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Diffuse pollutant unit loads of various transportation landuses

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ABSTRACT

A four-year monitoring study was conducted to determine the diffuse pollutant unit loads for the six representative transportation landuses (i.e., highway, parking lot, bridge, service area and toll gate) in urban areas in Korea. Pollutant event mean concentrations (EMCs) were calculated from 123 storm events at eleven sites and the average annual rainfall and runoff coefficients were determined to estimate the unit loads using the National Institute of Environmental Research (NIER) method. Apparent differences in the unit load values existed among landuses as explained by the high variability of EMCs for different rainfall events. The study has found that runoff from bridges and highways contained the highest loadings of TSS and COD while service areas are the primary sources of nutrients and metals. The results of this study could be used by the Ministry of Environment (MOE) to separate the unit loads of transportation landuses from the urban area category in the current unit load system. The values obtained are also useful for planning and simulation purposes especially in the total maximum daily load (TMDL) programs and diffuse pollution abatement measures.

Keywords: Diffuse pollution; Event mean concentration; Landuse; Paved area; Transportation; Unit load

1. Introduction

The majority of diffuse pollutant loads in urban areas come from impervious surfaces [1–4]. Schueler (2000) defines impervious area as the sum of roads, parking lots, sidewalks, highways, and other impermeable surfaces in urban landscapes [5]. The composition of impervious areas is mainly from transportation landuses which are usually paved with asphalt or concrete and heavily exposed to vehicle activities. These infrastructures are designed to collect stormwater runoff carrying pollutants; convey it out of the watershed, typically in existing surface water channels such as streams and rivers and also seepage water and groundwater.

According to UNESCAP (2007), 87% of the total roads in Korea were paved. In addition, the density of roads per unit of surface area in 2003 was more or less 985 km per 1,000 km^2 which had almost doubled between the 1990s and 2000s [6]. Furthermore, based on the Environmental Impact Assessment (EIA) reports between 2000 and 2005 development periods, more than 36% of the construction projects were attributed

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to road construction alone while 17% was from urban development [7]. The increase in paved surfaces has been spurred on not only by urban development, but also by a steady increase in the use of automobiles. Motorization rates rose considerably to 223, corresponding to an increase of more than 150 cars per 1000 people [6].

Motor vehicular traffic is directly responsible for the deposition of substantial amounts of pollutants including toxic hydrocarbons, metals (from exhaust emissions, worn off tires, clutch and brake linings, lubricants, coolants, rust and decomposing coatings dropped from the underside of mudguards and undercarriages), asbestos and oils. The particulates contributed by traffic are primarily inorganic [8,9]. Only a small portion (<5%) of the traffic related pollution was directly traced to vehicle emissions. However, the pollutants that motor vehicles emit are among the most important because of their potential toxicity. In addition to traffic density and vehicle pollutant emissions, pavement conditions and compactions are significant in determining the traffic impact on pollutant loads [10,11]. The large nationwide studies on the quality of runoff from 28 highway sites in the USA showed average concentrations of total phosphorus (TP), lead (Pb) and zinc (Zn) of 0.42 mg/l, 0.18 mg/l and 0.20 mg/l, respectively [12].

Different landuse patterns could account for a different magnitude of the 'unit load' in respect to pollution constituents. A *unit load* represents the mass of pollution with respect to any water quality characteristic, exported from a unit drainage area per unit time. It is related to a specific landuse practice. The pollutant unit loads from urban areas are strongly affected by the drainage volume [13]. The lowest pollutant unit loadings are typical of sub-urban areas with so called 'natural surface drainage', and other developed open spaces. The highest pollutant loadings are emitted from highly impervious densely populated or heavily used urban centers. Table 1 shows the average pollutant unit loads in seven landuse types in Korea while Tables 2 and 3 provide the pollutant unit load data from typical landuses in USA. Clearly, the pollutant unit loadings in urban areas are far higher compared to other landuses. Based on the tables,

Table 1
Average pollutant unit loads for each respective landuses in Korea (kg/km^2/d) [14]

Landuse	BOD	TN	TP
Wet paddy fields	2.3	6.56	0.61
Dry paddy fields	1.6	9.44	0.24
Forest	1.0	2.20	0.14
Urban areas	85.9	13.69	2.10
Prairies	35.1	5.37	1.72
Golf courses	1.0	3.56	2.76
Others	1.0	0.06	0.03

