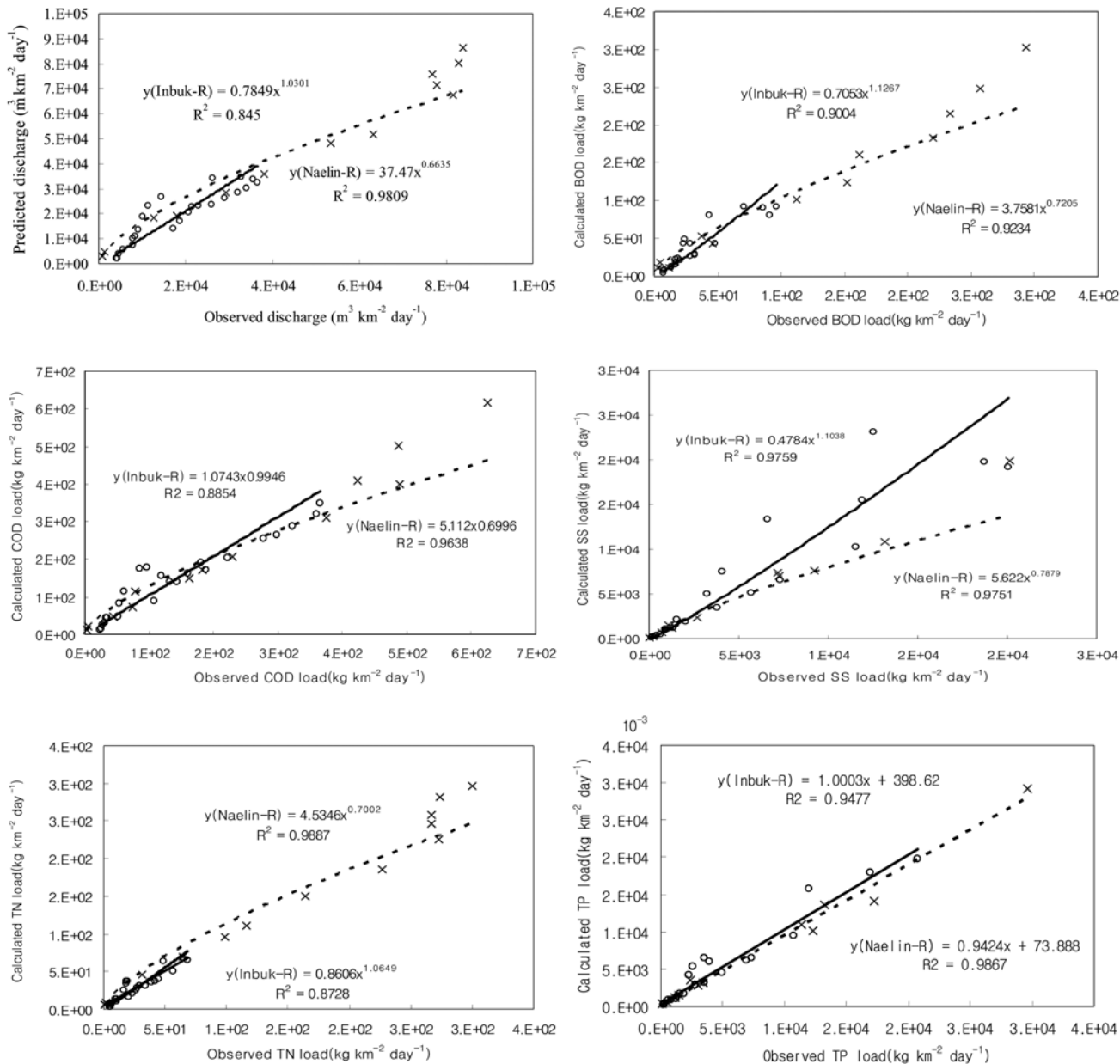
Fig. 2. The predicted specific pollutant fluxes versus observed pollutant fluxes based on calculated discharge (o: observed, − : calculated in Inbuk-R watershed; x: observed, ⋯ : calculated in Naelin-R watershed, respectively).

watershed during the rainy season may be more effective than treating a randomly released load during the dry season. Though further modeling testing based on other field data is needed, the results shown above will be helpful for controlling the pollutant flux release from forested watersheds during the rainy season.

Acknowledgements

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