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Modeling of highway stormwater runoff

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Abstract

Highways are stormwater intensive landuses since they are impervious and have high pollutant mass emissions from vehicular activity. Vehicle emissions include different pollutants such as heavy metals, oil and grease, particulates from sources such as fuels, brake pad wear and tire wear, and litter. To understand the magnitude and nature of the stormwater emissions, a 3-year study was conducted to quantify stormwater pollutant concentrations, mass emission rates, and the first flush of pollutants. Eight highway sites were monitored over 3 years for a large suite of pollutants. The monitoring protocol emphasized detecting the first flush and quantifying the event mean concentration. Grab and flow-weighted composite samples, rainfall, and runoff data were collected. A new runoff model with four parameters was developed that to describe the first flush of pollutants for a variety of rainfall and runoff conditions. The model was applied to more than 40 events for 8 pollutants, and the parameters were correlated to storm and site conditions, such as total runoff, antecedent dry days, and runoff coefficient. Improved definitions of first flush criteria are also presented.

Keywords: Best management practice; Event mean concentration; First flush; Highway; Washoff; Stormwater

1. Introduction

The United States Environmental Protection Agency (US EPA) developed the Nationwide Urban Runoff Program (NURP) to expand the state of knowledge of urban runoff pollution by instituting data collection and applied research projects in selected urban areas throughout the United States (Driscoll et al., 1990; US EPA, 1994, 1995, 1996). The discovery that significant quantities of organics, nutrients, pesticides, herbicides, and heavy metals are present in runoff caused the US EPA to require regional urban planning agencies to conduct planning studies to reduce pollution from urbanized areas under section 208 of the Amendments to the Clean Water Act (EPA, 1994).

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Best Management Practices (BMPs) are usually required to mitigate non-point source pollution and refer to management practices and engineering methods to control pollutants in runoff (Silverman et al., 1986; Jefferies et al., 1999; Smullen et al., 1999). In an urban setting, BMPs are of two types: source and treatment controls. Source controls are preventative practices that keep pollutants from entering the runoff, such as covering storage areas, diverting runoff from pollutant sources, street sweeping, and household hazardous waste recycling programs. Treatment control BMPs refer to devices that remove pollutants from the runoff, such as vegetated swales and buffers strips, infiltration ponds, detention basins, and catch basin inserts (EPA, 1994; Jefferies et al., 1999).

The quantity and magnitude of runoff pollution is a function of landuse, and highways are higher emitters. Highway runoff contains pollutants from vehicular activities (metals from brake pad wear, combustion by-products, deicers, tire wear, and corrosion products), pollutants from wet and dry atmospheric deposition, and gross pollutants such as litter, vegetation, and construction debris. The runoff concentration from these varied sources is usually quantified using an event mean concentration (EMC), which is a flow-weighted average (Bertrand-Krajewski et al., 1998) as shown in Eq. (1)

$$\mathrm{EMC} = \frac{\int_0^t C(t)\cdot Q(t)\mathrm{d}t}{\int_0^t Q(t)\mathrm{d}t} \qquad (1)$$

where, $C(t)$=pollutant concentration; and $Q(t)$=runoff flow rate discharged at time t.

One of the key difficulties in calculating the EMC is how to express the concentration. It is usually cost prohibitive to measure $C(t)$ at frequent intervals and some lesser number of samples are collected. Rainfall or runoff can usually be measured automatically and it is common to record them on 1 to 5 min intervals. Flow-weighted automatic samplers solve the concentration problem, but are expensive and provide no information on the time-varying changes of concentration or mass emission rate.

The total mass emission is the product of rainfall, catchment area, runoff coefficient, and EMC, and can also be calculated by multiplying the measured total runoff and the EMC. Historical records for rainfall as well as runoff coefficients and areas are usually available, which has made the EMC useful for estimating the contribution of runoff to receiving waters (Corwin and Vaughan, 1997; Irish et al., 1998).

The EMC does not provide information on the time varying changes in pollutant concentration or mass emissions, which are often important for BMP development, or understanding shock loads. Pollutant concentration often declines over time, which tends to create greater emission rate at the beginning of runoff. This phenomenon is often called a "first flush", and the existence of a first flush can influence the selection of best management practices. The decline in concentration is sometimes offset by an increasing runoff rate as a storm progresses.

To evaluate first flush effects and BMP selection, models are often used to predict pollutant concentration. Regression models, stochastic, and deterministic simulation models have all been used (Irish et al., 1998). Most of the models commonly use mass emission rate as a governing equation and express concentrations or loads of pollutants as function of time. The variables are usually dependent upon runoff volume, rainfall intensity, traffic intensity, antecedent dry days, surrounding landuse, and other parameters. Generally, it is difficult to consider all affecting factors for a governing equation because many different site-specific conditions exist, such as presence or absence of street sweeping, soil saturation, wind direction, among others. These regression models have been criticized as being site specific and poor predictors of future events (Driscoll et al., 1990).

The existence of first flush is debated and many defining criteria exist. Thornton and Saul (1987) defined the first flush as the initial period of storm flow during a storm event. Geiger (1987) defined a first flush as occurring when the slope of normalized cumulative mass emission plotted against normalized cumulative volume is greater than 45%. Later investigators have also used this definition (Gupta and Saul, 1996; Sansalone and Buchberger, 1997; Larsen et al., 1998; Sansalone et al., 1998). Vorreiter and Hickey (1994) proposed using only the first 25% of runoff volume in defining first flush. Deletic (1998) used standard statistical methods including a multiple regression model, and restricted first flush to the first 20% of runoff. Saget et al. (1995) and Bertrand-Krajewski et al. (1998) defined a first flush as occurring when at least 80% of the pollutant load is emitted in the first 30% of the runoff volume.

First flushes have most often been observed in small watersheds, particularly if the imperviousness is high. Large watersheds have longer time of travel, so that the early runoff from areas far from the sample location is mixed with later runoff from areas adjacent to the sample location. The concept of seasonal first flush also exists in regions with extended dry periods (Kim et al., 2004). Under such conditions, storms that mark the end of the dry season have disproportionally larger mass discharges.

The disparity of definitions is confusing and leads many researchers to conclude that there is no first flush when others confirm a first flush. A new definition is needed that quantifies the magnitude of the mass runoff in the early part of a storm or the mass in the first storms of the wet season. Such a definition can be used consistently by all, and value judgments can be avoided.

In this research we investigate the existence of first flush as a function of site-specific variables as well as storm characteristics. The sites are small, and avoid problems associated with time of travel in large watersheds. The objectives of the study are to suggest a new model that can be used to describe runoff concentrations and to use the model to estimate EMCs and mass loading rates.

