Desalination and Water Treatment
www.deswater.com
19 (2010) 64–73
July

doi: 10.5004/dwt.2010.1897

Watershed-scale modeling to estimate delivery ratio of pollutant loads to support TMDL application in Korea

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Received 2 October 2009; Accepted 25 February 2010

ABSTRACT

The delivery ratio of pollutant loads can be defined as the ratio of the discharged pollutant load delivered to the point of interest divided by the mass of pollutants generated at the source. Assessing delivery ratios is important to watershed management planning for Total Maximum Daily Load because delivery ratios can indicate the characteristic pollutants of a watershed. To estimate exact delivery ratios, monitoring data of water quality and flow for the duration of flow are required. However, time, cost, and labor constraints mean that such data sets are often incomplete, and additional monitoring efforts are needed to supplement data. Watershed-scale models that are properly calibrated and verified can provide estimates of water flow and quality to fill gaps in data. In this study, model outputs were used to calculate the delivery ratio. The results demonstrate the usefulness of the watershed-model method for estimating the delivery ratio. Construction of a nationwide watershed model for South Korea and the model outputs for target water quality station will be useful for local governments. The watershed model used in this study adequately simulated watershed characteristics and is recommended for use in estimating delivery ratios to support TMDL management.

Keywords: Delivery ratio; TMDL; Watershed-model

1. Introduction

South Korea is a densely populated country with over 48 million people living in an area of less than 100,000 km^2. Rapid industrialization until the late 1980s in South Korea had negative environmental impacts, which are now the focus of restoration efforts. Population growth and economic development have increased the demand for water and degraded water quality due to waste disposal. In addition, rapid urbanization has increased pollutant loads and their concentration and water quality of many streams is often below the standards.

Growth and development are directly linked to water consumption. However, clean water has not always been readily available to meet demands, although water quality and quantity are necessary for sustainable develop ment. Water quality management has been driven by the control of point pollution sources but non point-source pollution has not been controlled.

South Korea has not achieved water quality standards. As a result, the nation's impaired water bodies have become a threat to public health. In 1999, the Ministry of Environment (MOE) required local governments to develop a Total Maximum Daily Load (TMDL) for each of the major rivers. The National Institute of Environmental Research established guidelines for the development of

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TMDL programs in 2003 [1]. In 2004, South Korea began the first stage of its compulsory TMDL policy. The process can be applied to bodies of water without violating the water quality standards specific to the purpose of the water body. Nonpoint-source pollution contributes 42–69% of the total pollutant load in Korea's four major rivers, depending on watershed characteristics [1]. As part of the TMDL project, many local governments have developed plans to reduce point-source pollution, such as by tertiary treatment of waste water; however, greater reduction of nonpoint source pollution is also necessary.

TMDL of pollutants is often used as a framework for water quality regulations designed to attain ambient water quality standards by controls on diffuse and point sources of pollution [2]. The TMDL establishes the allowable loadings for specific pollutants that a waterbody can receive without exceeding water quality standards thereby providing the basis to establish water quality based controls [3, 4]. The TMDL is the sum of point- and nonpoint-source loads and is used worldwide to assess water quality as well as to control point-source and nonpoint-source pollution.

It has been realized that water quality improvement is hardly achievable without proper controlling of nonpoint source pollution. Nonpoint sources are characterized by multiple discharge point and much of the nonpoint source pollution occurs during rainstorms or spring snowmelts, resulting in high flow rates that make treatment even more difficult [5]. Nonpoint source pollution is associated with land use activities such as agricultural cultivation, grazing of livestock, and forest management practices and occurs over side areas [6]. Large portions of pollutant loads occur due to activities undertaken by nonpoint sources, however, where export occurs via overland run-off and movement of water through the soil profile, thereby making the identi fication of the sources impossible or prohibitively expensive.

