한국환경농학회지 제19권 제5호(2000)
Korean Journal of Environmental Agriculture
Vol. 19, No. 5, pp. 419~425

Pollutant Loading Estimates from Watershed by Rating Curve Method and SWMM

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ABSTRACT : Rating curve method and SWMM (Storm Water Management Model) were applied to estimate pollutant loading from Hwa-Ong watershed in Kyunggi-Do. Rating curves were derived from sampling sites and applied to the whole watershed. SWMM version 4.4 was calibrated by field data of sampling sites and applied to the whole watershed. The pollutant loading estimated by rating curve was slightly higher than the one by SWMM, but the difference was not significant considering diffuse pollution characteristics of wide variation. Land use effect of the subcatchments could not be incorporated logically in rating curve method and difficulty in extrapolation was experienced, therefore, the estimate by rating curve method was thought to be less confident. SWMM was satisfactory in estimation of pollution loading, and its great flexibility worked well to describe complex nonurban land uses. Neither of them could exactly describe complex natural phenomena, but SWMM was preferred in this study due to its flexibility and logical hydrologic processes including land use effects. Use of reasonable watershed model rather than rating curve method for watershed pollutant loading estimate can be more practical and is recommended.

Key words : Rating curve method, SWMM, Watershed, Pollutant loading estimate, Subcatchment, Land use, Nonurban area, Calibration, Extrapolation.

INTRODUCTION

Korea is a land limited country and polder projects have been practiced for last decades along the western coast of the Korean peninsula. Polders are effective to compensate the loss of farmland caused by rapid expansion of residential and industrial areas, however, environmental concerns are arising these days and current polder projects are under debate.

Water quality problem of the reservoir is one of the apparent issues at polders. Reservoirs usually have a large watershed and high-volume source streams. The watershed may carry extensive agricultural nonpoint nutrients, silts, and organic matter discharges, making loading very high and difficult to protect water quality (USEPA, 1990). The water quality of a reservoir is greatly influenced by watershed drainage, and accurate estimation of pollutant loading from the watershed is important in the reservoir management.

Several options exist for estimation of diffuse pollution loading which include unit loads, constant concentration, spreadsheet, statistical, regression and rating curve, and buildup/washoff (Donigian et al, 1995). Unit loads are perhaps the simplest concept which consist of values of mass per area per time for various pollutants. Such loadings are highly site specific and must be based on typical runoff volume, but they can conveniently incorporate best management practices.

Constant concentration assumes that the concentration is constant for a given pollutant, and annual runoff volume can be multiplied by the constant concentration to produce an annual runoff load. The concept is useful because it may be used with any hydrologic models, but using one constant concentration needs careful selection of that value. The spreadsheet may be used to automate and extend the concept of the constant concentration idea. The spreadsheet approach is suited to the estimation of long-term load, but is hard to obtain the variation of predicted loads and concentrations. The statistical method concept is a derived frequency distribution for expected mean concentration, and has been used extensively for runoff quantity but not much for quality predictions.

Regression and rating curve approach is a special form of regression analysis in which concentration and/or loads are related to flow rates and/or volumes. The rating curves obtained from regression analysis of monitoring data may provide reasonable prediction for, however, they are notoriously difficult to apply beyond the original dataset from which the relationships were derived. Buildup/washoff concept involves buildup of pollutants during dry weather and washoff during subsequent storm events. This model may provide adequate comparison of control measures but cannot be used for prediction of absolute values of concentrations and loads without adequate calibration and verification data. Many of these options have been incorporated in computer models to estimate.

In this study, pollutant-loading estimates were made for the Hwa-Ong polder watershed using rating curve method and SWMM where rating-curve option and buildup/washoff concepts are incorporated as built in functions. The results of these methods were compared and analyzed.

MATERIALS AND METHODS

Study area

The Hwa-Ong watershed locates at the western coast of the Korean peninsular as shown in Figure 1, and total area is about 23,580ha, in which 4,482ha of polder and 1,730ha of reservoir will be made once the polder project is completed. It has population of about 35,000 and also significant number of livestock. The number of cow, pig, and deer is about 20,000, 38,000, and 900, respectively (Rural Development Corporation, 1997). Average annual precipitation is 1,324mm, and seasonal variation is apparent that usually two thirds of the annual precipitation concentrate during summer and rest of the year has monthly precipitation of less than 50mm. The watershed was divided into 19 subcatchments as shown in Figure 1 for modeling purpose, and land use distributions for them are summarized in Table 1.