Table 2
Range of pollutant unit loads for typical landuses in USA (kg/km^2/d) [15]

Landuses	SS	TP	TN	Pb	Cu	Zn
General urban	55–1315	0.08–1.3	0.05–5	0.04–0.14	0.005–0.06	0.08–0.3
Residential	170–630	0.1–0.4	1.4–2	0.02	0.008	0.005
Commercial	14–227	0.03–0.25	0.5–3	0.05–0.3	0.02–0.04	0.07–0.12
Industrial	123–466	0.2–1.1	0.5–3.8	0.6–1.9	0.08–0.4	0.96–3.3
Developing urban	7534	6.3	17.3	0.82	–	–

Table 3
Average pollutant unit loads for typical landuse subcategories in USA (kg/km^2/d) [16]

Landuses	Pb	Zn	TP	TKN	BOD	COD
Freeway	1.4	0.7	0.3	2.4	–	–
Parking lot	0.3	0.3	0.02	1.6	15	905
High density residential	0.3	0.2	0.3	1.3	8	52
Medium density residential	0.05	0.05	0.1	0.8	3.8	22
Low density residential	0.003	0.01	0.01	0.008	–	–
Commercial/industrial	0.8	0.7	0.5	2.1	19	129
Park	0.001	–	0.008	0.4	–	0.6
Construction	–	–	25	–	–	–

landuse categorization for the pollutant unit loads in USA is more specifically designated unlike in Korea where it is broadly categorized.

Unit loads allow for the calculation and prediction of pollutant loads from a catchment basin, by adding the contribution of all individual sub-catchments with characteristic landuse practice and corresponding pollutant loads. Part of the TMDL studies of the Ministry of Environment (MOE) in Korea is the landuse assessment which aims to determine the specific pollutant loadings for each landuse particularly dividing the landuses in urban areas into distinct categories similar to USA practice. Proper identification of unit loads with respect to the type of landuse practice is required to investigate the impacts of landuse activities and to evaluate management and design options for controlling water quality in urban waterways and receiving waters. However, it should be noted that unit loads are highly site-specific and depend on numerous demographic, geographic and hydrologic factors. Accurate estimates of diffuse pollutant unit loads can be achieved if event monitoring is undertaken to determine the event mean concentration (EMC) for the catchment representing more adequately the actual runoff quality.

This research was conducted to determine specific pollutant unit loadings of various transportation landuses. The unit loads under the 'urban area category' in the current unit load category system was divided into more distinct categories composing of various landuses in the urban areas; thus, providing a better estimate of the unit loads. The pollutant unit loads were determined using storm-runoff on the basis of rainfall, runoff coefficient, and EMC data. The results could be used to investigate shorter term impacts, determine seasonal characteristics of urban runoff, study alternative water quality management options, and as inputs to water quality models.

2. Materials and methods

2.1. Description of monitoring sites

Eleven monitoring sites related to transportation landuses like highway, road, parking lot, bridge, service area, and toll-gate were used in this study. Table 4 summarizes the characteristics of the sites. All eleven sites were paved with asphalt having 100% imperviousness, and the typical runoff coefficient was between 0.5 and 0.9. Fig. 1 shows the location of the sites; specifically, sites 1 to 5, 8, and 9 were located within the Geum River watershed in Chungnam Province while sites 6, 7, 10, and 11 in Gyeonggi Province at the headwaters of the Han River watershed. Han and Geum rivers, together with the other two major rivers in Korea are of high priority due to the detrimental impacts of diffuse pollution to these watersheds. Some of the sites were also used for the best management practice (BMP) pilot projects by the MOE.

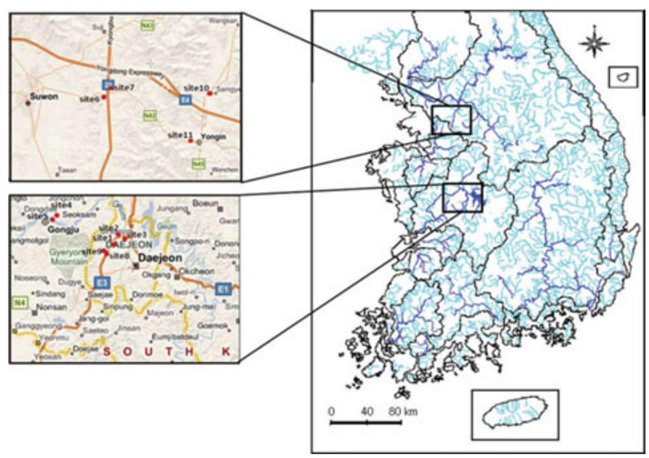

Fig. 1. Locations of the monitoring sites.

