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Multiple linear regression models of urban runoff pollutant load and event mean concentration considering rainfall variables

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Abstract

Rainfall is an important factor in estimating the event mean concentration (EMC) which is used to quantify the washed-off pollutant concentrations from non-point sources (NPSs). Pollutant loads could also be calculated using rainfall, catchment area and runoff coefficient. In this study, runoff quantity and quality data gathered from a 28-month monitoring conducted on the road and parking lot sites in Korea were evaluated using multiple linear regression (MLR) to develop equations for estimating pollutant loads and EMCs as a function of rainfall variables. The results revealed that total event rainfall and average rainfall intensity are possible predictors of pollutant loads. Overall, the models are indicators of the high uncertainties of NPSs; perhaps estimation of EMCs and loads could be accurately obtained by means of water quality sampling or a long term monitoring is needed to gather more data that can be used for the development of estimation models.

Key words: event mean concentration (EMC); multiple linear regression model; load; non-point sources; rainfall; urban runoff

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Introduction

Stormwater runoff from urban areas can be highly polluted with various materials, indicating a significant non-point source (NPS) of pollution to receiving water bodies (US EPA 1983; Shaver, 1986; FHWA, 1996; Brezonik and Stadelmann, 2002; Kim et al., 2005). A number of factors affect the quantity and quality of urban runoff even before treating it using stormwater management practices and finally reaching the receiving water bodies. Site and event parameters found to have significant influences on urban runoff include total event rainfall, antecedent dry period, cumulative seasonal rainfall, drainage area, and annual average daily traffic. The intensity, washed-off rate, and the dilution effects of accumulated contaminants, and their transportation to the receiving waters, depend on the rainfall intensity and runoff volume during the rainfall period (Chui et al., 1982; Tsihrintzis and Hamid, 1997). Irish et al. (1998) and Brezonik and Stadelmann (2002) determined that loads for each constituents were dependent upon a unique subset of variables and that processes responsible for the generation, accumulation, and washoff of urban runoff pollutants are constituent-specific. Geographic and physical factors such as the type and intensity of urban land use, degree of imperviousness, tree cover, soil type and slope are also important parameters that may impact the quality of urban runoff (Sonzogni et al., 1980; Chui et al., 1982; Graves et al., 2004; Kayhanian et al., 2007). The extent to which urban runoff impacts the receiving water quality is still difficult to quantify although causal variables are known. Nonetheless, it is difficult to predict impacts, and design appropriate management and control practices without site-specific data (Brezonik and Stadelmann, 2002).

Runoff monitoring in Korea identified that highways are important pollutant sources in all landuse types (Lee et al., 2008). Some of the landuse types in that study are transportation related like highways (including roads, service areas and toll-gates); parking lots and bridges. Mean concentrations were reported as follows: 93.31 mg/L for total suspended solids (TSS), 91.22 mg/L for chemical oxygen demand (COD), 3.02 mg/L for total nitrogen (TN), 0.71 mg/L for total phosphorus (TP), and 0.28 mg/L for zinc (Zn). In addition, the pollutant unit loads in urban areas (i.e., paved surfaces) generated biochemical oxygen demand (BOD), TN and TP of about 6 to 85 times greater than that in forest areas. Nonetheless, soil loss rates are 7 to 80 times larger than areas under development in comparison to undisturbed areas (Maniquiz et al., 2009). Moreover, construction erosion was identified as the most common sources of urban pollution wherein the magnitude of soil loss rates depend mainly upon the construction activity. The study of NPS pollution is essential for the successful operation of the total maximum daily load (TMDL) program in Korea. TMDL is defined as the summation of the

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point and NPS loadings and a margin of safety corresponding to ten percent of the NPS loadings. Consistent studies and monitoring works have been conducted since 2004 to determine the impact of site and event characteristics on NPS pollutant concentrations and loads as well as to develop stormwater management policies and treatment systems for future implementation. In addition, the Water Environment Management Master Plan, a framework for planning a nationwide water environment management policy in Korea to secure and preserve aquatic ecosystem was established in 2006 and will be implemented until 2015 (Jung et al., 2008).