More than half of the watershed is occupied by forest, and small towns are scattered within the watershed. Main economic activity in the watershed is agriculture. Agricultural area involves paddy field for rice and upland for vegetables like corn, soybean, red pepper, and potato. Generally livestock farms are in feedlot type, and livestock area is considered as one of principal pollution dischargers although the area itself is not large. Residential area is not sewered and includes from small farm villages with less than 100 populations to sizeable towns with thousands of populations. Overall watershed characteristic belongs to a complex nonurban area rather than simply urban or agricultural area.

Table 1. Subcatchment land use classification

Subcatchment	Paddy field		Upland area		Residental area		Livestock area		Others		Total
	ha	%	ha	%	ha	%	ha	%	ha	%	(ha)
Ⅰ-1	20.40	18.45	20.40	18.50	6.40	5.80	0.01	0.01	63.09	57.20	110.30
Ⅰ-2	56.20	18.40	56.80	18.59	17.70	5.79	0.10	0.03	174.70	57.18	305.50
Ⅰ-3	245.00	30.80	100.20	12.60	8.80	1.11	0.78	0.10	440.62	55.40	795.40
Ⅰ-4	152.90	25.90	69.10	11.70	21.30	3.61	4.52	0.77	342.57	58.02	590.40
Ⅰ-5	551.10	30.60	261.20	14.50	41.40	2.30	4.74	0.26	942.66	52.34	1801.10
Ⅱ-1	301.20	31.12	85.90	8.88	22.50	2.32	13.49	1.40	544.71	56.28	967.80
Ⅱ-2	43.40	20.30	14.30	6.69	6.00	2.81	0.29	0.13	149.82	70.07	213.80
Ⅱ-3	71.90	19.70	28.10	7.70	10.20	2.80	3.85	1.06	250.85	68.74	364.90
Ⅱ-4	54.80	15.00	24.50	6.71	9.90	2.71	0.69	0.19	275.41	75.39	365.30
Ⅱ-5	291.00	39.97	93.90	12.90	13.10	1.80	1.17	0.16	328.83	45.17	728.00
Ⅱ-6	61.60	25.70	27.30	11.39	5.80	2.42	1.30	0.54	143.70	59.95	239.70
Ⅲ-1	418.30	28.40	213.60	14.50	38.30	2.60	6.33	0.43	796.37	54.07	1472.90
Ⅲ-2	997.20	28.31	574.40	16.31	88.10	2.50	25.09	0.71	1,838.01	52.17	3,522.80
Ⅲ-3	315.80	38.16	122.40	14.79	3.30	0.40	7.23	0.87	378.87	45.78	827.60
Ⅳ-1	165.70	32.77	68.70	13.59	10.10	2.00	2.49	0.49	258.71	51.16	505.70
Ⅳ-2	188.30	69.23	37.80	13.90	6.80	2.50	0.30	0.11	38.80	14.26	272.00
Ⅳ-3	327.10	47.11	126.40	18.20	19.40	2.80	0.84	0.12	220.66	31.78	694.40
Ⅳ-4	118.40	31.59	70.50	18.81	7.50	2.00	0.96	0.26	177.44	47.34	374.80
Ⅳ-5	742.90	23.10	392.40	12.20	70.80	2.20	9.86	0.31	2000.04	62.19	3216.00
Total	5,123.20	29.50	2,387.90	13.75	407.40	2.35	84.04	0.48	9,365.86	53.92	17,368.40