Table 4
Description of the monitoring sites

Landuse		Location	Area (m^2)	Pavement
Highway	Site 1	Highway 251 (North Bound 1), Daejon City	1120	Asphalt
	Site 2	Highway 251 (South Bound), Daejon City	1170	Asphalt
	Site 3	Highway 251 (North Bound 2), Daejon City	936	Asphalt
Parking Lot	Site 4	Kongju National University Parking Lot	172	Asphalt
	Site 11	Vehicle Registration Office parking lot at Yongin City	10,700	Asphalt
Bridge	Site 5	Kongju Bridge	632	Asphalt
Service Area	Site 6	Gihung Service Area (Highway 1, North Bound)	9522	Brick
Toll-gate	Site 7	Suwon Toll-gate (Highway 1)	82	Asphalt
	Site 8	Gaeryong Toll-gate 1 (Highway 251)	662	Asphalt
	Site 9	Gaeryong Toll-gate 2 (Highway 251)	311	Asphalt
Road	Site 10	Yongin City (Route 43)	5000	Asphalt

2.2. Sampling and analytical methods

A total of 123 storm events during May 2004 to September 2008 wet periods were analyzed. The monitoring protocol was based from California Department of Transportation (Caltrans) sampling strategy employed to characterize runoff both for long and short storms and with heavy or light rainfall [17]. However, in storm events having a short rainfall duration and light rainfall, fewer grab samples were collected. Moreover, the grab sampling only required one unit hydrograph for each storm event to determine the characteristics of runoff. In addition to stormwater runoff sample collection, hydrologic data which include antecedent dry day (ADD), event rainfall, runoff duration, average rainfall intensity, and runoff rate were gathered from the monitoring sites. Analytical analyses for typical water quality parameters such as total suspended solids (TSS), chemical oxygen demand (COD), dissolved organic carbon (DOC), heavy metals (Pb, Zn, etc.), total nitrogen and phosphorus (TN, TP) were performed in the laboratory within the recommended holding time for the samples. All runoff samples were analyzed based on ASTM standard test methods and detection limit was selected based on lab resources.

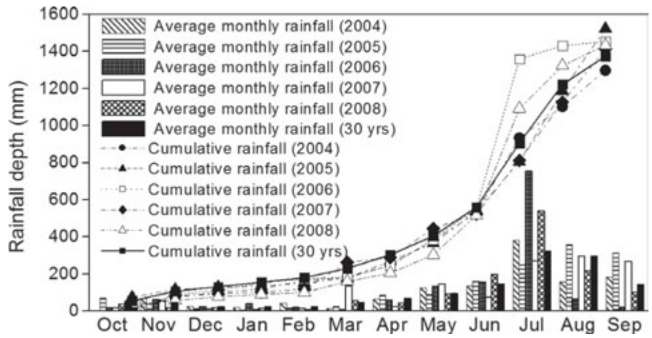

Fig. 2. Monthly rainfall during the study (Suwon, Korea).

3. Results and discussion

3.1. Rainfall and monitored events

The number of monitored events was dependent upon the distribution of rainfall. Fig. 2 shows the rainfall that occurred between 2004 and 2008 monitoring period as well as the cumulative rainfall for each year. It is apparent that the majority of the rainfall (60 to 65% of the total annual rainfall) typically occurs in the summer months of July, August, and September while very little rainfall (less than 7% of the total annual rainfall) during the winter months of December, January, and February. Based on the amount of rainfall that occurred each year, the average annual rainfall is approximately 1300 mm and comparatively similar for each year and in all the monitored site locations.