Due to the impacts on receiving waters and the expense involved in obtaining monitoring data on nonpoint source pollution data, interest has grown in analyzing existing/measured data to develop estimation models for urban stormwater loads and concentrations (Ashley et al., 1997; Brezonik and Stadelmann, 2002; Thomson et al., 2007). Such models will be very helpful to estimate concentrations for unmonitored watersheds. Consequently, parameters which are relatively easy to monitor can serve as indicators to other constituents reducing labor and time. This sort of data summary and analysis was done particularly in the United States in several metropolitan areas and sites (Driver and Tasker, 1990; US EPA, 1983). However, most of the studies are only related to loading estimates and not actually concentration estimates. Because many streams of concern in an urban area consist primarily of stormwater runoff during wet weather, the ability to predict the distribution of event mean concentration (EMC) is useful for the assessment of levels of exceedance of water quality standards. Some regression analysis has been performed to try to relate loads and EMCs to catchment, demographic, and hydrologic characteristics (Tasker and Driver, 1988). Rainfall, runoff, and quality data were assembled for 98 urban stations in 30 cities in the United States for multiple regression analysis by the United States Geological Survey (Tasker and Driver, 1988; Driver and Tasker, 1988). Thirty-four multiple-regression models (mostly log-linear) of storm runoff constituent loads and storm runoff volumes were developed, and 31 models of storm runoff EMCs were developed. Regional and seasonal effects were also considered. The two most significant explanatory variables were total storm rainfall and total contributing drainage area. Models for estimating loads of dissolved solids, TN, and total ammonia plus organic nitrogen (total Kjeldahl nitrogen) typically were the most accurate, whereas models for suspended solids were the least accurate. The most accurate models were those for the more arid Western United States, and the least accurate models were those for areas that had large mean annual rainfall. Although many loading estimates have been reported for various landuses, high variability and inconsistencies exist among reported values. These differences may represent real variations or differences in sampling and analytical methods.

This research was conducted to develop estimation models of pollutant loads and EMCs from urban stormwater runoff as a function of rainfall variables using linear multiple regression analysis. The rainfall and runoff variability was explored by means of investigating correlations of parameters using the two-year data gathered from monitoring field works and experiments at two urban sites during rainfall events.

1 Materials and methods

1.1 Study sites

The two sites selected for this study were part of the national best management practice (BMP) pilot projects managed by the Ministry of Environment located at Yongin City, Gyeonggi Province, Korea. The road catchment having an impervious area of 5000 m^2 is a four-lane curbed urban road with a center median and asphalt surface. Runoff from the road drains at one particular discharge location (a beveled culvert inlet in the grass ditches where the water quality data were collected) and leads into an infiltration trench for stormwater treatment before discharging into the nearby stream. Another site is the Vehicle Registration Office parking lot paved with asphalt and 100 percent impervious. The surrounding land use consists of a mix of apartments, commercial and light industrial. The total contributing area to the surface runoff is 10,700 m^2. Runoff from the parking lot was directed into a filtration system for treatment where the runoff quality sampling point was located. Rainfall events in the study site are shown in Fig. 1.

1.2 Runoff sampling

Forty five rain events from June 2006 to October 2008 were monitored. Grab samples were taken from the runoff following the sampling strategy employed to characterize runoff both for long and short rain storms and with heavy or light rainfall (Caltrans, 2000). Samples were analyzed for typical water quality pollutants including TSS, BOD, COD, and dissolved organic carbon (DOC), inorganic metals such as lead (Pb), Zn, and iron (Fe), nutrients (TN, TP), oil and grease (OG), etc. Hydrologic data were gathered from each event which includes antecedent dry day, event rainfall, runoff duration, rainfall intensity and runoff rate.

