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Analysis of pollutant build-up model applied to various urban landuse

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Abstract. This study was conducted to analyse the application of pollutant build-up model on various urban landuses and to characterize pollutant build-up on urban areas as a source of stormwater runoff pollution. The monitored data from impervious surfaces in urban areas such as commercial (8 sites), industrial (10 sites), road (8 sites), residential (10 sites), recreational (5 sites) from 2008 to 2016 were used for the analysis of pollutant build-up model. Based on the results, the average runoff coefficients vary from 0.35 to 0.61. In all landuses except recreational landuse, the runoff coefficient is 0.5 or more, which is the highest in the commercial area. Commercial landuse where pollutants occur at the highest EMC in all landuse, and it is considered that NPS management is necessary compared with other landuses. The maximum build-up load for organic matter (BOD) was highest in the commercial area (4.59 g/m^2), and for particular matter (TSS) in the road area (5.90 g/m^2) while for nutrient (TN and TP) in the residential area (0.40 g/m^2, 0.14 g/m^2). The rate constants ranged from 0.1 to 1.3 1/day depending on landuse and pollutant parameters, which means that pollutant accumulation occurs between 1 and 10 days during dry day. It is clear that these build-up curves can generally be classified based on landuse. Antecedent dry day (ADD) is a suitable and reasonable variable for developing pollutant build-up functions. The pollutant build-up curves for different landuse shows that these build-up curves can be generally categorized based on landuse.

Keywords: Antecedent dry day (ADD); build-up; nonpoint source; stormwater runoff; urban

1. Introduction

Increasing stormwater runoff due to urbanization is a challenging issue in urban areas. Typical urban stormwater runoff pollutants include particulate matter, coliform, nutrients and heavy metals. Moreover, these pollutants put considerable stresses on receiving waters which consequently put risks to aquatic systems and human health (Tsihrintzis and Hamid 1997, Field *et al.* 1998, Tobio *et al.* 2015).

The sources of urban runoff pollution include wet and dry atmospheric deposition such as street dirt, traffic emissions, erosion, and road de-icing chemicals. Dry deposition includes dust particles that arise from unpaved roads, parking lots, construction and demolition sites, urban refuse litter or garbage, surrounding soils, and industrial activities (Kim *et al.* 2006). Pollutant accumulation in urban areas during dry periods is referred to as pollutant build-up. The influential factors affecting the load of accumulated pollutants depend on the landuse, traffic volume, and climate (Egodawatta and Goonetilleke 2006).

Landuse significantly influences the nature of anthropogenic activities, which are closely related to pollutant generation and accumulation on catchment surfaces and eventually, wash off (Li *et al.* 2008). Since landuse is a parameter which affects pollutant generation and accumulation, the logical approach to assess the influence of landuse on stormwater quality should be based on its pollutant build-up characteristics. Pollutant build-up is a dynamic process which is resultant of pollutant deposition, re-suspension, and removal (Duncan 1995). Typically, the pollutant build-up process is represented by the increasing rate function with ADD, until reaching a maximum build-up (Sartor and Boyd 1972). In effect, the load and composition of build-up pollutants available at the end of an antecedent dry period will influence the load and the composition of pollutants in wash-off. In fact, the pollutant wash-off load is a fraction of the pollutants available in build-up at the beginning of a storm event, and the fraction wash-off depends on rainfall, impervious surface, and pollutant characteristics (Egodawatta *et al.* 2007).

Therefore, the objective of this study is to identify the variations in pollutants build-up in different landuses. This study was conducted to analyse the application of pollutant build-up model on various urban landuses and to characterize pollutant build-up on urban areas as a source of stormwater runoff pollution.