For implementation of the TMDL program, it is important to have efficient estimations of pollutant loads from watersheds and accurate predictions of water quality in receiving waters. TMDL is calculated by the unit load method for watershed pollutant loads, which is a simple function expressing pollutant generation over space and time for each type of land use (mass per unit area and unit time). The summation of loads from different land uses is calculated after multiplying the annual unit load estimate by the contributing area of uniform land use. True loadings are highly site specific and depend on demographic, geographic, and hydrologic factors. To determine TMDL, delivery ratios must also be assessed, as they can indicate the characteristic pollutants in a watershed and aid in watershed management plans for TMDL. The delivery ratio depends on several factors, including the drainage area size, transport system, and texture of the pollutant material. Watershed characteristics such as relief, physiochemical properties, stream size, and surrounding environments also influence the delivery ratio. These factors as well as complicated and variable parameters such as geographical conditions of the watershed, hydrology, climate, and season make accurate estimation of the delivery ratio difficult.

The Korean Ministry of Environment (KMOE) moni tors data for TMDL on monthly (1990–present) and eight-day (2006–present) time scales. However, these data are unsatisfactory for assessing delivery ratios because high-flow data are often lacking. Accurate assessments of delivery loads are needed to scientifically estimate TMDL and allocate appropriate pollution permits to achieve water quality guidelines.

Therefore, watershed-scale modeling is needed to simulate water flow and quality, using conventional monitoring data for model calibration and verification. Parameter evaluation is a key precursor to calibration. The parameter database developed for each watershed model is a valuable source of initial starting values for many of the key calibration parameters. However, land use and drainage systems (particularly those related to rice paddies) in Korea may differ from those in other countries, and thus previously developed databases might not be directly applicable to modeling cases in Korea.

This study presents a methodology that uses conventional monitoring data to estimate delivery ratios via a watershed model.

2. Methods

To apply the watershed model to delivery ratio estimation, model parameters must be developed for each type of land use, considering water flow and quality characteristics. For this study, flow duration monitoring was performed as defined by the model parameter criteria to estimate reasonable runoff and pollutant loads for each relatively homogeneous land use type (e.g., urban, forest, paddy, and upland). The hydrological simulation program–Fortran (HSPF) model was selected. The modeling considered point- and non-point-source pollution discharges for each land use type and used conventional weather station and monitoring data.

2.1. The study area

The study area was Nogok Stream watershed, located in the middle of the Korean Peninsula and Korea's largest river system, the Han River watershed. Nogok

Stream drains an area of 51 km^2 (Fig. 1) and is crossed by three tributaries, Yujung, Jinwoo, and Gungpyeong streams (127″N, 37°E). Approximately 7,980 people live in the Nogok Stream watershed area. One conventional wastewater treatment plant is located downstream.

The average annual precipitation is 1,270 mm, approximately 70% of which falls in summer from July to September, with the remaining amount occurring from October to May. Due to the Asian monsoon cycle, precipitation has large seasonal and spatial variation.

Land use types for the study area were based on KMOE maps and classified from Landsat Thematic Mapper (TM) images (30m resolution) and Indian Remote Sensing Satellite (IRS-1C) panchromatic images (5.8m resolution) taken on 21 May 1999 and 29 February 2000, respectively. The original KMOE land use map distinguished 23 land use types. We reclassified the land uses into six categories: urban, paddy, upland, forest, pasture, and other. Table 1 lists the land uses in the watershed: 67.7% forest, 12.3% paddy, 7.4% urban, and 7.1% upland. The Kyeonggi Public Health and Environment Institute (KHEI) have been operating four conventional monitoring stations in the Nogok Stream watershed since 2006. These stations, labeled A1–A4, are also shown in Fig. 1.

2.2. Delivery ratio

The delivery ratio can be defined as the ratio of the discharge pollutant load delivered to the point of interest divided by the mass of pollutants generated at the

Table 1
Land use in the Nogok Stream watershed.

	Urban	Paddy	Upland	Forest	Pasture	Other	Total
Area (km^2)	3.75	6.25	3.62	34.53	1.39	1.46	51.00
Percentage of total land use	7.36	12.26	7.09	67.71	2.71	2.87	100.00