1.3 Calculations and modeling

The pollutant EMCs and loads were calculated to assess the characteristics of stormwater runoff quality and quantity of the monitored events and were used to determine correlations (using Pearson *r* correlation method) between the key pollutant of concern and four chosen rainfall variables; total rainfall (RAIN), antecedent dry day (ADD), rainfall duration (RAINDUR) and average rainfall intensity (AVGINT). Multiple linear regression (MLR) analysis was carried out to develop estimation models of total pollutant EMC and load with significant correlations to rainfall variables. SYSTAT 12 package software (SYSTAT Software, Inc., 2007) and OriginPro 7.5 SRO v7.5714 (B714) (OriginLab Corporation 1991-2003) were used for all statistical analysis of data and

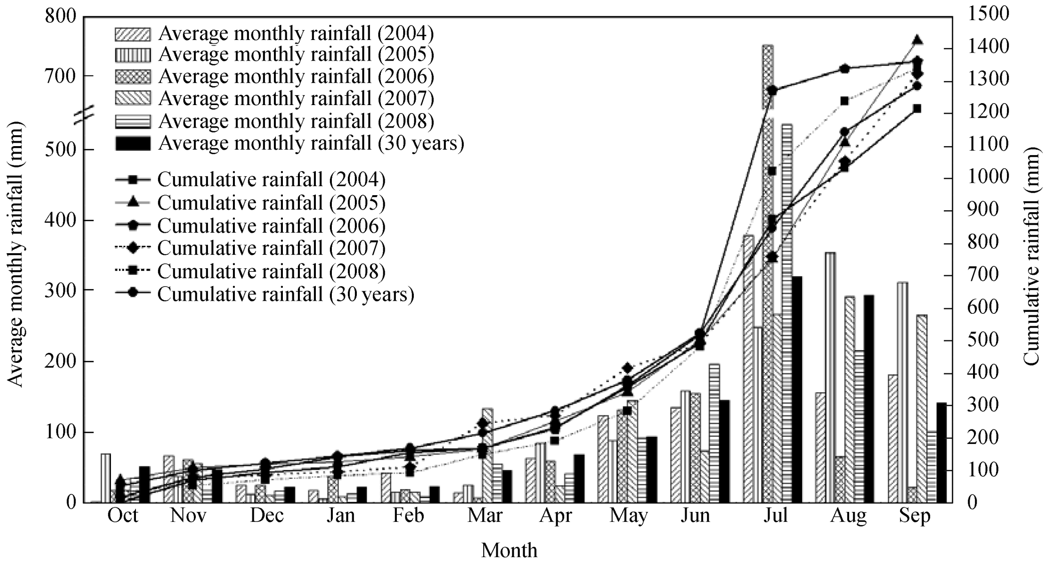

Fig. 1 Rainfall in the study site.

development of estimation models.

2 Results and discussion

2.1 Rainfall and runoff characteristics

In Korea, the rainfall usually changes much along the year and somewhat differs each year (Fig. 1). The summer, period with the highest temperatures and evaporation rates is the rainy season, and lasts for three to four months. The monthly rainfall average measurements in a 30 year period shows variations between a minimum of 23 mm (January) and a maximum of 324 mm (July). Eighty-two percent of the total yearly rainfall occurs in five months of the year, from May to September. During the summer season the antecedent dry periods are considerably shorter than in the rest of the year, typically less than a week which at times contributes to less runoff. If the rainfall pattern (intensity and duration) is different it may be adequate to evaluate and model pollutant loads and concentrations based on rainfall data.

Table 1 summarizes the monitored rainfall and runoff events during the period of study. ADD, RAIN and AVGINT show high variation (100% of the mean) and have relatively few high values (positive skew). RAIN is relatively high but only 39% of the events had greater than 20 mm of rainfall and approximately only 22% of the events produced less than 5 mm of rainfall. RAINDUR has a mean and median value of 7 hr and appears as normally distributed. The RAINVOL and RUNVOL are well correlated ($R^2 = 0.87$, $p < 0.001$) attributed to the similar physical characteristics of the sites. RUNVOL was between 17% and 37% of the total volume of rainfall, such small values may be due to low rainfall intensities.