2. Materials and methods

2.1 Monitoring area

The monitoring data used in this study cites rainfall runoff monitoring project report. Fig 1 shows the location of monitoring sites and Table 1 shows the specific location and catchment area of monitoring sites. The monitored data from impervious surfaces in urban area such as commercial

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Table 1 Specific location and catchment area of the monitored sites

Landuse	Code	Catchment area(m^2)	Location	Landuse	Code	Catchment area(m^2)	Location
Commercial	C-1	1,800	35°15'56.2"N 128°37'17.7"E	Road	R2-1	149	37°56'13.3"N 127°47'01.8"E
	C-2	4,788	36°20'42.3"N 127°22'54.0"E		R2-2	1,240	35°14'40.5"N 128°40'27.1"E
	C-3	6,100	36°23'29.7"N 127°18'51.2"E		R2-3	1,500	35°09'21.4"N 128°07'06.2"E
	C-4	8,000	37°24'49.1"N 127°07'53.1"E		R2-4	2,000	35°45'28.6"N 128°22'21.2"E
	C-5	10,384	35°09'26.6"N 126°51'07.4"E		R2-5	3,080	35°14'32.2"N 128°41'29.2"E
	C-6	10,960	35°13'17.8"N 128°40'31.8"E		R2-6	7,700	35°09'44.3"N 128°33'51.1"E
	C-7	12,586	35°09'33.6"N 126°50'50.1"E		R2-7	10,140	35°09'03.0"N 128°07'04.7"E
	C-8	20,000	37°24'58.1"N 127°09'01.7"E		R2-8	12,400	35°09'35.9"N 128°34'48.1"E
Industrial	I-1	1,507	36°26'43.1"N 127°24'26.6"E	Residential	R3-1	2,870	36°20'31.0"N 127°29'33.3"E
	I-2	1,771	35°04'16.5"N 126°44'28.3"E		R3-2	10,087	37°20'28.7"N 127°07'37.3"E
	I-3	2,950	37°26'35.4"N 127°10'48.8"E		R3-3	11,970	37°35'21.3"N 127°07'55.0"E
	I-4	12,000	35°18'14.0"N 128°52'34.0"E		R3-4	13,454	35°10'24.1"N 126°53'49.7"E
	I-5	12,546	37°26'30.9"N 127°10'48.0"E		R3-5	16,582	35°13'13.5"N 128°41'15.9"E
	I-6	13,000	35°05'54.8"N 128°51'10.4"E		R3-6	20,570	37°35'40.5"N 127°07'58.5"E
	I-7	16,655	37°26'35.3"N 127°10'17.8"E		R3-7	21,465	35°10'51.3"N 128°03'46.1"E
	I-8	23,520	36°16'26.3"N 127°35'21.1"E		R3-8	22,660	37°35'08.3"N 127°08'13.3"E
	I-9	55,474	35°52'07.1"N 128°49'44.7"E		R3-9	26,302	37°20'23.6"N 127°07'11.6"E
	I-10	1,206,730	35°10'24.9"N 128°06'50.3"E		R3-10	29,510	37°35'16.2"N 127°08'39.9"E
Recreational	R1-1	7,304	37°35'41.0"N 127°22'41.5"E				
	R1-2	15,883	35°10'51.3"N 126°53'04.7"E				
	R1-3	25,700	36°21'36.7"N 127°21'25.6"E				
	R1-4	28,333	35°13'26.0"N 126°50'40.5"E				
	R1-5	34,116	35°13'25.9"N 128°39'37.6"E				