2. Methods

Rainfall, runoff rate, and runoff quality were monitored at 8 freeway sites in Southern California over two rainy seasons (1999 to 2001). Each site was equipped with a flow meter, rainfall gauge, and flow-proportional automatic sampler for collecting a composite sample. Four-liter grab samples were also collected. Generally, 5 samples were collected in the first hour. The first sample was collected at the very beginning of runoff. Additional samples were collected each hour until the end of runoff. EMCs were calculated by integrating the product of runoff rate and concentration and compared to the results from

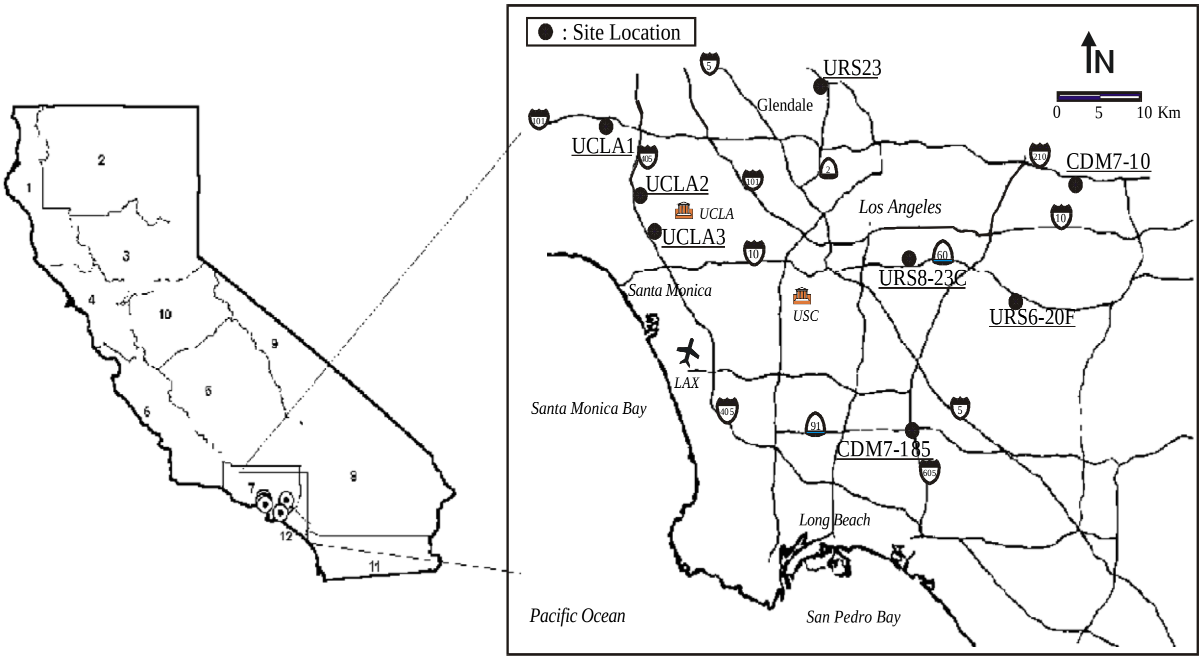


Fig. 1. Study areas in Southern California, USA.

the automatic sampler. A large suite of water quality parameters was measured, including chemical oxygen demand (COD), dissolved organic carbon (DOC), particulate and soluble heavy metals, and nutrients (Stenstrom et al., 2001). Analysis were performed at UCLA and used approved US EPA methods, including guidelines for sample preservation and holding.

2.1. Descriptions of sites and events

Fig. 1 shows the monitoring locations. All events above a minimum rainfall (generally >0.3 cm rainfall) were monitored. Detail summaries of sites and events are shown in Table 1, which includes site area, date, average daily traffic (ADT), antecedent dry days,

Table 1
Monitoring site descriptions

Sites	Highway watershed area (m^2)	ADT (cars/day)	Event date (mm/dd/yy)	Antecedent dry days (days)	Storm duration (h:min)	Total rainfall (cm)	Total volume of runoff (m^3)
UCLA 1	12,800	328,000	01/25/00	8.00	19:21	1.68	213.18
			02/27/00	3.90	4:26	0.30	16.14
			10/26/00	33.60	10:57	2.34	255.20
			01/08/01	69.40	6:34	0.38	43.70
			02/19/01	5.40	4:08	0.71	80.86
			03/04/01	4.00	10:32	1.17	136.13
UCLA 2	16,900	260,000	01/25/00	7.90	19:23	2.36	396.70
			02/10/00	9.90	19:01	0.69	106.47
			02/12/00	1.20	3:00	0.98	168.71
			04/17/00	39.80	8:34	4.42	300.78
			10/26/00	33.60	10:57	2.31	194.41
			01/08/01	69.40	4:18	0.48	49.60
			03/04/01	4.00	5:05	0.89	140.17
UCLA 3	3900	322,000	01/25/00	8.20	7:53	1.75	68.02
			02/12/00	1.10	4:42	1.78	59.46
			03/04/00	5.00	1:33	0.58	20.50
			10/26/00	33.60	11:47	2.59	94.53
			02/19/01	5.30	6:56	2.97	110.53
			02/24/01	1.00	11:36	1.12	37.29
			04/07/01	31.60	10:46	2.16	55.43
CDM7-10	48,100	176,000	01/25/00	25.20	10:04	1.50	557.23
			02/12/00	2.10	2:50	2.31	950.31
			02/20/00	3.20	13:05	5.64	2598.24
			02/23/00	2.10	13:00	4.24	1737.42
			02/27/00	4.00	5:45	1.09	400.49
			03/08/00	1.00	10:06	2.74	1145.46
			04/17/00	38.90	7:20	4.24	1745.43
CDM7-185	2300	220,000	02/12/00	2.00	2:30	1.88	36.98
			02/23/00	2.00	9:35	2.49	56.53
			02/27/00	4.00	1:05	0.38	4.00
			03/08/00	3.00	8:45	2.06	45.70
			04/17/00	39.00	6:55	3.18	70.39
URS23	29,100	122,000	01/26/01	33.00	7:48	0.89	95.61
			02/10/01	14.60	9:12	0.99	120.42
			02/19/01	5.70	6:24	0.94	116.82
URS6-20F	1700	216,600	10/26/00	33.00	10:00	3.18	33.13
			01/26/01	33.00	7:18	1.19	10.53
			02/10/01	14.50	6:36	0.51	2.75
			02/19/01	5.60	5:40	1.04	7.72
URS8-23C	2500	229,000	01/26/01	33.00	12:48	0.53	6.59
			02/19/01	5.50	7:12	0.43	10.66

rainfall, storm duration, and total volume of runoff. The event rainfall varies from 0.3 cm to 5.64 cm and antecedent dry days vary from 1 to 69 days. The smallest catchment area is 1700 m^2 at site URS6-20F and the largest area is 48,100 m^2 at site CDM7-10.