2.2 Runoff quality and variability

EMC is a statistical parameter commonly utilized in stormwater studies as characteristics for runoff concentrations. An EMC is defined as the total mass load of a parameter yielded from a site during a storm divided by the total runoff water volume discharged during the storm (Kim et al., 2005). Pollutant loads are calculated based on EMC and runoff flow rate. Table 2 presents the statistics of EMC and load for some of the constituents measured. Loads vary to a large extent for all pollutants as shown by the standard deviations; variations are between 135% and 200% of the mean while 50% to 125% in the case of EMCs. Among the EMCs, the largest variability was observed in TSS, OG, and Pb. In most runoff studies, EMCs vary from event to event and coefficient of variation (CV) of 0.75 or higher has been found as a typical value (US EPA, 1983; FHWA, 1996). Although exceptions have been stated, the lognormal probability distribution seems to represent well the EMC distribution for several pollutants (FHWA, 1996; Hvitved-Jacobsen and Yousef, 1991; Smullen et al., 1999).

The average TSS EMC (76 ± 95 mg/L) obtained in this

Table 1 Summary of monitored events for combined sites (2006/06–2008/10)

	ADD (day)	RAIN (mm)	RAINDUR (hr)	AVGINT (mm/hr)	RAINVOL (m^3)	RUNVOL (m^3)
No. of events	45	45	45	45	45	45
Minimum	1	1.5	1	0.21	7.5	0.1
Maximum	33	84	14	16.2	594	157
Median	4	13	7	2	80.3	13.3
Mean ± SD	7.04 ± 7.2	20.4 ± 20.3	6.9 ± 4.1	3.3 ± 3.3	152 ± 160	33 ± 43

ADD: antecedent dry day; RAIN: total rainfall; RAINDUR: rainfall duration; AVGINT: average rainfall intensity; RAINVOL: volume of rainfall; RUNVOL: volume of runoff.
SD: standard deviation.

Table 2 Summary of EMC and load data for combined sites

Parameter	EMC (mg/L)			Load (kg)		
	95% LCL	95% UCL	Mean ± SD	95% LCL	95% UCL	Mean ± SD
TSS	47.6	104.4	76 ± 95	0.81	2.3	1.56 ± 2.42
BOD	13.6	19.7	16.6 ± 10.1	0.24	0.6	0.39 ± 0.53
COD	28.2	38.5	33.3 ± 17.2	0.5	1.4	0.93 ± 1.42
DOC	12.7	19.1	15.9 ± 10.6	0.23	0.62	0.41 ± 0.62
TN	3.5	5.2	4.3 ± 2.8	0.07	0.2	0.12 ± 0.19
TP	0.68	0.92	0.8 ± 0.4	0.02	0.05	0.022 ± 0.03
OG	0.91	1.7	1.3 ± 1.3	0.02	0.08	0.026 ± 0.05
Pb	0.81	1.6	1.2 ± 1.3	0.017	0.06	0.033 ± 0.06
Zn	0.25	0.36	0.3 ± 0.2	0.006	0.02	0.0093 ± 0.01

LCL: lower confidence limit; UCL: upper confidence limit; n = 45 for EMC and n = 43 for load.

study was smaller in comparison to other transportation sites in Korea (average TSS EMC = 93.3 mg/L) (Lee et al., 2008), specifically the parking lot site was contributing less solids than the road site. COD was almost three times smaller whereas TN and TP were 1.7 and 1.3 greater in magnitude. It was observed that a large variability of pollutant concentrations existed between different sites, which is the result of a complex interaction between many factors. It is very difficult to distinguish between the influences of variables such as the rainfall pattern, traffic density, type of pavement, existence of curbs, maintenance practices, land use of the surrounding catchment and its size, and ADD (FHWA, 1996).