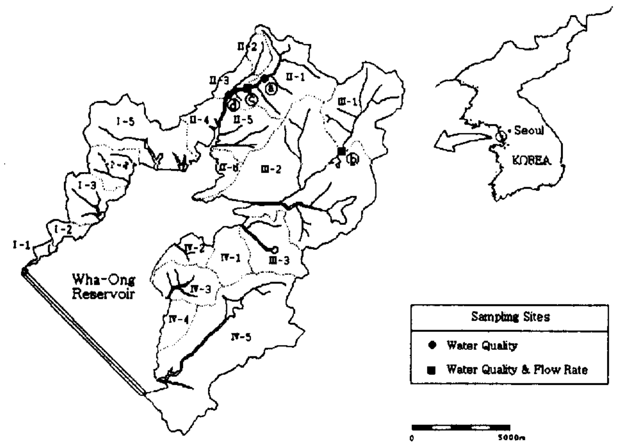

Fig. 1. Study area and sampling sites

Table 2. Analytical methods used for constituents

Constituents	Methods*	Remark
COD (chemical oxygen demand)	SM 5220-B	$K_2Cr_2O_7$ used
SS (suspended solids)	SM 2540-D	
T-N (total nitrogen)		
Organic nitrogen	SM 4500-N_{org}-C	
NH_3-N	SM 4500-NH_3-D	BÜCHI 435와 B-316
NO_2^--N	SM 4110-B	Dionex DX-100
NO_3^--N	SM 4110-B	Dionex DX-100
T-P (total phosphorus)	SM 4500-P E	HP8452A Spectrophotometer

* SM : Standard Methods (APHA, 1995).

Sampling and analysis

In dry days, routine samples were collected in every two weeks at ⓐ, ⓑ, ⓒ, and ⓓ in Figure 1. In wet days, samples were collected at ⓑ and ⓒ from beginning of the storm to the end of it and these data were used to derive rating curves and to calibrate SWMM. Wet day sampling was performed for two independent storms and they were 58.5mm on May 03, 1999 and 293mm on August 01, 1999. Water quality constituents were analyzed by Standard Methods (APHA, 1995) and specific methods used are summarized in Table 2.

RESULTS AND DISCUSSION

Rating curves for sampling sites

Concentration of the pollutant was multiplied by stream flow to produce pollutant loading. From the relationship between flow rate (Q, $L\cdot sec^{-1}$) and pollutant loading (L, $mg\cdot sec^{-1}$), rating curves were developed for each sampling site and they were used to estimate pollutant loadings of associated subcatchments. Flow rate was calculated by multiplication of flow speed and cross section which obtained several points of the stream. Water level was recorded continuously in sampling sites of ⓑ and ⓒ by pressure water gauge.

Rating curves for the sampling sites are summarized in Table 3 and Table 4. Notice that the curves for sites ⓑ and ⓒ developed from data including wet day measurements, while the curves for ⓐ and ⓓ used less with dry day data only.

SWMM calibration for sampling sites

The original version of the SWMM was developed mainly for the analysis of combined sewer overflows (Metcalf and Eddy, 1971), but its scope has vastly broadened since the original release. SWMM is a widely used storm water management model and has been used in many locations (Balascio, et al., 1998; Loganathan, et al., 1994; Park and Johnson, 1998; Zug et al, 1999; Zech, et al., 1994). SWMM version 4 (Huber and Dickinson, 1988) was used in the study.

The model was calibrated and verified for the flow rates with two independent storms of 5-3-1999 (58.5mm) and 8-1-1999 (293mm, the greatest of the year), and calibration results are illustrated in Figure 2. The results showed that SWMM could simulate watershed hydrologic process quite accurately, it was proved that SWMM could be calibrated conveniently with diverse builtin functions. The calibration

Table 3. Rating curves between flow rate and depth for the sampling site

Sampling site		Relationship	R^2
ⓑ		$Q = 0.3209 \times H - 30.009$	0.99
ⓒ	Diversion weir closed	$Q = 4\times 10^{-86}\ H^{37.779}$	0.98
	Diversion weir open	$Q = 4\times 10^{-14}\ H^{6.151}$	0.99

Table 4. Rating curves between loading and flow rate for the sampling site

Sampling site	Constituent ($mg\cdot L^{-1}$)	Relationship	R^2
ⓑ	COD	$L = 2.74 \cdot Q^{1.29}$	0.94
	T-N	$L = 5.40 \cdot Q^{1.11}$	0.98
	T-P	$L = 0.18 \cdot Q^{1.25}$	0.93
ⓒ	COD	$L = 2.77 \cdot Q^{1.21}$	0.96
	T-N	$L = 2.98 \cdot Q^{1.09}$	0.98
	T-P	$L = 0.04 \cdot Q^{1.31}$	0.88