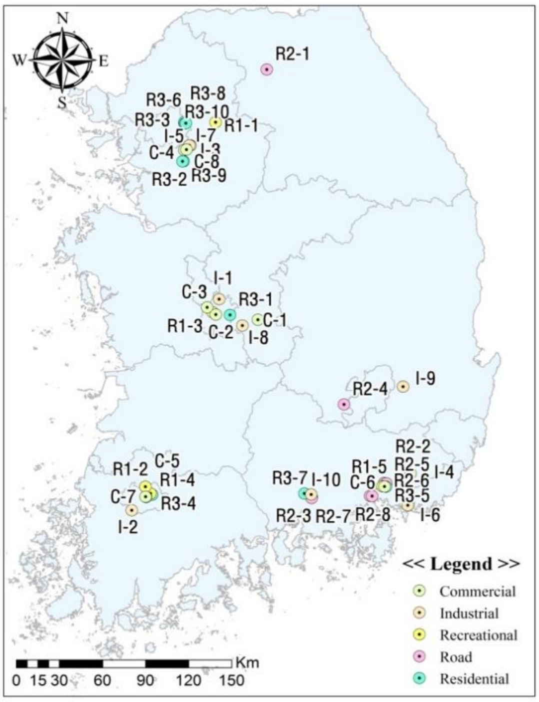

Fig. 1 Location of the monitored sites

(8 sites), industrial (10 sites), road (8sites), residential (10 sites), recreational (5 sites) during 2008 to 2016 were used for the analysis of pollutant build-up model. The smallest catchment area site, R2-1, is 149 m^2 and the largest area, I-10, is 1,206,730 m^2. Monitoring was conducted using the runoff monitoring method (NIER 2012).

2.2 Pollutant build-up functions

In urban nonpoint source pollution models, pollutant build-up and wash-off modules are the core components. In most previous studies, build-up models are based on ADD and have been expressed as linear, power, exponential, or other functions with respect to time. Many models adapt the exponential representation because it is simple and can be derived as a first-order process (Kim *et al.* 2006, Wang *et al*. 2011). It has been used to develop pollutant accumulation models in many approaches on urban surface pollutant accumulation process (Sutherland and Jelen 1998). Pollutant build-up that accumulates within a landuse category is described by mass (kg) per unit of sub-catchment area or curb-length. The amount of build-up B (kg/ha) is a function of the number of antecedent dry days (t) and landuse type and is computed using Eq. (1) (Rossman 2010):

$$B=C_1(1-e^{-C_2 t}) \tag{1}$$

where C_1 is the maximum possible build-up (kg/ha) and C_2 is the build-up rate constant (1/day) as a function of landuse.

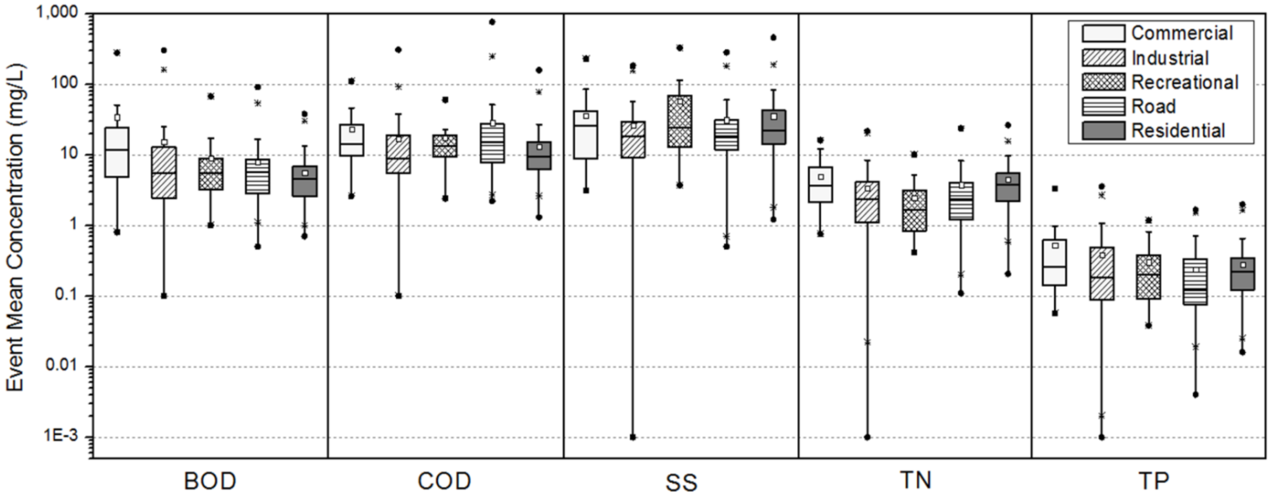

Fig. 2 Comparison of pollutants EMC for all landuse

Table 2 Statistical summary of the monitored events for various landuses (mean ± standard deviation)