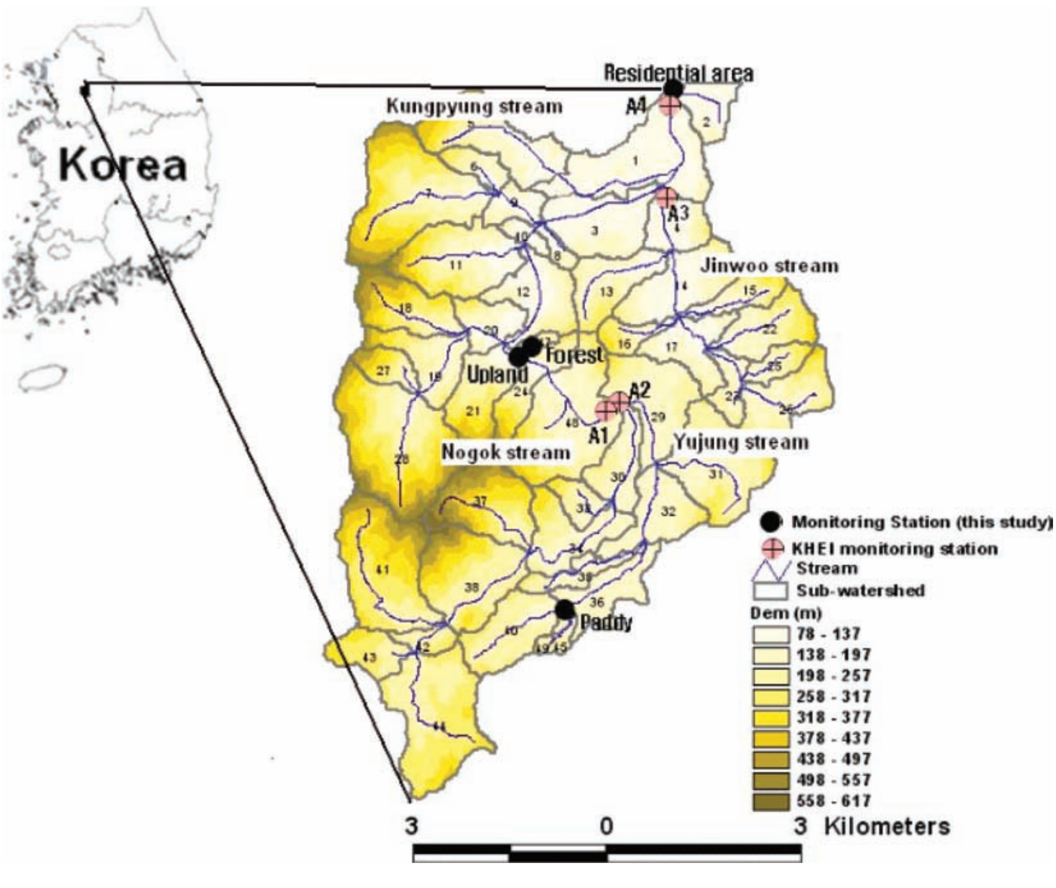

Fig. 1. Location of the study area and monitoring station.

source. The delivery ratio has been calculated by simply dividing the pollution load by the load discharged from a specific watershed:

$$DL = \frac{L'}{L_O} \quad (1)$$

DL = Delivery ratio
L' = Delivery load
L_O = Discharge load

Delivery loads are used as boundary conditions for estimating TMDL. To calculate the delivery ratio, data on low flow loading and average annual loading are essential. Here, low flow is considered to be the 275th-greatest daily flow of a given year. However, conditions are not always suitable for implementation of all TMDL measures. Critical conditions are influential and important because they can violate water quality standards.

2.3. Monitoring

Four monitoring stations were established for the land use groups of urban, paddy, upland, and forest, as shown in Fig. 1. Water samples were collected by both grab sampling and automatic sampling where available. Automatic samplers allow for more convenient automatic collection of data. Monitoring devices (automatic samplers, rain gauges, and flow meters) were installed at each sampling point, and these allowed for easy collection of runoff data. Physical and climate data are needed to apply the model to a watershed. Furthermore, runoff and water quality data are required for model calibration and verification. Monitoring was carried out between July and September 2008. Runoff monitoring was performed approximately five to nine times for the selected sites depending on site conditions. To determine flow, the depth of the channel or storm sewer was converted using the rating curve for the section being measured. In this study, ultrasonic flow meters and flow level meters were used during the monitoring period.