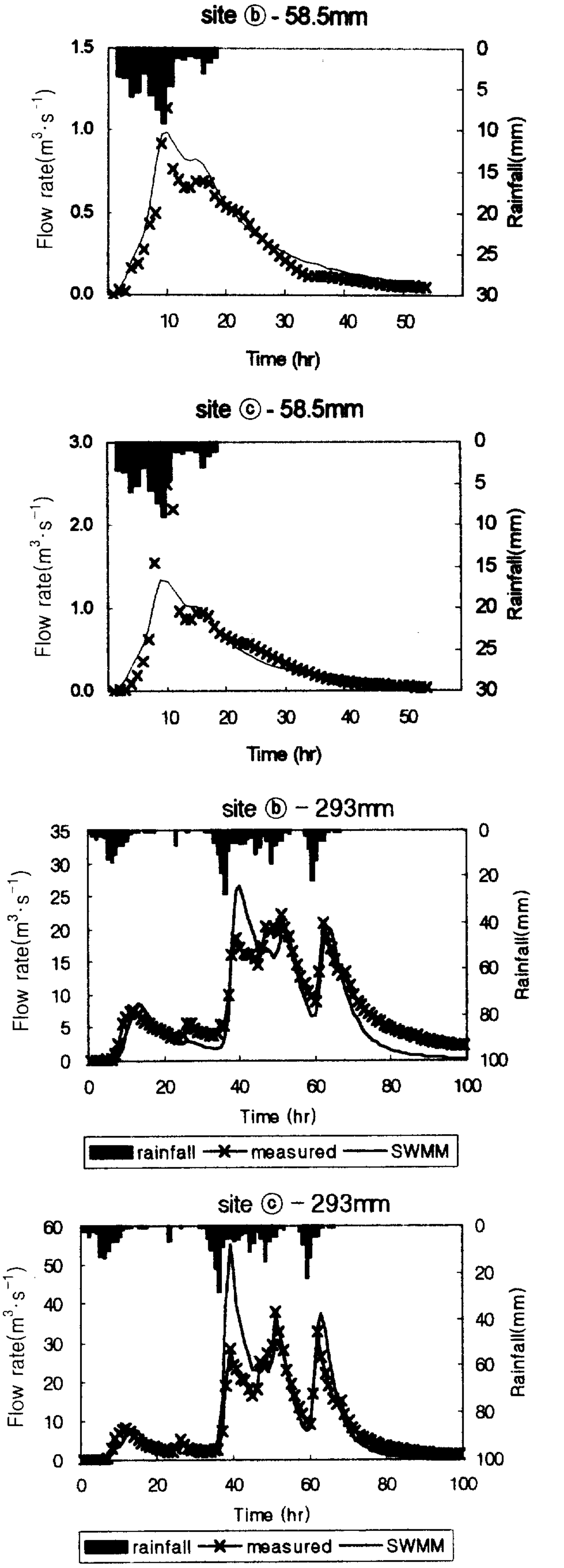

Fig. 2. Comparison of flow rates between measured data and model output

result was satisfactory and the calibrated model parameters were used for other subcatchments in the watershed.

It has strength in analysis of urban hydrologic process, and also has a great flexibility to analyze general hydrologic process in nonurban area. Flow rates were calibrated with two independent storms for two sampling sites of ⓑ and ⓒ where continuous monitoring data were available, and they showed generally good agreements between field data and model output.

In the estimation of pollutant loading, the power-exponential washoff equation was used for the residential area, and the rating-curve option was used for other land uses such as paddy, upland, livestock, and forest areas shown in Table 1. The former can simulate effectively a first flush effect and may work better in residential areas, and the latter can work better for the case where pollutant concentration varies with flow rate. The rating-curve option of SWMM is a built in function in the model and different from the curves mentioned in Table 3. The pollutant loading was calibrated with the storm of 5-3-1999 and the results are shown in Figure 3.