Landuse	Monitoring period	Antecedent dry day (ADD, day)	Total rainfall (mm)	Rainfall duration (hr)	Runoff coefficient
Commercial	2009.03-2014.11	7.4±5.0	29.9±37.3	11.3±10.0	0.61±0.22
Industrial	2011.04-2015.11	6.2±5.3	26.8±30.0	8.3±7.4	0.50±0.31
Recreational	2009.03-2015.10	5.7±4.0	32.2±24.3	10.9±5.3	0.35±0.26
Road	2009.05-2014.09	6.8±5.9	29.4±27.8	9.2±6.6	0.53±0.23
Residential	2008.03-2016.09	6.5±4.9	43.7±69.3	17.8±22.8	0.50±0.23

2.3 Model calibration and verification

In this study, the Levenberg-Marquardt method was chosen for model calibration. The best fitting parameters were estimated and determined with the objective of minimizing the sum of squared residuals (SSE). The value of the Nash-Sutcliffe model efficiency (NSE) coefficient should be near 1.0 for both hydraulic and water quality. The NSE was used to assess the prediction reliability of the simulation model.

3. Results and discussion

3.1 Hydrologic characteristics in various landuse

Table 2 summarizes the site information and event descriptions. ADD, rainfall duration, total rainfall, and runoff coefficients. Average event rainfall varied from 26.8 to 43.7 mm, and average antecedent dry days varied from 5.7 to 7.4 days. The average runoff coefficients vary from 0.35 to 0.61, with lower values occurring during smaller events. The lower coefficient reflects infiltration and evaporation during the event, which are more significant in smaller events. Antecedent dry periods are also known to affect runoff coefficients. In all landuses except recreational landuse, the runoff coefficient is 0.5 or more, which is the highest in the commercial area. The runoff coefficient is closely related to direct runoff and is affected by landuse. According to the Sewerage system standard (KWWA 2011), the range is 0.60 to 0.75 for urbanized area and 0.10 to 0.40 for landscaped and area.

Table 3 Estimated parameter values for the build-up model

Landuse	C_1(g/m^2)				C_2 (1/d)			
	BOD	SS	TN	TP	BOD	SS	TN	TP
Commercial	4.589	1.344	0.184	0.089	0.398	0.432	0.280	0.159
Industrial	0.654	1.912	0.275	0.030	0.901	1.101	1.349	0.436
Recreational	0.176	1.829	0.066	0.011	0.730	0.074	0.660	0.671
Road	0.176	5.900	0.150	0.021	0.730	0.162	0.506	0.221
Residential	0.675	2.655	0.400	0.140	0.653	0.464	0.753	0.054

3.2 Pollutant EMC

Investigating the influence of landuse on stormwater quality is also important to derive a holistic understanding of the influence of catchment characteristics on urban stormwater quality. Fig. 2 shows the pollutants EMC for all landuse. As a result of EMC calculation by landuse, BOD, SS, TN, and TP were found to be 5.6 to 34.0 mg/L, 26.0 to 57.8 mg/L, 2.43 to 4.94 mg/L and 0.24 to 0.52 mg/L, respectively. All pollutant parameters except SS were the highest in commercial areas. The maximum BOD, TN and TP EMC were highest in the commercial area, while SS EMC in the recreational area. In the case of the recreational area, there was a high SS EMC value due to the large amount of soil in the landscape and playground during rainfall. Reflecting these results, it is concluded that the commercial area where pollutants occur at the highest EMC in all landuse, and it is considered that NPS management is necessary compared with other landuses.