2.2. Derivation of new washoff model

EMCs cannot be determined by simple statistical averaging of measured pollutant concentration in stormwater runoff because of random characteristics of runoff quality and quantity. The sources of uncertainty are broadly caused by uncertainties in rainfall intensity and magnitude, experimental errors, and lack of sufficient data. To overcome this difficulty, a number of regression or averaging methods have been proposed.

Gupta and Saul (1996) used multiple linear regression analysis for data interpolation and Larsen et al. (1998) calculated EMCs using the medium point method. A number of previous researchers used an exponential washoff model derived from mass emission rate to fit observations with a smooth function that can be integrated to estimate EMCs (Charbeneau and Barrett, 1998; Deletic and Mahsimivic, 1998; Irish et al., 1998; Osuch-Pajdzinska and Zawilski, 1998; Deletic et al., 2000).

Many different trends in concentration were observed over the 2 years of monitoring. Fig. 2 shows the pollutographs observed during monitoring periods. The graph shows runoff rate, concentration, and rainfall rate as a function of time. Many parameters such as oil and grease and COD (upper left box) show an exponential declining trend. Other trends, described as dilution were also observed, and cannot be predicted with an exponential model. Dilution reduces the concentration when a finite pollutant quantity of pollutant mixes with a large runoff volume. Dilution in stormwater occurs as a continuous process, and varies with rainfall rate.

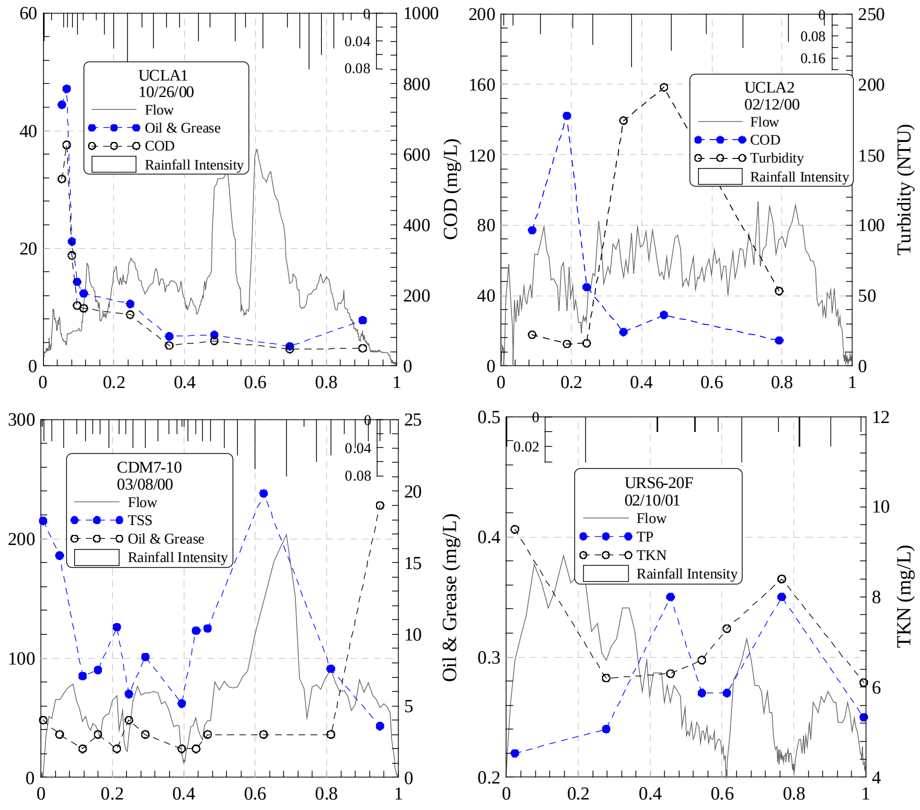


Fig. 2. Types of observed pollutographs.

It is generally assumed that a pollutant has an initial mass on the watershed area that existed before the rainfall, and a remaining mass that still exists after the rainfall. The washoff mass is the difference between total and remaining mass. The total mass on the watershed changes with time due to inputs from wet or dry deposition, automobiles, and other sources. The mass deposited by vehicles during a storm event by wet deposition has not been well quantified, but is though to be high (Shaheen, 1975).

Mechanism affecting the concentration changes in runoff with time includes dilution of initial pollutant mass as well as contributions from wet deposition and automobiles during a storm event. It can create the opposite trend by continuously adding to the washed-off mass.

The washoff rate can be described in Eq. (2).

$$\frac{\mathrm{d}[C(t)]}{\mathrm{d}t} = -\alpha \cdot \frac{Q(t) \cdot C(t)}{V_{\mathrm{TRu}}} \quad (2)$$

where, α=washoff rate coefficient; $C(t)$=pollutant concentration at time t; V_{TRu}=total runoff volume= $\int_0^T Q(t)\mathrm{d}t(m^3)$.

Rearranging Eq. (2).

$$\frac{\mathrm{d}[C(t)]}{C(t)} = -\alpha \cdot \frac{Q(t)}{V_{\mathrm{TRu}}}\mathrm{d}t \quad (3)$$

Integrating Eq. (3), we obtain:

$$\ln[C(t)] = -\alpha \cdot \frac{\int_0^t Q(t)\mathrm{d}t}{V_{\mathrm{TRu}}} + \ln(\beta) \quad (4)$$

where, β=integration constant.

In Eq. (4), the initial concentration is as follows at t=0: $\ln[C(0)]=\ln(\beta)$.

By letting $\frac{\int_0^t Q(t)\mathrm{d}t}{V_{\mathrm{TRu}}} = \frac{\int_0^t Q(t)\mathrm{d}t}{\int_0^T Q(t)\mathrm{d}t} = V_{\mathrm{nRu}}(t)$, Eq. (4) becomes:

$$\ln[C(t)] = -\alpha \cdot V_{\mathrm{nRu}}(t) + \ln(\beta) \quad (5)$$

where, $V_{\mathrm{nRu}}(t)$=normalized cumulative volume, $0 \le V_{\mathrm{nRu}}(t) \le 1.0$.