Considering wide variation in the characteristics of pollution loading, the graph exhibits reasonable agreements between field data and model output even with some outliers. Unfortunately, water quality data for the storm of 8-1-1999 was missing and the pollutograph could not be verified.

Pollutograph calibration was also satisfactory in SWMM because its result was used for loading estimates in other nonmonitored subcatchments. Pollutant export coefficients obtained from calibration was within the normal range.

Loading estimates for total watershed

In SWMM method, the calibrated SWMM was used to estimate wet day pollutant loading for each subcatchment using all the rainfalls greater than 5mm from January to December 1999, and sum of them produced total loading for the whole watershed in wet days. In dry day loading estimates by SWMM method, average base flow per area was calculated with dry day monitoring data and it was used. Physical properties of each subcatchment were obtained from 1:50,000 map and available GIS data for the watershed, and parameters for pollutant migration of the specified land use were kept same as the calibrated model for all the subcatchments. The results are summarized in Table 5 and Figure 4.

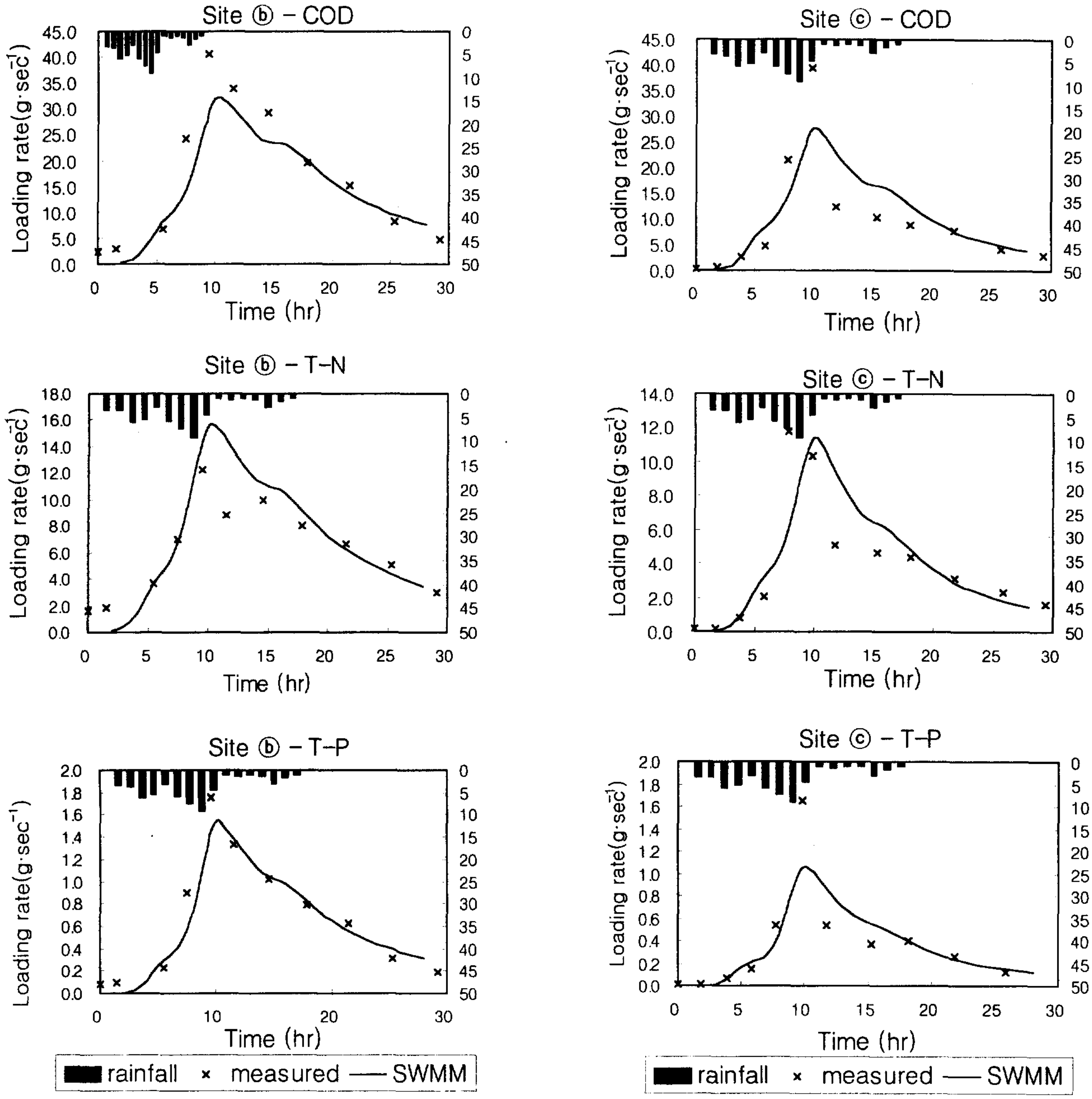

Fig. 3. Comparison of pollutant loadings between measured data and model output

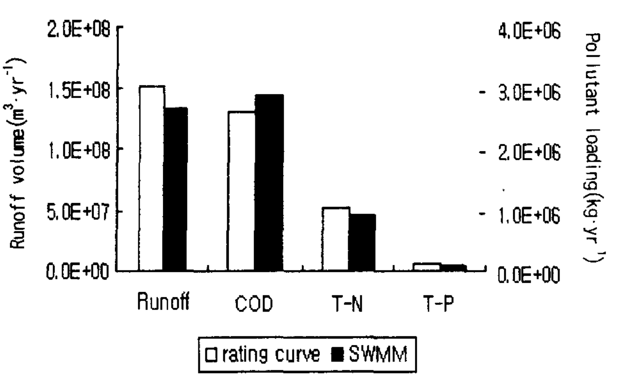

Fig. 4. Comparison of loading estimates between rating curve and SWMM

Another method used for pollutant loading estimate was applying rating curves obtained from sampling sites (Table 3 and Table 4) to the whole watershed. The flow rates of non-monitored subcatchments were calculated by area times average loading rate obtained from sampling sites. The appropriate rating curve was selected and