2.4. Watershed modeling

2.4.1. The hydrologic simulation program–Fortran model

The HSPF model is a sophisticated continuous watershed model capable of simulating hydrologic time series of runoff quantity–quality events (version 12.0) [7]. The HSPF model can be applied to determine flows (hydrographs) and conventional pollutants (pollutographs). Furthermore, the HSPF can be applied to the lumped-parameter continuous simulation model that has evolved out of Stanford Watershed Model, the US EPA agricultural runoff management model, and non-point source model. HSPF can also be used as a distributed parameter model, as it reproduces spatial variability by dividing a basin in hydrologically homogeneous land segments and simulating runoff for each land segment independently.

HSPF has been used to simulate water flow and water quality for water resource management in Korea [8–13, 14, 15]. HSPF has been widely used for watershed management to simulate various hydrologic conditions [16, 17] and transport of various nonpoint source pollutions, including contaminated sediment [18–20] and land use management and flood control scenarios [21, 22]. HSPF is a better predictor of temporal variations of daily flow and sediment [23]. HSPF simulated hydrology and water quality components more accurately than other model at all the monitoring considering differences in annual loads and the trend of monthly loads [15]. In Ref. [24] reported that HSPF performance of average annual flows was better than other model. The HSPF model has been widely used to estimate nutrient and sediment loads from watersheds [9, 11, 13, 14, 25, 26, 27]. To simulate nutrients, HSPF includes modules for simulating hydrology and nitrogen cycling processes, including nitrogen input, mineralization, nitrification, denitrification, immobilization, plant uptake, leaf fall, transport of nitrogen in soil layers and discharge. Therefore, application of HSPF would be expected to be a useful tool for this study.

In this study, the HSPF model was selected to simulate pollution discharge from each land use type using the acquired monitoring data. The study area was located between the Yangpyeong and Icheon stations of the Korea Meteorological Administration. Hourly weather data such as precipitation, air temperature, dew point temperature, wind speed, cloud cover, solar radiation, evaporation, and evapotranspiration were obtained from those stations.

Each sub-watershed was determined by using natural drainage boundaries using a digital elevation map (DEM) and "automatic delineation utility" in the better assessment science integrating point and nonpoint sources (BASINS) environmental analysis system. Sub-basins delineation and land use divisions generally require much time and effort, and involve substantial personal subjectivity. However, BASINS allows an easy-to-use approach and provides more objectivity in the watershed model simulation.

After automatic delineation, sub-watershed was slightly modified to calibration using monitoring data each land use and four conventional monitoring data. Based on the Korean Hydrologic System shape file, the Nogok Stream watershed was divided into sub-watersheds.

2.4.2. Analytical methods

Statistical measures of root mean-square error (RMSE), the Nash–Sutcliffe efficiency index (EI) [28], the coefficient of determination (R^2) and percent difference (% Diff) [29] were used to evaluate the model simulations. The R^2 value is an indicator of the strength of the relationship between the observed and simulated values. EI indicates how well the plot of observed versus simulated value fits the 1:1 line. The RMSE measures both systematic and random errors. Lower values of R^2 and EI (i.e., close to zero) indicate a poorer model prediction, whereas values closer to 1.0 represent a more accurate prediction [30]. In Ref. [31] suggested that model predictions with R^2 and EI values greater than 0.6 and 0.5, respectively, are acceptable or satisfactory. Table 2 shows some general guidelines of % Diff for calibration/verification tolerances or targets that have been provided to model users in HSPF training workshops over the past 10 years [32]. The percent difference values of water quality are <15~35%, and the simulation results can be judged as “Very good” to “Fair”. In this study, simulation accuracy was assessed using a combination of RMSE, EI, R^2, and % Diff.

Table 2
General calibration and verification targets of tolerances for HSPF application [33].

	Very good	Good	Fair	Poor
% Diff				
Water quality	<15	15~25	25~35	–

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2}. \tag{2}$$

$$\mathrm{EI} = \frac{\sum_{i=1}^{n}(M_O - O_i)^2 - \sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(M_O - O_i)^2}. \tag{3}$$

$$R^2 = \frac{1}{n} \times \frac{\sum_{i=1}^{n}(S_i - M_s)\times(O_i - M_O)}{(\sigma_s - \sigma_O)}. \tag{4}$$

$$\%\mathrm{Diff} = \frac{\left(\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} S_i\right)}{\sum_{i=1}^{n} O_i} \times 100. \tag{5}$$

where O, S, M, and σ represent the observed, predicted, average, and standard deviation, respectively.