Taking the exponential of both sides, Eq. (5) becomes:

$$C(t) = \beta \cdot \mathrm{Exp}[-\alpha \cdot V_{\mathrm{nRu}}(t)] \quad (6)$$

Finally, as stated earlier, the mass input during a storm event can be considered as another concentration term (γ), which originates from automobiles, air, and other impacting factors. Thus,

$$C(t) = \beta \cdot \mathrm{Exp}[-\alpha \cdot V_{\mathrm{nRu}}(t)] + \gamma \quad (7)$$

where, the concentration can also be defined from mass emission rate:

$$M(t) = C(t) \cdot Q(t) \quad (8)$$

where, $M(t)$=pollutant mass emission rate at time t.

$$C(t) = \frac{\Delta M(t)}{\Delta Q(t)} = \frac{\int_{t-1}^{t} M(t)\mathrm{d}t}{\int_{t-1}^{t} Q(t)\mathrm{d}t} = \frac{\int_{t-1}^{t} M(t)\mathrm{d}t}{\int_0^t Q(t)\mathrm{d}t - \int_0^{t-1} Q(t)\mathrm{d}t} \quad (9)$$

The denominator of Eq. (9) after integrating becomes

$$\int_0^t Q(t)\mathrm{d}t - \int_0^{t-1} Q(t)\mathrm{d}t = [V_{\mathrm{nRu}}(t) - V_{\mathrm{nRu}}(t-1)] \cdot V_{\mathrm{TRu}} \quad (10)$$

The difference in two normalized volumes over time t and $t-1$, which is a normalized flow rate for prediction, let

$$\beta_1 = \frac{[V_{\mathrm{nRu}}(t) - V_{\mathrm{nRu}}(t-1)]}{V_{\mathrm{nRu}}(t)} \quad (11)$$

By substituting Eq. (11) into Eq. (9) and using Eq. (10), we obtain;

$$C(t) = \frac{1}{\beta_1 \cdot V_{\mathrm{nRu}}(t)} \cdot \frac{\int_{t-1}^{t} M(t)\mathrm{d}t}{V_{\mathrm{TRu}}} \quad (12)$$

The normalized flow rate will not be known if the model is used for prediction. If a parameter is used for this value, the parameter can be estimated from previous storms or weather prediction, which allows the model to be used for prediction. Later it will be shown that this parameter is correlated to average runoff velocity, or the average flow rate divided by the catchment area.

The right side of Eq. (12) has units of [mass]/[volume] or concentration. This new concentration term is a key premise of the model. If we let $\int_{t-1}^{t} M(t)\mathrm{d}t/V_{\mathrm{TRu}} = \mathrm{NewConc.}[V_{\mathrm{nRu}}(t)]$, Eq. (12) can be expressed such as follows:

$$C(t) = \frac{1}{\beta_1 \cdot V_{\mathrm{nRu}}(t)} \cdot \{\mathrm{NewConc.}[V_{\mathrm{nRu}}(t)]\} \tag{13}$$

By equating Eqs. (7) and (13), we obtain:

$$\beta \cdot \mathrm{Exp}[-\alpha \cdot V_{\mathrm{nRu}}(t)] + \gamma = \frac{1}{\beta_1 \cdot V_{\mathrm{nRu}}(t)} \cdot \{\mathrm{NewConc.}[V_{\mathrm{nRu}}(t)]\} \tag{14}$$

Summarizing and letting $\beta \cdot \beta_1 = \beta^*$ and $\gamma \cdot \beta_1 = \gamma^*$, the new washoff model is expressed as follows:

$$\mathrm{NewConc.}[V_{\mathrm{nRu}}(t)] = \beta^* \cdot V_{\mathrm{nRu}}(t) \cdot \mathrm{Exp}[-\alpha \cdot V_{\mathrm{nRu}}(t)] + \gamma^* \cdot V_{\mathrm{nRu}}(t) \tag{15}$$

In Eq. (15), a parameter is needed to describe the initial condition, which ideally should be related to antecedent dry periods. The new washoff model is finally expressed as follows:

$$\mathrm{NewConc.}[V_{\mathrm{nRu}}(t)] = \delta + V_{\mathrm{nRu}}(t) \cdot \{\gamma^* + \beta^* \cdot \mathrm{Exp} \times [-\alpha \cdot V_{\mathrm{nRu}}(t)]\} \tag{16}$$

The new washoff model has two different parts or functions. The first is linear, $\gamma^*\ V_{\mathrm{nRu}}(t)+\delta$, and the second takes the form of a gamma type function, $\beta^* \cdot V_{\mathrm{nRu}}(t) \cdot \mathrm{Exp}[-\alpha \cdot V_{\mathrm{nRu}}(t)]$.

In order to use the model as a predictive tool, it is necessary to predict the total runoff volume, which must be based upon weather forecast or other information. Eq. (13) has four parameters that are related to antecedent dry periods, rainfall intensity, and runoff coefficient. The δ is an initial concentration related to antecedent dry periods. The parameters α and γ^* are related to total runoff. The β^* is related to rainfall, runoff coefficient, and storm duration.

2.3. Sensitivity analysis

A sensitivity analysis was performed to define the model's sensitivity with each parameter. The model has more flexibility than previous models,

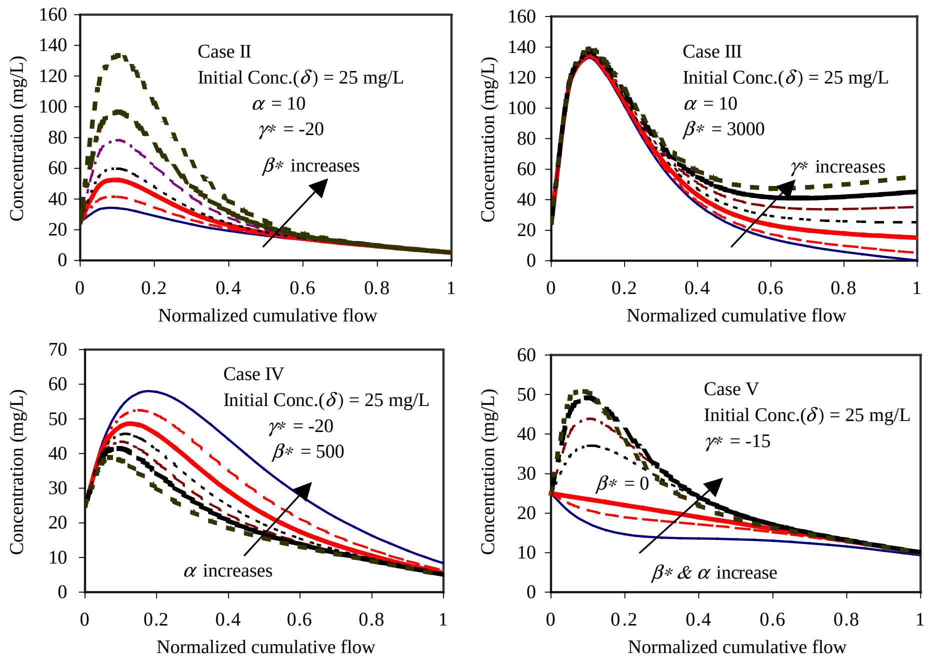


Fig. 3. Sensitivity analysis of model parameters.

which can be important because many storms do not shown the ideal, decreasing exponential trend in concentration. The model can be used to more accurately fit a greater number of storm events.