Table 5 shows the summary of the 123 monitored storm events for each respective landuses. Generally, storms greater than 10 mm were monitored accounting for 60% of the monitored rainfall events. However, most of the rainfalls in Korea are relatively small; in fact three-fourths of the annual rainfall was below 10 mm. ADD was based on the days since at least 1 mm of rainfall. The mean ADD was normally one week. The runoff rates were calculated dividing the total runoff by the product of the total rainfall and catchment area. Large runoff coefficients were observed in highway and bridge landuse in the range of 0.57 to 0.93 and 0.68 to 0.92, respectively. The variation of runoff coefficients was attributed on the amount of initial loss (due to the water filling on the surface depressions and pores) and the number of rainy days [2]. In road landuse, the proportion of rainfall that becomes runoff was low because of small rainfall events. Mean runoff duration is between 5.2 and 8.3 h and the average rainfall intensity is determined from 0.3 to 15.2 mm/h.

Table 5
Summary of monitored storm events

Landuse	No. of events	Recorded mean and range values				
		ADD (d)	Total rainfall (mm)	Runoff duration (h)	Avg. rainfall intensity (mm/h)	Runoff coefficient
Highway	25	7 (2–18)	23.3 (7–68)	5.2 (1–9.3)	5.1 (0.9–13)	0.8 (0.57–0.93)
Bridge	7	6 (2–18)	36.2 (35.5–36.5)	7.2 (4.8–10.8)	3.8 (0.8–7.2)	0.8 (0.68–0.92)
Service area	9	8 (2–15)	28.7 (18–35.5)	8.3 (2–18)	6.3 (4.3–9.1)	0.62 (0.23–0.98)
Toll-gate	32	7 (2–15)	8.5 (3–15.5)	6.2 (0.8–20)	2.5 (1.4–4.3)	0.7 (0.34–1)
Road	22	7 (1–33)	23.7 (1.5–84)	7.3 (1–14.3)	3.5 (0.2–15.2)	0.22 (0.2–0.4)
Parking lot	28	7 (1–33)	30 (1.5–77.5)	6.8 (0.6–14.3)	3.3 (0.2–15.2)	0.5 (0.2–0.94)
Combined sites	123	7	22.2	6.5	3.7	0.6

3.2. Stormwater runoff quality

The stormwater flow rates and pollutant concentrations for the landuses vary during an individual storm and between storms. Generally, constituent fluctuations are a result of deposition; buildup during dry weather, intensity, and length of the storm; and time between storms. Fig. 3 shows some examples of hydro- and polluto-graphs generated from the monitoring. It was observed that the highest pollutant concentrations were captured at the near beginning of the storm, usually the first half hour, the so-called 'first flush'. The first flush effect would be expected to occur in a watershed with a high level of imperviousness, but the National Stormwater Quality Database (NSQD) data indicated the highest concentration in first flushes occurred less than 50% of the time for the most impervious areas [18].

The EMCs were calculated to assess the characteristics of stormwater runoff quality of the monitored events. The EMC is defined as the pollutant load washed off by a storm event divided by the event runoff volume [19]. As the EMC can vary considerably between storms, monitoring should be carried out over several events, and the EMCs of the different storms averaged to provide the EMC value for the catchment. The EMC is used because most of the loads are transported by the big events.

The summary statistics of EMC for each of the five landuses are shown in Fig. 4. Among the landuses, the parking lot landuse exhibited the least EMCs for all the pollutants. In terms of TSS and COD EMCs, bridge landuse has the greatest TSS EMC (155.4 mg/l) and COD EMC (137.1 mg/l) but has a smaller Pb and Zn EMCs. Service area landuse has the highest nutrient EMCs, 4.6 mg/l and 1.4 mg/l for TN and TP, respectively. The order in terms of overall EMCs is service area > toll gate > bridge > highway > parking lot.

3.3. Pollutant unit loads

Pollutant unit loads for various transportation landuses were calculated using the National Institute of Environmental Research (NIER) method. The NIER Method is a simple method that estimates pollutant unit loads carried in stormwater runoff on the basis of rainfall, associated EMCs, landuse, and runoff coefficient. The equation of unit load for any landuse is:

$$UL = EMC \times AAR \times R_z/365 \qquad (1)$$

where UL is the unit load, kg/km²·d; EMC is the event mean concentration, mg/l; AAR is the average annual rainfall, mm/y; and R_z is the runoff coefficient (dimensionless).