3. Results and discussions

3.1. Monitoring data

For this study, stormwater runoff was monitored during approximately five to nine rain events at the monitoring stations. Samples were analyzed for total suspended solids (TSS), biochemical oxygen demand (BOD_5), total nitrogen (TN), and total phosphorous (TP) [3]. Table 3 shows the results. The mean concentrations of

Table 3
Characteristics of monitoring data from the study area.

Monitored watershed	Parameter	TSS (mg/L)	BOD_5 (mg/L)	TN (mg/L)	TP (mg/L)
Urban (7 events, n = 113)	Mean	83.5	15.9	7.9	0.60
	S.D.	355.8	23.8	5.5	0.50
	Max.	3,620.0	122.7	43.6	2.98
	Med.	20.0	7.7	6.4	0.41
	Min.	0.0	0.5	1.5	0.03
Upland (5 events, n = 57)	Mean	124.6	15.2	1.4	2.25
	S.D.	176.2	9.1	0.7	2.66
	Max.	997.0	43.0	3.9	13.40
	Med.	63.5	12.4	1.4	1.40
	Min.	2.0	3.0	0.4	0.23
Paddy (9 events, n = 167)	Mean	98.5	0.6	1.0	0.08
	S.D.	178.7	0.9	0.5	0.08
	Max.	1,133.0	9.7	2.4	0.30
	Med.	40.0	0.4	0.9	0.05
	Min.	3.7	0.0	0.1	0.00
Forest (5 events, n = 57)	Mean	5.7	2.4	0.9	0.28
	S.D.	5.9	0.9	0.4	0.12
	Max.	38.0	5.9	2.4	0.69
	Med.	4.0	2.3	0.8	0.23
	Min.	2.0	0.8	0.3	0.11

S.D., standard deviation; Max., maximum; Med., median; Min., minimum.

TSS and TP were the highest in the watershed dominated by upland land use. Fertilizer usage and slope conditions effected the TP concentration, but the mean concentration of TN was lower than that in other watersheds. The BOD_5 and TN concentrations were 15.9 and 7.9 mg/L in the urban watershed, respectively, due to the first flush effect. The first flush effect was obvious in the more impervious area of the urban watershed and was detected during monitoring.

3.2. Modeling results

The available monitoring data failed to represent the full range of conditions. Use of model simulations, such as by the HSPF model, can be a solution to monitoring limitations [7]. The model can express the relationships between water quality and discharge from land surfaces. In this study, the HSPF model was applied to the Nogok Stream watershed. Simulations were run at hourly time steps, with the output displayed in both daily and hourly time steps (Figs. 2 and 3, Tables 4 and 5). For model calibration, we used hourly data from the monitoring stations and daily data from conventional monitoring stations and monitoring was carried out between July and September 2008.

The simulation was then based on the input meteorological and hydrological time series and on the parameters determined by calibration. Model calibration and validation are critical steps in model application. Model validation is in reality an extension of the calibration process. HSPF was able to best reproduce the trend of flow and pollutant load during the calibration period. Monitoring data were not sufficient to evaluate model performance because monitoring period was short, approximately three month, but the model output was reasonably close to observed data. Table 4 shows simulation results for hourly runoff and pollutant loads. The R^2 and EI of flow were calculated as 0.62~0.94 and 0.54~0.95, respectively, the simulated flow closely represents the observed flow. The R^2 and EI of pollutant loads were calculated as 0.47~0.84 and 0.34~0.81, respectively, and the percent difference values of pollutant loads were calculated as 7.41~34.44% and were generally in the range of "Very good" to "Fair". The results of runoff and pollutant load and observations were fairly congruent. It is noteworthy that the verification process for two independent data sets was successful; implying that the calibrated HSPF model adequately simulated the watershed over diverse and long term conditions. Some deviations were observed in the simulation; however, they were within expectations,