Constituent seasonality is important in assessing the need to segregate the data into groups where the mean and variance indicate that the groups are from different populations. A time series for TSS and TN EMC and load were constructed (Fig. 2). It was observed that the variability was high for all the events; however, there was no seasonal trend or pattern that greatly affects either the TSS or TN EMC and load. One event in fall 2008 resulted to a peak in TSS due to the road-salting practices during the first snowmelt few days before the sampling was conducted. It was accompanied by an increased in TN EMC as well. However, both the TSS and TN loads remained on the base levels. Brezonik and Stadelmann (2002) made a seasonal analysis of urban runoff in Minnesota, USA. According to their study, the largest range in event loads for typical pollutants was during the spring and summer seasons. In addition, ranges of EMCs were also the largest in spring. However, median EMCs for nutrients such as TP and TN were greater in winter. It was comparable in this study that loads were usually high in spring to summer not only in TSS but also in the case of TN. It was safe to assume that rainfall and runoff patterns were such factors that contribute to the variability of EMCs and loads.

2.3 Correlations

To be able to determine the potential rainfall variables in estimating the EMCs and loads of pollutants of concern, correlations were investigated. Among the rainfall variables, RAIN was correlated with RAINDUR (r = 0.50) and AVGINT (r = 0.62), but duration is negatively correlated with AVGINT (r = –0.16). No significant correlation was found with ADD, only highest was RAINDUR (r = –0.24). RUNVOL and RAINVOL were also correlated with rainfall variables. RUNVOL was highly correlated with RAINVOL (r = 0.93), RAIN (r = 0.85), RAINDUR (r = 0.43) and AVGINT (r = 0.49). RAINVOL also showed relative correlations: RAIN (r = 0.87), RAINDUR (r = 0.46) and AVGINT (r = 0.56). Both RUNVOL and RAINVOL were negatively and weakly correlated with ADD (r = –0.14 and –0.15). The inter-parameter correlations among rainfall variables showed that ADD was an independent parameter and it was difficult to be used in regression models.

Correlation coefficients (r) between pollutant EMCs and loads and rainfall variables are shown in Table 3. From the correlation matrix, RAIN appears to be positively correlated with all the pollutants; r values ranged from 0.64 (TP and Pb) to 0.78 (OG). RAINDUR and AVGINT showed positive correlations to pollutant loads but some coefficients were low. BOD, COD, TN, TP, OG and Pb were better correlated to AVGINT than RAINDUR; however, TSS, DOC and Zn correlate more with RAINDUR than AVGINT. It was observed that ADD was weakly and negatively correlated to all pollutant loads (the highest was with OG, r = –0.28). These correlations were resulted due to the fact that pollutant load is a function of EMC, flow rate and catchment area which could be dependent on rainfall and runoff in particular.

Table 3 Pearson correlation coefficients (r) for pollutant loads and EMCs and rainfall variables

Parameter	ADD	RAIN	RAINDUR	AVGINT
Pollutant loads (n = 43)				
TSS	–0.02	0.71	0.39	0.31
BOD	–0.14	0.74	0.35	0.42
COD	–0.08	0.68	0.32	0.38
DOC	–0.13	0.72	0.40	0.30
TN	–0.10	0.65	0.28	0.36
TP	–0.23	0.64	0.11	0.52
OG	–0.28	0.78	0.21	0.57
Pb	–0.13	0.64	0.12	0.60
Zn	–0.20	0.65	0.39	0.26
Pollutant EMCs (n = 45)				
TSS	–0.15	–0.25	–0.10	–0.26
BOD	0.10	–0.44	–0.32	–0.29
COD	0.07	–0.30	–0.29	–0.26
DOC	–0.05	–0.29	–0.20	–0.35
TN	–0.11	–0.22	–0.14	–0.21
TP	0.26	–0.29	–0.55	0.09
OG	–0.20	–0.16	–0.32	0.01
Pb	0.03	0.07	–0.10	0.16
Zn	–0.07	–0.18	–0.02	–0.18