The average annual rainfall is the summation of the average monthly rainfall based on 30 y rainfall data according to catchment's location. The runoff coefficient is dependent on the landuse impervious cover. It is typically about 0.7 to 0.95. For asphalt or concrete pavement, 0.83 was used and 0.8 for brick pavement.

Table 6 gives the summary statistics of the pollutant unit loads for various transportation landuses. As shown on the table, the unit loads vary by more than an order of magnitude between landuse types for some pollutants (e.g., COD, TN, TP) and comparatively close to few. On average, the coefficients of variation were between 0.7 and 1.3. Significant variations mostly occur for metal unit loads because of undetection of concentrations. Apparently, the highest TSS and COD unit loads were from bridge landuse whereas the highest nutrient unit loads (TN and TP) were from service area landuse attributable to high EMC values. Thus, differences between pollutant unit loads are primarily the result of the differences in the EMCs of pollutants as the annual average rainfall and runoff coefficient used were almost similar among the landuses.

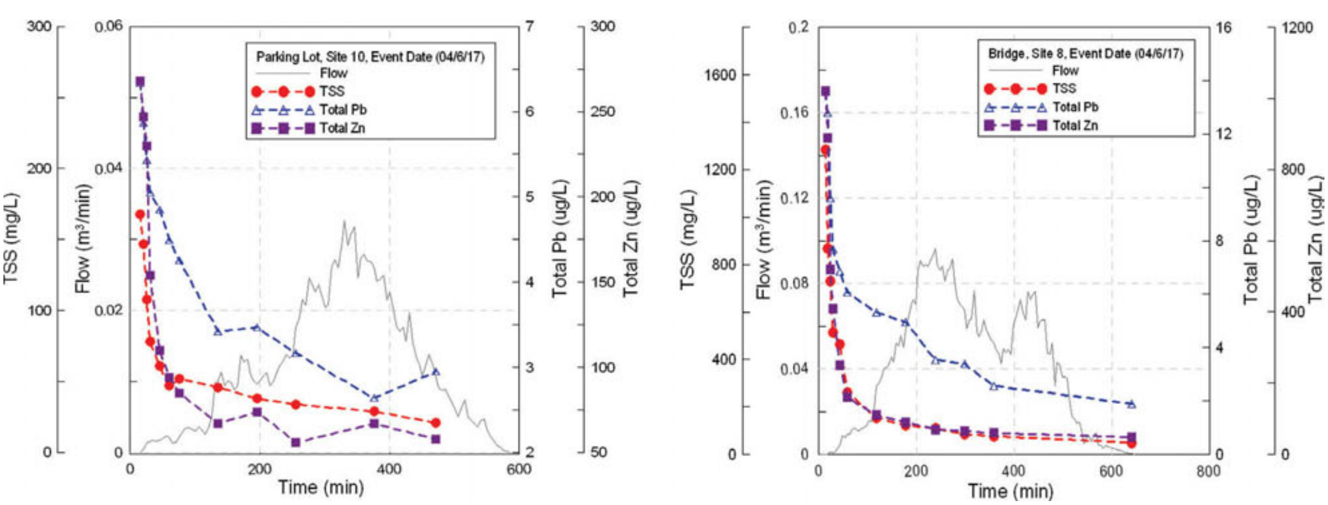

Fig. 3. Hydro- and polluto-graphs for various landuses.