3.3 Analysis of pollutant build-up

The best fitting parameter values in the build-up model were estimated for four types of pollutants (BOD, SS, TN,

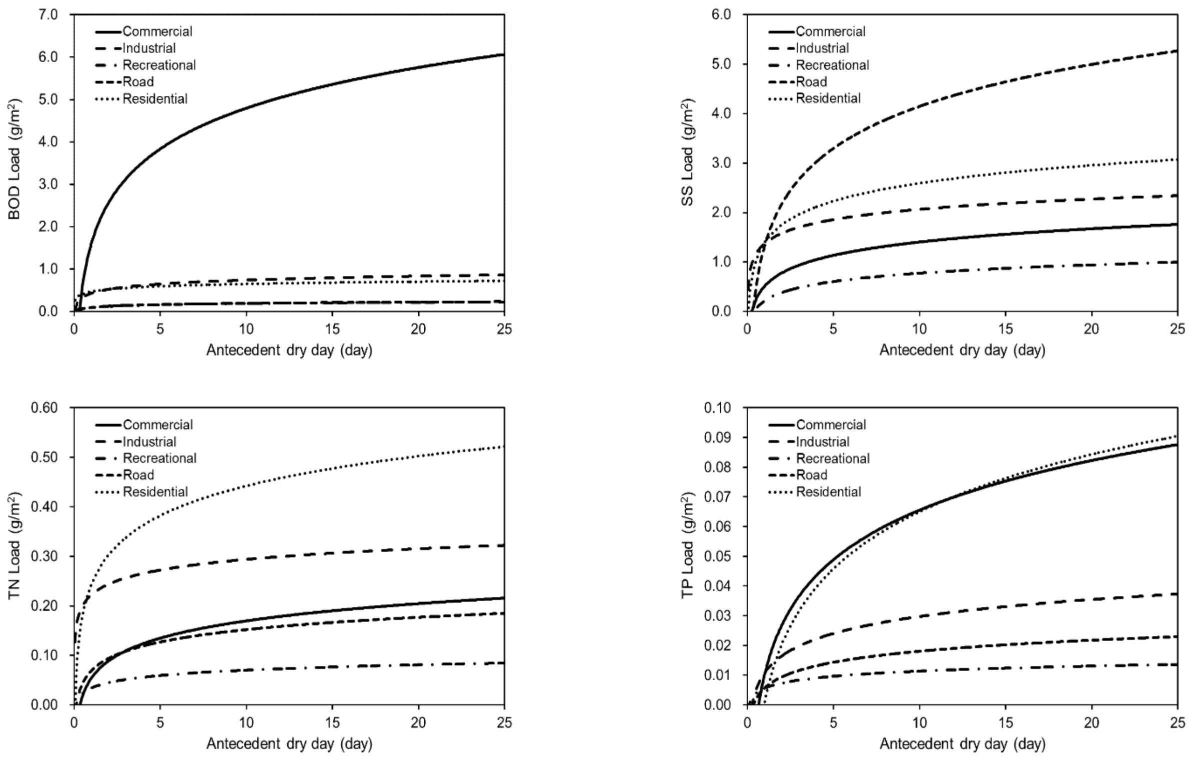

Fig. 3 Relationship between the pollutant loads and antecedent dry days

and TP) as presented in Table 3. C_1 ranged from 0.176 to 4.589 g/m^2 for BOD, 2.655 to 5.900 g/m^2 for SS, 0.066 to 0.400 g/m^2 for TN, and 0.011 to 0.140 g/m^2 for TP. The maximum C_1 for BOD was highest in the commercial areas, that for SS was highest in the road areas, while those for nutrients were highest in the residential areas. The physical meaning of C_2 is the pollutant removal rate in dry weathers. The rate constants ranged from 0.1 to 1.3 1/day depending on landuse and pollutant parameters, which means that pollutant accumulation occurs between 1 and 10 days during the dry days.