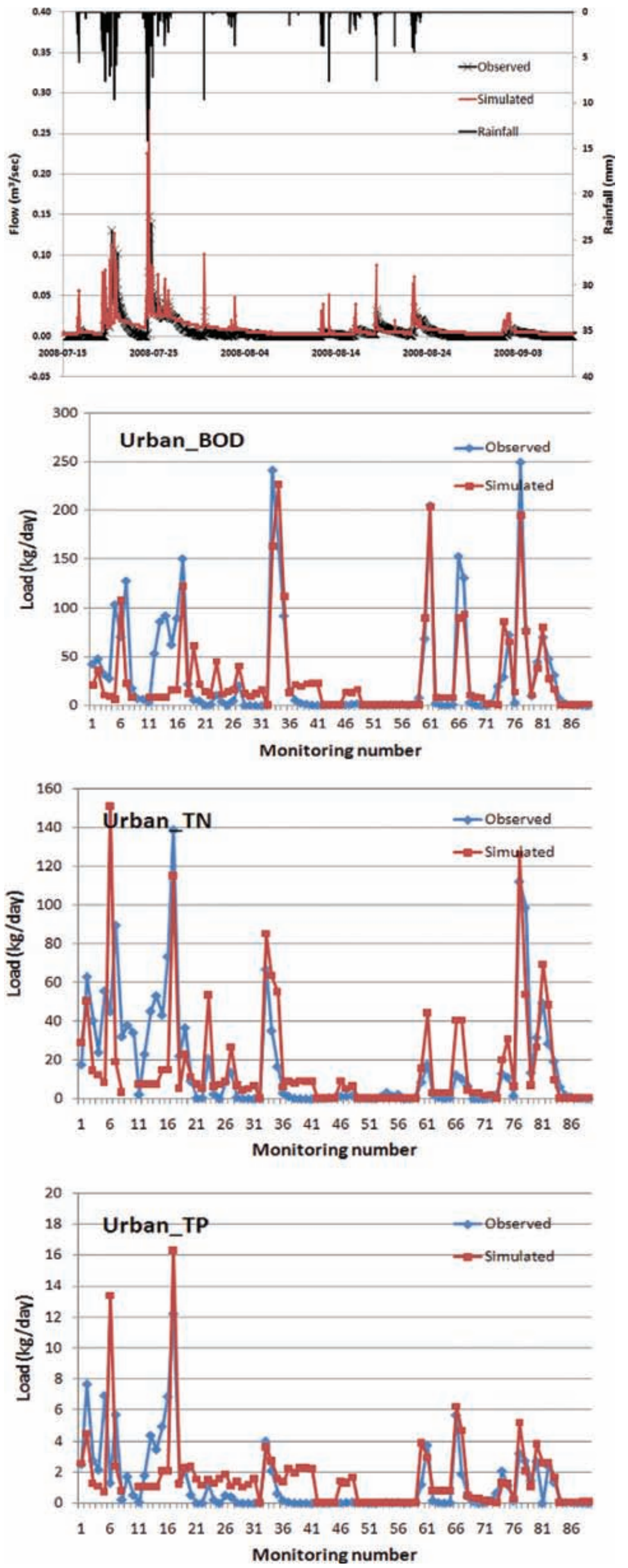

Fig. 2. Comparison of observed and HSPF-simulated hourly runoff and pollutant loads.