Fig. 3 shows four sets of model responses for changing parameters. Increasing β^* generally increases the peak concentration. As β^* tends to zero, the concentration trend becomes linear. Increasing γ^* increases the final remaining pollutant concentration. Increasing α increases the rate and mass of runoff. All trends are consistent with the governing equation.

An important use of the model is for data interpolation after a storm event to calculate EMCs and mass loading. The model provides a smooth estimate of concentration and can be used in lieu of discrete data points. Another use is for predicting pollutant loading and EMCs before a storm event, which will require reliable parameter estimates.

Storm duration varies from event to event, which makes it difficult to predict concentration as a function of time. The new model avoids this problem by using normalized cumulative flow.

3. Results

The model was applied to data collected from the eight freeway sites over 2 years and shows good agreement. This section shows several types of results and its application for estimating EMCs and potential impacts on BMP selection.

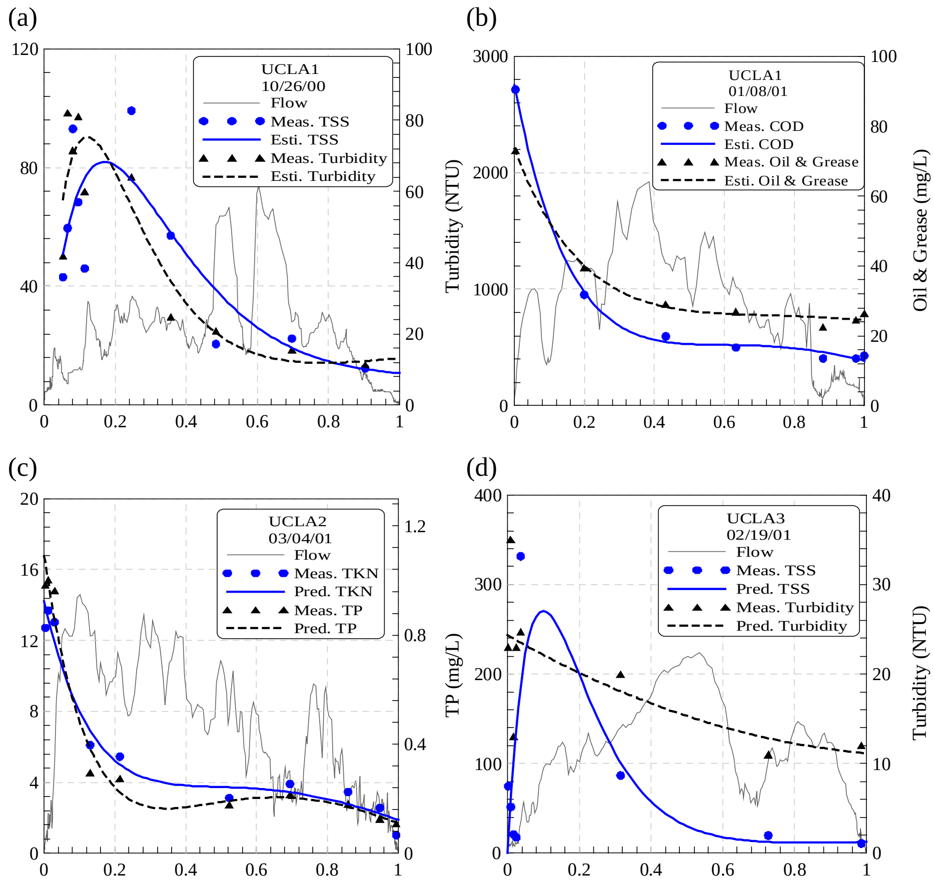


Fig. 4. Concentrations distributions for monitored and modeled results.

3.1. Runoff coefficient

The runoff coefficients ranged from 0.35 to 0.95 depending on rainfall intensity, antecedent dry days (ADD), and catchment area. The mean value was 0.87. The lower values were for smaller storms and higher ADD. For large rainfall events it was always greater than 0.95. This is expected and is caused by depression storage and the limited infiltration that occurs in paved areas. The depression storage and