Fig. 3 shows the pollutant build-up curves for different landuses. This figure shows the changes in the accumulation amount of pollutants as the ADD increases by landuse. Therefore, it is possible to estimate the pollutant accumulation load according to the ADD. According to Egodawatta *et al.* (2007), more than 66% of the particulate matter accumulates over 2 days in the dry season. In all landuses, the accumulation of pollutants gradually increased from 5 to 10 days of ADD. BOD has the highest accumulation in the commercial area (4.589 g/m^2), while it has the lowest value on the road (0.176 g/m^2). On the other hand, SS has the highest accumulation on the road (5.900 g/m^2) and low value in the commercial area (1.344 g/m^2). Nutrients (TN and TP) showed the highest value in the residential area (0.400 and 0.140 g/m^2), but the lowest value in the road (0.150 and 0.021 g/m^2). It is evident that these build-up curves can be generally categorized based on landuse.

Pollutant load in storm runoff depends not only on ADD and total runoff volume, but also on landuse, wind speed, traffic, rainfall intensity, bottom shear stress, and other factors (Kim *et al.* 2006). It is difficult to obtain sufficient data to cover all possible factors affecting pollutant wash-off (wind speed, traffic, rainfall intensity), but exploratory data analysis suggests that several factors dominate pollutant wash-off. ADD is an important factor which directly affects accumulated pollutant amount on a catchment surface. Other factors, such as wind speed, traffic, and bottom shear stress vary greatly and are hard to be quantified and monitored. Therefore, ADD is a suitable and reasonable variable for developing pollutant build-up functions (Wang *et al.* 2011).

Table 4 Comparison of NSE coefficients of the build-up model

Landuse	BOD	SS	TN	TP
Commercial	0.225	0.283	0.248	0.625
Industrial	0.085	0.292	0.065	0.257
Recreational	0.147	0.572	0.512	0.997
Road	0.147	0.916	0.288	0.468
Residential	0.195	0.118	0.153	0.667

Table 4 presents the comparison of Nash-Sutcliffe Efficiency Coefficients of build-up model. The accordance degrees between measured and predicted load of SS and TP are better than those of BOD and TN. NSE ranges between -∞ and 1.0 (1 inclusive), with NSE = 1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values < 0.0 indicates that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance (Moriasi *et al.* 2007). The limitations of this study are confirmed through NSE analysis. In this study, sufficient collection and analysis of water quantity and quality data are needed to improve the low NSE value. It is also required to consider other factors than ADD in the accumulation of pollutants. In particular, statistical analysis should be additionally considered to increase confidence in the monitoring data.

4. Conclusions and recommendations

This study was conducted to analyse the application of pollutant build-up model on various urban landuses and to characterize pollutant build-up on urban areas as a source of stormwater runoff pollution. The results of the study are as follows:

- The average runoff coefficients vary from 0.35 to 0.61. In all landuses except recreational landuse, the runoff coefficient is 0.5 or more, which is the highest in the commercial area. Commercial landuse where pollutants occur at the highest EMC in all landuse, and it is considered that NPS management is necessary compared with other landuses.
- In all landuses, the accumulation of pollutants gradually increased from 5 to 10 days of ADD. The maximum build-up load for organic matter was highest in the commercial area, and for particulate matter in the road area while for nutrient in the residential area. It is evident that these build-up curves can be generally categorized based on landuse.
- ADD is a suitable and reasonable variable for developing pollutant build-up functions. The pollutant build-up curves for different landuse evident that these build-up curves can be generally categorised based on landuse.
- The build-up model was used to represent available field measurements collected from various urban landuse and also, the data were used to estimate the parameters of all of the different pollutants build-up equations used in the model. The estimated parameters revealed which of the different pollutants build-up equations best represented the field data. It should be noted that other user-defined pollutants build-up models can be integrated into the model. With further application of the model on various landuse, a range of values for the different model parameters can be established.

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