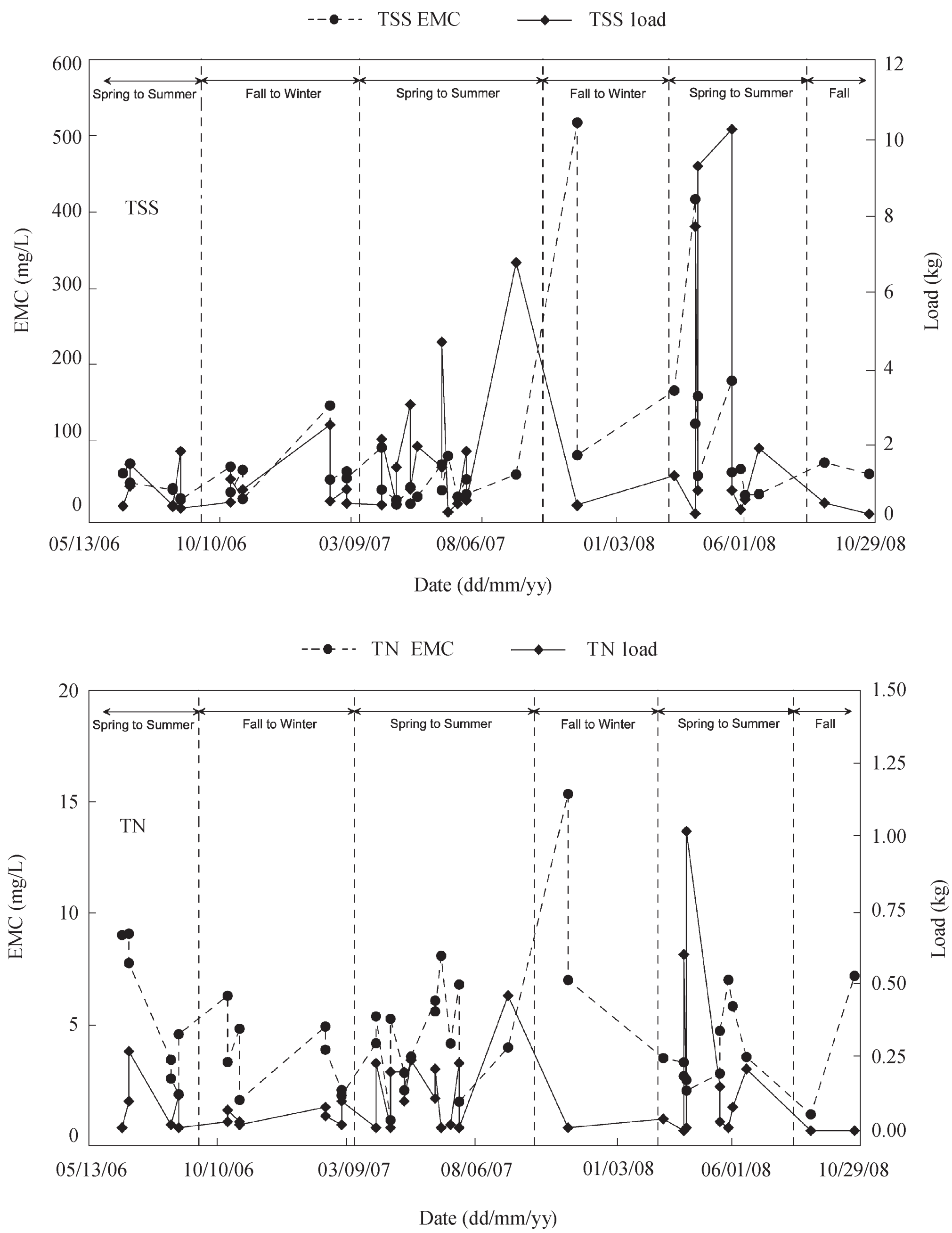

Fig. 2 Time series of EMC and load for TSS and TN.

Apparently, the rainfall variables do not display significant correlations to pollutant EMCs and mostly were negatively correlated. Unlike pollutant loads, pollutant EMCs were weakly correlated to total rainfall. The strongest relationships were for organics: BOD (r = –0.44), COD (r = –0.30), and DOC (r = –0.29). The same observation holds in the case of RAINDUR and AVGINT, where most EMCs were either negatively correlated or the coefficients were low. Due to the minimal inter-parameter correlations between EMC and rainfall variables, it was hypothesized that big rainfalls with longer duration and high intensities produce more dilute runoff. However, the weak correlations also explain that not only rainfall variables contribute to runoff pollutant loads and EMCs, other factors should also be considered.