applied to the each subcatchment to estimate pollutant loading based on land use distribution. For example, subcatchment I-5 used the curves for sampling site ⓑ because the land use distribution of it was similar to the one of subcatchment III-1 at which sampling site ⓑ located.

Table 5. Comparison of loading estimates from Wha-Ong watershed in 1999

sub-catchment	Runoff volume		COD		T-N		T-P	
	SWMM	Rating curve	SWMM	Ratingcurve	SWMM	Ratingcurve	SWMM	Ratingcurve
Ⅰ-1	805,295	1,003,339	9,231	9,741	4,992	5,091	215	299
Ⅰ-2	2,221,848	2,780,408	31,055	33,347	14,591	15,474	634	1,138
Ⅰ-3	5,958,481	7,238,166	66,017	105,865	16,746	43,936	1,434	3,987
Ⅰ-4	4,658,821	4,958,765	101,441	60,880	42,729	27,930	2,749	2,117
Ⅰ-5	13,327,727	16,387,234	236,132	283,941	70,920	107,124	4,995	11,633
Ⅱ-1	8,945,716	8,790,588	296,538	271,724	107,094	116,868	9,044	12,515
Ⅱ-2	1,830,513	1,946,158	10,276	21,677	7,981	10,487	701	713
Ⅱ-3	3,068,015	3,316,942	68,255	77,213	29,927	39,549	2,280	3,710
Ⅱ-4	2,800,877	3,324,784	18,337	41,382	10,862	18,807	956	1,439
Ⅱ-5	5,634,599	6,114,186	68,655	78,398	22,023	35,098	1,384	2,786
Ⅱ-6	1,961,151	2,181,256	28,022	24,877	11,998	11,875	835	828
Ⅲ-1	11,227,179	12,378,818	228,333	183,726	64,400	75,755	5,199	7,021
Ⅲ-2	26,831,907	29,577,593	884,111	525,926	264,251	195,889	24,659	21,986
Ⅲ-3	5,729,255	7,531,050	157,902	111,058	42,701	45,879	3,273	4,200
Ⅳ-1	4,295,580	4,247,623	72,916	50,501	26,886	23,591	1,843	1,729
Ⅳ-2	1,947,514	2,285,267	20,674	23,892	76,520	11,998	222	767
Ⅳ-3	4,894,388	5,832,095	77,520	74,052	23,390	33,336	978	2,619
Ⅳ-4	3,064,048	3,410,719	51,352	42,052	15,807	19,337	941	1,487
Ⅳ-5	25,332,150	29,286,519	451,087	572,400	146,491	201,800	12,912	24,896
Total	134,535,063	152,591,511	2,877,854	2,593,273	931,442	1,039,825	75,252	105,871
Difference	12%		11%		10%		29%	