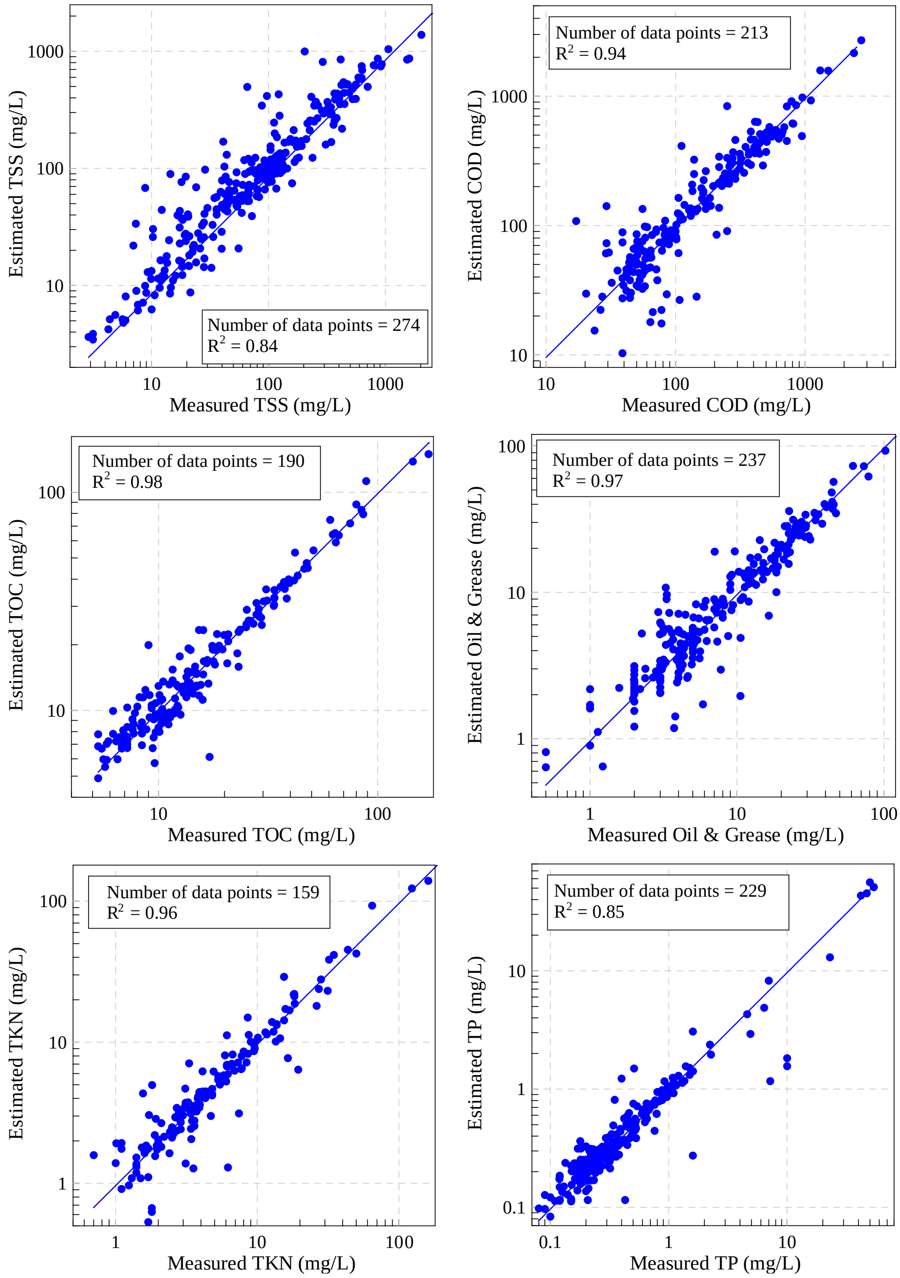


Fig. 5. Relationships between measured and estimated concentrations.

infiltration is low when compared to large rainfall events. Antecedent dry periods are also important because they will affect infiltration.

3.2. Comparison of monitored and modeled concentration

The washoff model was used for all events to predict concentration profiles. The model can predict the various functional types such as linear, exponential, and Gamma distributions, which is more general than models based upon exponential and or power laws. Fig. 4 shows concentration distributions of monitored and modeled for different events and six different parameters. The agreement between predictions and data is generally good and the model fits approximately 70% of the events as well as shown in Fig. 4. The lack of fit was most obvious for oil and grease, and if oil and grease were excluded in the comparison, the agreement between predictions and data would be approximately 90%. To use this for prediction, the parameters should be generalized to show their relationship to storm characteristics such as total runoff, ADD, ADT, etc.

The comparison of distributions between measured and estimated concentrations is another important way to assess the model's accuracy. Fig. 5 shows the comparison of the monitored and modeled results. The points on these plots are the values from grab samples compared to the model output for the same point in the storm. The R^2 for all water quality constituents is between 0.84 and 0.98 and the residuals (not shown) are generally randomly distributed and unbiased. Oil and grease and TSS have lower R^2, which can be observed in this figure. A possible reason for the divergence is the dependence of these two parameters on rainfall intensity.

3.3. EMCs and washed-off mass loading for each parameter

Table 2 shows the EMCs for eight water quality parameters. The EMCs were calculated from the calibrated model results for each storm. The range, mean, median, and standard deviations are shown. The number of events ranged from 17 to 39, and differs because the number of sampled parameters varied in different years. Alkalinity and TKN were not sampled in the first year. The difference between mean and median EMCs is quite large with mean being twice as large for most parameters. This results because the stormwater runoff data are log-normally distributed.

The TSS EMCs ranged from 5 mg/L to 880 mg/L and COD EMCs range from 13 mg/L to about 780 mg/L. The EMC ranges for oil and grease range from

Table 2
Statistical summaries of event mean concentrations and mass loading

Parameters		Basic statistics						Confidence interval	
		No. of events	Min.	Max.	Median	Mean	S.D.	95% upper	95% lower
TSS	EMC	39	5.21	874	87.5	160	175	216	103
	Mass loading		0.06	17.3	0.83	2.43	3.91	3.7	1.14
COD	EMC	26	13.5	776	103	178	182	252	104
	Mass loading		0.10	3.23	0.98	1.19	0.91	1.6	0.83
TOC	EMC	21	7.36	59.3	12.8	18.1	13.3	24.1	12.1
	Mass loading		0.03	0.85	0.14	0.22	0.23	0.33	0.12
TKN	EMC	19	1.93	33.8	3.15	6.30	8.06	10.2	2.4
	Mass loading		0.01	0.15	0.02	0.04	0.04	0.06	0.02
TP	EMC	31	0.11	1.54	0.31	0.41	0.32	0.53	0.30
	Mass loading		0.00	0.04	0.00	0.01	0.01	0.01	0.00
Oil and grease	EMC	37	0.52	34.6	5.23	8.00	7.73	10.6	5.4
	Mass loading		0.01	0.39	0.05	0.08	0.08	0.11	0.05
Hardness	EMC	36	8.36	291.	44.6	70.8	59.8	90.5	51.2
	Mass loading		0.00	5.68	0.52	0.82	1.02	1.16	0.49
Alkalinity	EMC	17	8.98	75.5	21.8	26.9	18.6	36.4	17.3
	Mass loading		0.05	0.49	0.22	0.24	0.13	0.31	0.18

Units of EMC are mg/L and mass loading are g/m^2. EMCs and mass loading were calculated using the new model.

0.5 mg/L to 34 mg/L. The large range shows the difficulty of predicting EMCs for even a single land use type.

Fig. 6 is a notched box plot that shows the difference between EMCs calculated with the new model, exponential model, and medium point method (Larsen et al., 1998). The median values, represented by the middle of the notch, are similar for all three methods, but in all cases, the range of the results for the new model, represented by the 25 and 75% interquartiles, is narrower.

The reductions in variability are even greater if one considers the maximum and minimum values. For example, the maximum TSS EMC calculated using the exponential method is 1200 mg/L, 750 mg/L using the medium point method, and 890 mg/L using the new model,. The large values calculated with the exponential model occur when the fit is poor (i.e., concentration not declining). The medium point method is easy to apply, but decreases in accuracy and precision when the number of grab samples decreases. The new model produced more precise results for the same raw data.