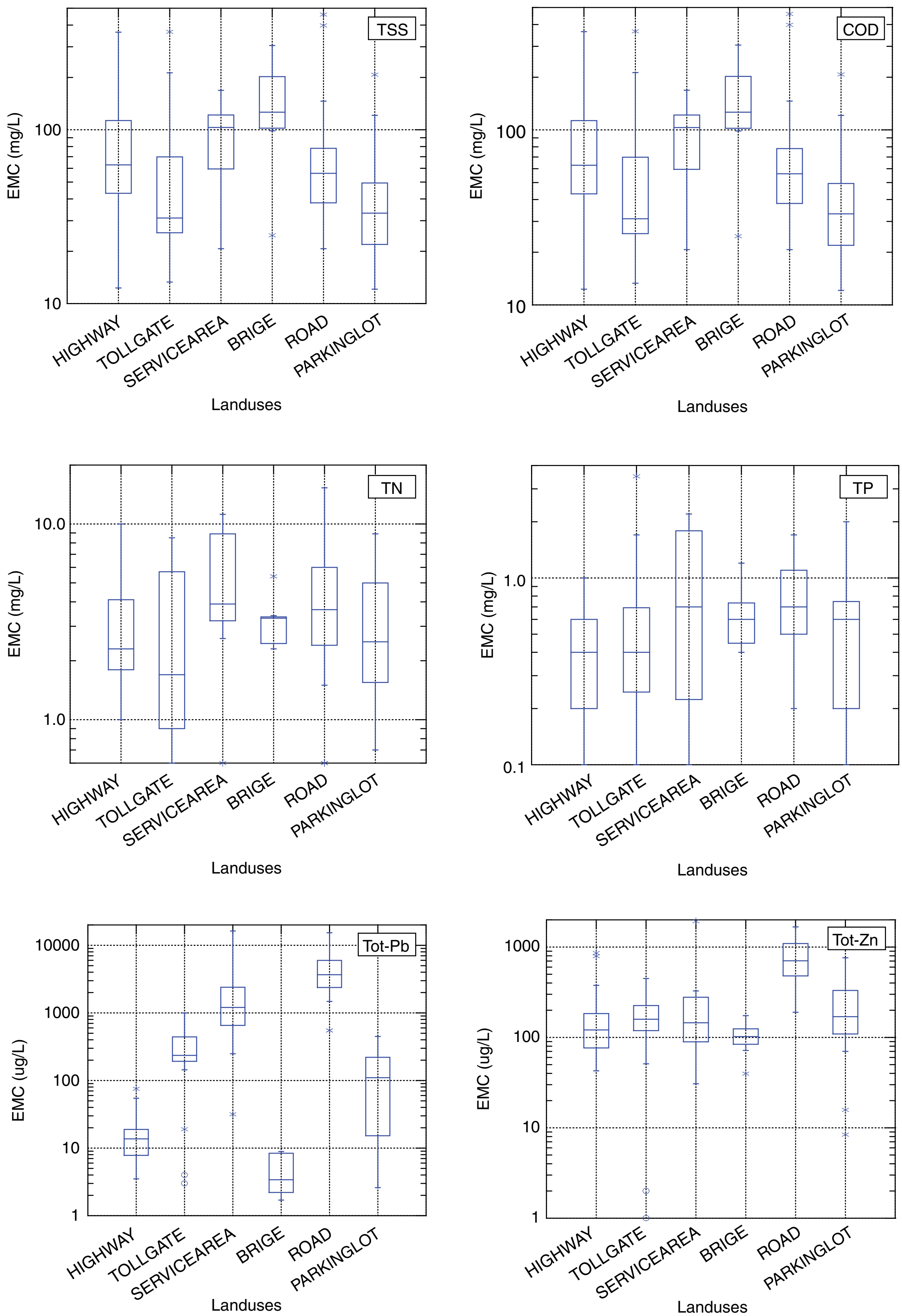

Fig. 4. Summary statistics of pollutant EMCs for each landuse.

Table 6
Summary statistics of pollutant unit loads (kg/km²/d) for various transportation landuses