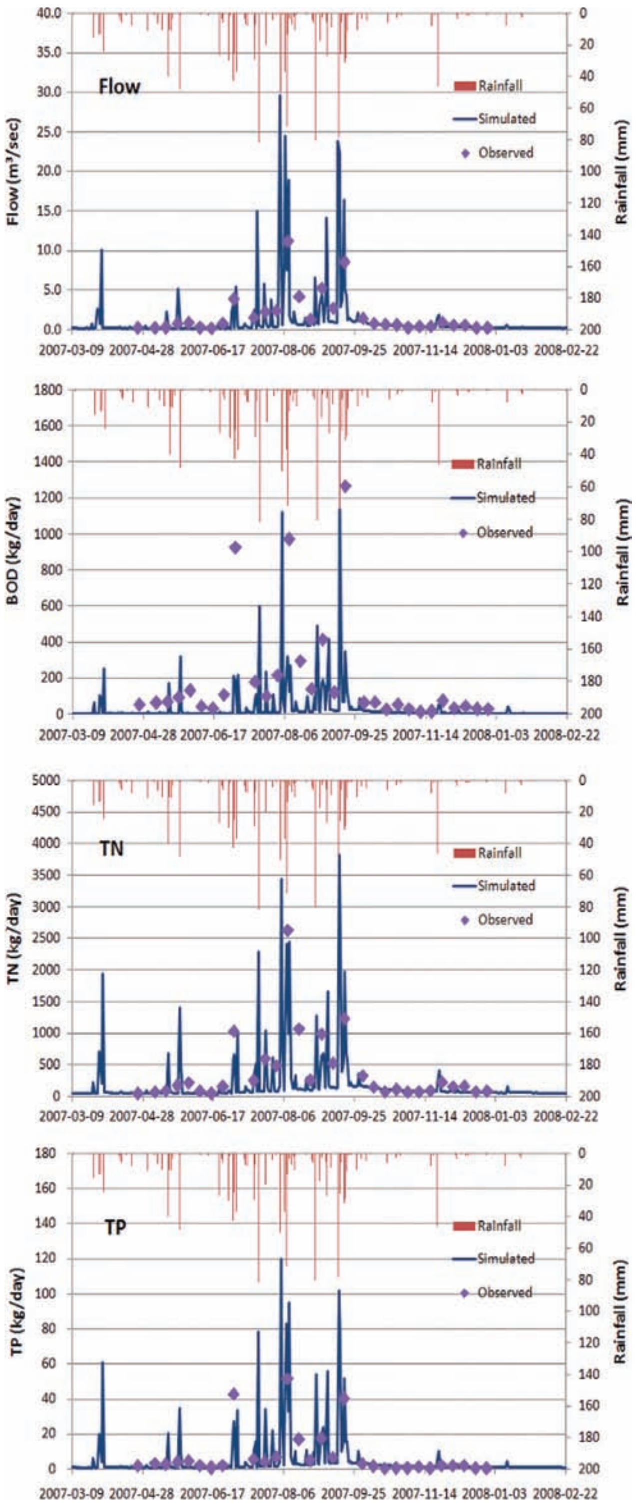

Fig. 3. Comparison of observed and HSPF-simulated daily runoff and pollutant loads.

considering inherent errors in the input and observed data, as well as the model formulation. It is essential to obtain acceptable agreement between observed and simulated concentration for the procedure of watershed water quality calibration, maintaining the instream water quality parameters within physically realistic bounds, and the non-point loading rates within the expected ranges from the literature.

Hourly data from watersheds of relatively homogeneous land use were used to estimate runoff. Table 5 shows simulation results for daily runoff and pollutant loads. The R^2 and EI of flow were calculated as 0.73~0.94 and 0.67~0.86, respectively, the simulated flow closely represents the observed flow. The R^2 and EI of pollutant loads were calculated as 0.48~0.98 and 0.40~0.93, respectively, the percent difference values of pollutant loads were <35% and generally in the range of "Very good" to "Fair". The output data agreed reasonably well with observations.

The HSPF model has a modular structure and is a lumped parameter model. Pervious land that can infiltrate water is modeled with the PERLAND module, impervious land such as an urban surface is simulated with the IMPLND module, and water bodies are treated by the RCHRES module. The modules have several components related to hydrologic and water quality processes. The PERLND and IMPLND modules were applied using the hourly data sets for the watersheds. The obtained parameters were then used in daily simulation for the whole watershed.

The HSPF model was calibrated using daily datasets from the conventional monitoring stations. Runoff and pollutant load parameters were used in the watershed-scale application. Model calibration was performed using the reach/reservoir routing (RCHRES) module. The simulated flow was close to observed data; simulated and observed pollutants also agreed reasonably well.

3.3. Calculation of the delivery ratio

The delivery ratio is usually calculated by Eqs. (5) and (6) below, reflecting the water quantity. Table 6 shows the comparison of delivery ratios. Equation (1) calculates the real discharge load value that is applied for the TMDL project. However, these values are not adequate because monitoring data are only collected every 8 days. As a result, the HSPF model was used to estimate values for the missing data. The delivery ratio was calculated using the output data. The average delivery ratios of BOD, TN, and TP using the model output

Table 4
Summary of HSPF simulation results for hourly runoff and pollutant loads.