The mass loading or washed-off mass was calculated using the continuous model and the measured runoff flow rate. Concentrations at 1-min intervals were generated using the washoff model. The washed-off masses were normalized by dividing by the total rainfall (units of rainfall in cm). The washed-off mass ranged from 0.06 g/m^2 to 17.3 g/m^2-cm for TSS and about 0.1 to 3.23 g/m^2 for COD. The volume of runoff can still affect the washed-off mass and EMCs because of dilution effect during a storm event. Generally, the differences between minimum and maximum washed-off mass are large because of event and site characteristics, such as rainfall intensity and duration and ADD. These parameters are not normalized by the total rainfall. The washed-off masses can be used to estimate pollutant loadings from highways. These estimates could be useful in developing Total Maximum Daily Load (TMDL) allocations.

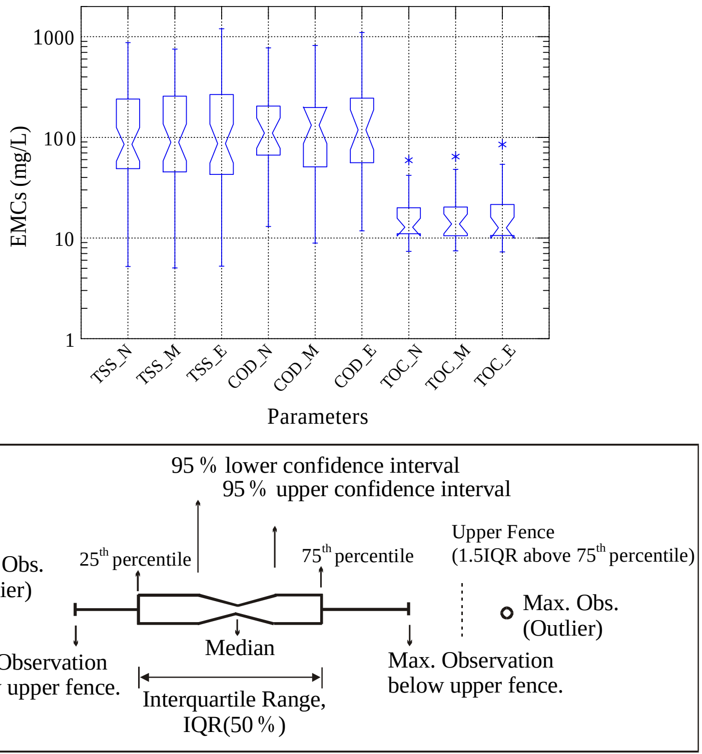
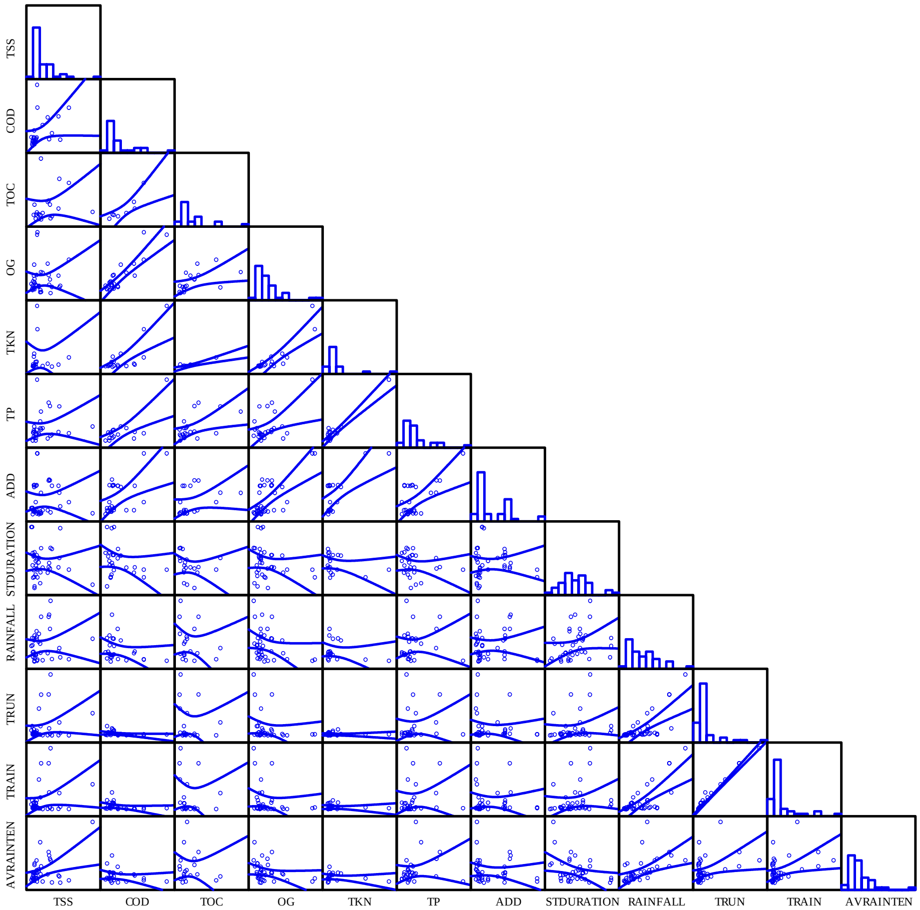


Fig. 6. Comparison of event mean concentrations (N=new model, M=medium point method, and E=exponential model).



	TSS	COD	DOC	O&G	TKN	TP	ADD	STDURATION	RAINFALL	TRUN	TRAIN	AVRAINTEN
TSS		0.82	0.75	0.61	0.74	0.18	0.51	0.09	-0.13	-0.70	-0.68	-0.19
COD	0.05		0.87	0.92	0.81	0.16	0.03	-0.44	0.05	-0.66	-0.64	0.16
DOC	0.08	0.03		0.86	0.99	-0.08	-0.16	-0.43	-0.13	-0.38	-0.35	0.04
O&G	0.20	0.01	0.03		0.77	0.07	-0.30	-0.55	-0.08	-0.60	-0.59	0.14
TKN	0.09	0.05	0.00	0.07		-0.06	-0.13	-0.40	-0.17	-0.29	-0.26	-0.01
TP	0.73	0.77	0.88	0.89	0.91		0.15	0.11	-0.49	-0.36	-0.40	-0.55
ADD	0.31	0.95	0.77	0.56	0.80	0.78		0.70	0.12	-0.38	-0.37	-0.21
STDURATION	0.86	0.39	0.39	0.26	0.43	0.84	0.12		-0.41	-0.24	-0.24	-0.65
RAINFALL	0.80	0.93	0.80	0.89	0.75	0.33	0.83	0.43		0.27	0.29	0.94
TRUN	0.12	0.16	0.45	0.21	0.58	0.48	0.46	0.64	0.60		1.00	0.30
TRAIN	0.14	0.17	0.49	0.22	0.62	0.43	0.47	0.64	0.58	0.00		0.32
AVRAINTEN	0.72	0.77	0.94	0.79	0.98	0.26	0.70	0.16	0.01	0.56	0.54	

Note: ADD (Antecedent Dry Days, days), STDURATION (Storm Duration, hours), TRUN (Total Volume of Runoff, m^3), and AVRAINTEN (Average Rainfall Intensity, cm/hr)

Fig. 7. Matrix of correlationship and Pearson coefficients.