Overall, the two methods produced comparable results in both flow rate. Estimation of pollution from watershed is an inexact science, and many variables affect pollutant migration. Considering these limitations, the outcome of two methods was comparable and the difference was within the tolerance. Generally, SWMM estimated slightly less loading than the one by rating curve for each subcatchment, and the reason might be a relatively lower flow rates compared to the rating curve method.

The subcatchments Ⅲ-2 and Ⅳ-5 had the largest area with 20 and 19% of total watershed, respectively, and showed similar loadings by rating curve method because they both used same curves from sampling site ⓒ. However, loading from Ⅲ-2 was about double the one from Ⅳ-5 in SWMM estimates for each constituent because the former subcatchment included more livestock area than the latter. The difference in livestock area can make large difference on pollutant loading because its export coefficient was significantly larger than other land uses. Land use effects can be incorporated in SWMM conveniently while it can hardly be incorporated in rating curve methods unless unit loads and delivery ration for all land uses are identified. Most subcatchments showed more loadings in SWMM but some subcatchments showed the opposite, and the less flexibility in rating curve method could partly explain the discrepancy.

Rating curves are exercise attempted at most monitoring sites and has a historical basis in sediment discharge rating curves developed as a function of flow rate in natural river channels (Donigian et al., 1995). However, the problem experienced for the estimation of diffuse pollution was that they were developed from subcatchments with specific land use distribution, and their application to other sites was difficult if land use distribution was significantly different. Caution should be taken to apply the rating curves beyond the original data set from which the relationships were derived. They are subject to large potential errors when used to extrapolate to different sites.

In the calibration procedure of this study, the SWMM demonstrated good agreements between measured and predicted data in flow rate and pollutant loading. It has a variety of options for quality simulations including traditional buildup and washoff functions, as well as rating-curves and regression techniques. Advantages of SWMM compared to the rating curve method in pollutant loading estimates include well-known accuracy in flow rate prediction and adequate incorporation of land use effects.

Rating curve method can be more accurate for the site where continuous monitoring is available. Estimation of total loading from the whole watershed will become accurate if all the tributaries are monitored. However, it appears to be not practical and there should be a more feasible approach for loading estimate. One supplemental approach for the rating curve method is an incorporation of emission and delivery ratio concept. Efforts were made to estimate the emission of pollutants from source area and delivery ratio to the sampling sites. The emission was estimated by unit load and land uses, but delivery ratio of pollutants for each land use could not be clearly separated. Instead, SWMM provided a reasonable approximation of the measured data in flow rate and loading for sampling sites, and it also could be applied to other subcatchments more logically.

CONCLUSIONS

Rating curve and SWMM methods were applied to estimate pollution loading from Wha-Ong watershed in Kyunggi-Do, and the results can be summarized as below.

1. Rating curves derived from sampling sites illustrated high correlation coefficients between flow rates and pollutant loadings for sampling sites. In application of these rating curves to other sites, land use effects could not be incorporated logically and only limited accuracy was expected. The difficulty of extrapolation of rating curves was experienced throughout the study and the loading estimate was less confident.
2. SWMM calibration process approximated field data reasonably, and the calibrated model was applied to the whole watershed. The pollutant loading estimated by SWMM was slightly higher than the one by rating curves, but the difference was not significant considering diffuse pollution characteristics of wide variation. SWMM was proved to be satisfactory in estimation of diffuse pollution loading from nonurban area, and its great flexibility worked well to describe complex land uses and their effects.
3. Both of rating curve and SWMM methods, generally, were satisfactory in estimation of pollutant loading of nonurban area. Neither of them could exactly describe complex natural phenomena, but SWMM was preferred in this study due to its flexibility and logical hydrologic processes including land use effects.

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