Station	Analytical method	Flow	BOD	TN	TP
Urban	RMSE	0.04	13.43	14.93	1.32
	EI	0.95	0.77	0.69	0.64
	R^2	0.78	0.84	0.63	0.58
	% Diff		13.59 (good)	5.49 (very good)	30.85 (fair)
Upland agriculture	RMSE	0.01	29.23	3.84	3.77
	EI	0.92	0.55	0.47	0.81
	R^2	0.94	0.78	0.74	0.64
	% Diff		17.68 (good)	0.30 (very good)	7.41 (very good)
Paddy	RMSE	0.05	4.80	3.55	0.17
	EI	0.73	0.34	0.67	0.61
	R^2	0.73	0.60	0.61	0.65
	% Diff		17.87 (good)	32.63 (fair)	26.26 (fair)
Forest	RMSE	0.02	6.22	1.46	0.69
	EI	0.54	0.66	0.71	0.44
	R^2	0.62	0.47	0.48	0.61
	% Diff		28.27 (fair)	24.25 (fair)	34.44 (fair)

Table 5
Summary of HSPF simulation results for daily runoff and pollutant loads.

Station	Analytical method	Flow	BOD	TN	TP
A1	RMSE	0.19	4.16	8.00	1.22
	EI	0.67	0.74	0.68	0.61
	R^2	0.78	0.96	0.98	0.53
	% Diff		12.0 (very good)	30.3 (fair)	11.6 (good)
A2	RMSE	0.38	7.65	8.09	0.89
	EI	0.73	0.85	0.80	0.89
	R^2	0.73	0.95	0.97	0.88
	% Diff		15.8 (good)	27.0 (fair)	3.5 (very good)
A3	RMSE	0.09	6.16	9.04	1.81
	EI	0.68	0.80	0.68	0.40
	R^2	0.94	0.66	0.93	0.48
	% Diff		29.5 (fair)	20.2 (good)	16.2 (good)
A4	RMSE	0.06	4.63	9.69	0.21
	EI	0.86	0.93	0.79	0.93
	R^2	0.86	0.97	0.89	0.97
	% Diff		32.1 (fair)	30.2 (fair)	3.1 (very good)

Table 6
Comparison of delivery ratios using KHEI data for station A4.

Calculation method	275th low-flow condition			185th low-flow condition		
	BOD	TN	TP	BOD	TN	TP
Equation (1)	0.229	0.596	0.131	0.139	0.665	0.076
Equation (5)	0.100	0.238	0.030	0.090	0.282	0.036
Equation (6)	0.005	0.047	0.064	0.001	0.041	0.043
HSPF	0.203	0.540	0.089	0.132	0.445	0.081

were calculated as 0.203, 0.540, and 0.089, respectively. The results of Eq. (1) were compared values of Eqs. (5), (6) and HSPF. Comparison results showed that values of HSPF were in acceptable range of accuracy.

$$DL = aQ^b \tag{6}$$

DL = Delivery ratio
Q = Water flow
a,b = Constant

$$DL = a\left(\frac{Q}{A}\right)^b \tag{7}$$

DL = Delivery ratio
Q = Water flow
A = Watershed area
a,b = Constant

4. Conclusions

This study was initiated to find practical way to estimated pollutant delivery ratio in TMDL application. The HSPF model was used to generate simulation data for the estimation of delivery ratio. The model was calibrated using existing and additional rainy-day data from existing monitoring stations and obtained by additional field monitoring. The simulated flow closely represents the observed flow and the percent difference values of pollutant loads were < 35% and generally in the range of "Very good" to "Fair". In this study, model outputs were used to calculate the delivery ratio. The results demonstrate the reliability of the watershed-model method for estimating the delivery ratio. The watershed model used in this study adequately simulated watershed characteristics and is recommended for use in estimating delivery ratios to support missing data. Overall, the watershed-scale modeling satisfactorily simulated not only water flow and quality in the watershed, but also estimated pollution delivery ratios for the watershed system. For enhanced TMDL applications, accurate estimations of delivery ratios are needed to that govern the waste load allocation process. The watershed-scale modeling approach described here is recommended for this purpose, after a proper calibration process.

Acknowledgements

This study was carried out with the support of "Development of delivery load method to manage total maximum daily loads of the Han River" project of the National Institute of Environmental Research, Republic of Korea.

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