Landuse	Basic statistics	Parameter						
		TSS	COD	DOC	TN	TP	Pb	Zn
Highway	Min / Max	37 / 1,082	88 / 514	9.5 / 96	3.1 / 29.8	0.30 / 3.0	0.01 / 0.22	0.13 / 2.6
	Mean / Median	**290 / 187**	**229 / 212**	**39 / 34**	**9.3 / 6.8**	**1.2 / 1.2**	**0.05 / 0.04**	**0.58 / 0.36**
	Std Dev / CV	270 / 0.9	114 / 0.50	24.3 / 0.62	6 / 0.64	0.67 / 0.55	0.05 / 0.97	0.62 / 1.1
Toll gate	Min / Max	40 / 1,065	21.7 / 1,236	8.3 / 164	1.8 / 24.8	0.18 / 10.3	0.43 / 56	0.15 / 7.5
	Mean / Median	**202 / 92**	**123 / 74**	**37 / 27**	**9.5 / 5.0**	**1.7 / 1.1**	**3.47 / 0.94**	**0.89 / 0.50**
	Std Dev / CV	226 / 1.1	214 / 1.7	31 / 0.85	7.8 / 0.82	1.9 / 1.1	10 / 2.9	1.4 / 1.6
Service Area	Min / Max	59 / 476	21.9 / 1,043	14.2 / 129	1.6 / 31.6	0.06 / 6.3	0.09 / 46	0.00 / 5.5
	Mean / Median	**261 / 291**	**230 / 136**	**51 / 48**	**15.2 / 11.0**	**2.3 / 1.5**	**8.21 / 3.4**	**0.94 / 0.41**
	Std Dev / CV	136 / 0.52	311 / 1.4	36 / 0.70	10.4 / 0.69	2.5 / 1.1	14.5 / 1.8	1.7 / 1.8
Bridge	Min / Max	77 / 950	141 / 619	28.9 / 152	7.2 / 16.7	1.1 / 3.6	0.01 / 0.03	0.12 / 0.54
	Mean / Median	**483 / 393**	**426 / 423**	**71 / 50**	**10 / 10.4**	**2.0 / 1.7**	**0.02 / 0.01**	**0.33 / 0.32**
	Std Dev / CV	318 / 0.66	171 / 0.40	45 / 0.63	3.3 / 0.33	0.91 / 0.45	0.01 / 0.67	0.13 / 0.41
Road	Min / Max	63 / 1,410	40 / 266	9.5 / 138	1.7 / 47.0	0.58 / 5.1	0.31 / 2.0	0.12 / 1.3
	Mean / Median	**286 / 172**	**100 / 88**	**48 / 38**	**13.5 / 11.3**	**2.4 / 2.2**	**0.92 / 0.77**	**0.69 / 0.72**
	Std Dev / CV	349 / 1.2	50 / 0.50	30.2 / 0.63	10 / 0.74	1.2 / 0.50	0.54 / 0.59	0.27 / 0.39
Parking lot	Min / Max	38 / 636	34 / 264	6.2 / 91	2.2 / 27.4	0.16 / 6.1	0.01 / 1.4	0.03 / 2.3
	Mean / Median	**132 / 102**	**98 / 87**	**34 / 29**	**10.3 / 7.8**	**1.9 / 1.7**	**0.45 / 0.34**	**0.74 / 0.52**
	Std Dev / CV	121 / 0.91	55 / 0.56	20.2 / 0.59	6.7 / 0.65	1.4 / 0.75	0.42 / 0.92	0.59 / 0.80
Combined sites	Min / Max	37 / 1,410	21.7 / 1,236	6.2 / 164	1.6 / 47.0	0.06 / 10.3	0.01 / 56	0.00 / 7.5
	Mean / Median	**239 / 145**	**160 / 100**	**41 / 33**	**10.8 / 9.3**	**1.8 / 1.6**	**1.8 / 0.54**	**0.73 / 0.48**
	Std Dev / CV	255/ 1.1	174/ 1.1	30/ 0.71	7.8/ 0.72	1.5 / 0.83	6.7 / 3.7	0.94 / 1.3

4. Conclusions

This research provided the diffuse pollutant unit loads for categorized transportation landuses in urban areas. Six representative landuses specifically highway, parking lot, bridge, service area and toll gate were selected for this study. The pollutant unit loads were determined using storm-runoff on the basis of rainfall, runoff coefficient, and EMC data obtained from 123 monitored storm events at eleven sites during May 2004 to September 2008 period.

Based on the analysis of data, the pollutant unit loads were not comparable with the transportation landuses, which as explained by the high variability of EMCs for different rainfall events. Moreover, the pollutant unit loads computed for various landuses indicated that each has different potential to impact water quality and may require remediation by appropriate stormwater management measures. Findings revealed that the highest unit loads for some pollutants were from bridge and service area landuses and least in parking lot landuse. The differences in unit loads were primarily the result of the differences in the EMCs of pollutants although other factors such as average annual rainfall and runoff coefficients affected the amount of unit loads to some extent. Despite the fact that the landuses have similarities in terms of imperviousness, the stormwater flow rates and pollutant concentrations vary during an individual storm and between storms. Thus, a good event monitoring program is essential where accurate estimates of pollutant unit loads are required.

The values obtained from this study could be very useful for planning and simulation purposes and input data for models. As part of the TMDL program of the MOE, the data will be utilized to investigate impacts of diffuse pollution and its abatement measures and to study alternative water quality management options.

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