2.4 Multiple linear regression models

The general multiple linear regression (MLR) equation used to develop estimation equations for pollutant EMCs and loads is shown as:

$$\text{EMC or load} = f(\text{ADD, RAIN, RAINDUR, AVGINT})$$
$$\text{EMC or load} = \alpha \pm \beta \times \text{ADD} \pm \gamma \times \text{RAIN} \pm \delta \times \text{RAINDUR} \pm \varepsilon \times \text{AVGINT} \quad (1)$$

where, α is the arbitrary constant; β, γ, δ, and ϵ are the dependent parameter constants; and ADD (day), RAIN

Table 4 Multiple linear regression (MLR) equations for estimating loads and EMCs*

	α	β	γ	δ	ϵ	*n*	R^2	*p*	SEE**
Pollutant loads									
TSS	0.60	–	0.12	–0.099	–0.26	43	0.55	< 0.00001	1.7
BOD	0.05	–	0.02	–0.008	–0.016	42	0.54	< 0.00001	0.37
COD	0.27	–	0.06	–0.048	–0.08	43	0.48	< 0.00001	1.06
DOC	0.16	–	0.03	–0.024	–0.07	42	0.56	< 0.00001	0.43
TN	0.05	–	0.008	–0.007	–0.01	40	0.44	0.0001	0.15
TP	0.006	–	0.0008	–0.0004	0.002	29	0.45	0.0017	0.03
Pb	–0.02	–	0.001	0.00006	0.006	39	0.48	0.00003	0.05
Zn	0.002	–	0.0005	–0.00002	–0.001	37	0.45	0.0002	0.01
Pollutant EMCs									
TSS	159	–	0.07	–4.9	–9.13	45	0.09	0.28	93.5
BOD	126	–	0.016	–0.75	–8.2	45	0.23	0.014	9.2
COD	25.6	–	–0.058	–2.12	–0.8	45	0.20	0.028	16
DOC	52	–	0.23	–1.22	–2.7	45	0.22	0.017	9.8
TN	27.5	–	0.18	–0.14	–2.09	45	0.07	0.37	2.8
TP	5.9	0.007	0.009	–0.05	–0.24	45	0.32	0.001	0.35
Pb	2.6	–	–0.002	–0.04	–	45	0.03	0.72	1.3
Zn	1.2	–	0.004	0.002	0.04	45	0.04	0.63	0.18

* All equations are expressed as: TSS load = 0.6 + 0.12RAIN – 0.099RAINDUR – 0.26AVGINT. ** SEE refers to the standard error of the estimate.

(mm), RAINDUR (hr), AVGINT (mm/hr) are the input variables. Using the MLR equation, pollutant EMC and load can be calculated in mg/L and kg, respectively.

The results of the MLR analyses are provided in Table 4. It was found out that the most important rainfall variables to estimate loads and EMCs were RAIN, RAINDUR, and AVGINT, all were associated with RUNVOL. In this case, the model could be more applicable in estimating loads than EMCs. RAINDUR and AVGINT were mostly negative indicating the dilution effect during long storms. Due to relatively weak correlations of pollutant loads and EMCs to ADD, it was eliminated from the equations. The coefficient of determination (R^2) is stronger in loads (R^2: 0.44–0.56, $p \leqslant 0.002$) and low for EMCs (R^2 : 0.03–0.32, $p \leqslant 0.72$).

3 Conclusions

The most important variables to predict event loads and EMCs are total rainfall, rainfall duration and average rainfall intensity. Considerable positive correlations were found between loads and rainfall variables except ADD. ADD could not be used to predict neither loads nor EMCs. Pollutant EMCs were mostly negatively correlated in all rainfall variables, which suggest that runoff EMCs are widely distributed and have very high uncertainties due to site and event characteristics. The regression models generated had a better estimation ability in few but not all cases and more applicable to estimate loads rather than EMCs. Nevertheless, the estimation models are useful in predicting the future trend of loads and concentrations for watersheds. Therefore, water quality sampling would be necessary to accurately predict pollutant loads and EMCs.

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