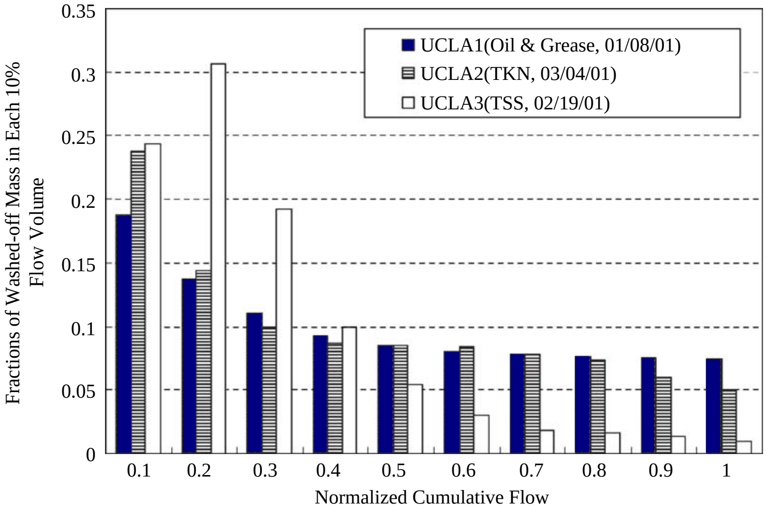


Fig. 8. Normalized fractional mass washed-off as function of flow.

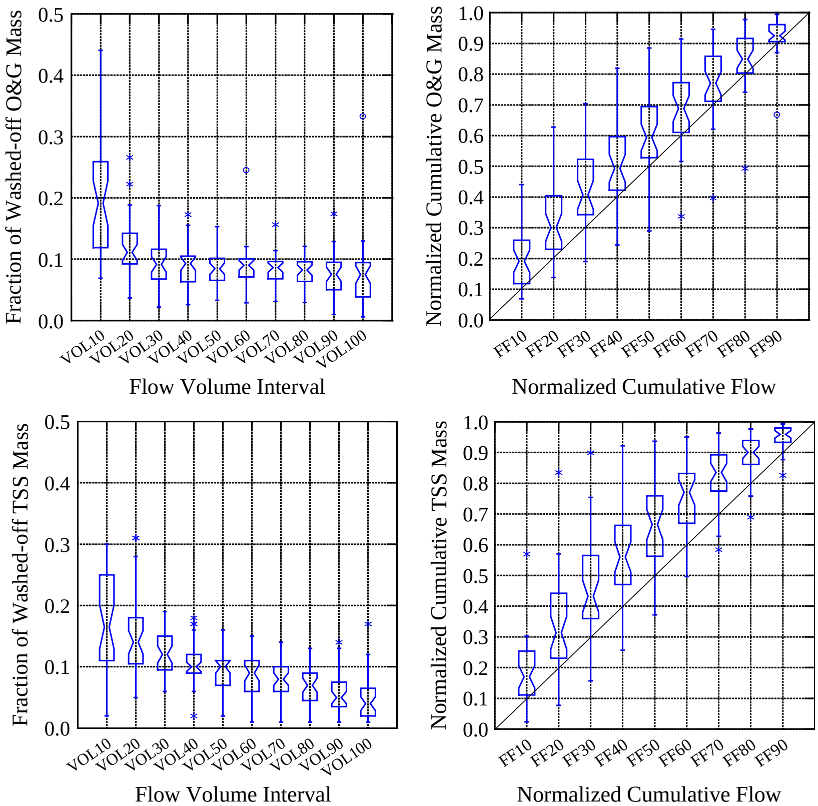


Fig. 9. Washed-off pollutant mass and volume with new washoff model.

3.4. Factors affecting the EMC

Fig. 7 is a Pearson correlation matrix showing the relationships between EMCs and a number factors potentially affecting the concentration. The upper part of the figure is a scatter gram showing the data points and ± 10 confidence intervals (smooth lines). The data distribution is shown as a histogram in the right-most boxes. The lower table shows correlation coefficients (R) above the diagonal and confidence values (P values) below the diagonal.

Water quality parameters of TSS, COD, DOC O and G, TKN, and total phosphorus (TP) and storm parameters of ADD, storm duration (STDURATION), total rainfall, total runoff volume (TRUN), and average rainfall intensity are included. The water quality parameters are highly correlated with each other, with the exception of TP, which is not correlated to any other parameters. The EMCs are negatively correlated to storm duration, total rainfall, total volume of runoff, and average rainfall intensity, although the significance is modest (0.1 to 0.2) for TSS, COD and O and G, and very low for the other water quality parameters. Smaller EMCs should be associated with larger storms and runoff volume due to the dilution effect. The lack of correlation between water quality and storm characteristics is disappointing and is the subject of ongoing research.

3.5. First flush criteria

Fractions of washed-off mass for each 10% flow volume interval are shown on Fig. 8. The figure is an example for selected parameters such as oil and grease, TKN and TSS. The fractions of washed-off mass are very high in first 30% of runoff, which is indicative of a first flush. After 30% of the volume is discharged, the differences in washed-off mass for subsequent flow volume intervals decrease. Using this approach, the first flush can be characterized in mass terms. It is useful to characterize the first flush in terms of normalized mass discharged in the first fraction of the normalized runoff volume.

This concept is shown in Fig. 9 for all storms for O and G and TSS. The left graphs are notched box plots of the discharged mass in each volume interval (10% of total volume). The figure shows, for example, that 0.19 (19%) of the total O and G and 0.17 (17%) of the total TSS mass is washed off in the first 10% of the volume. The right side of Fig. 9 shows the running total washed off as a function of normalized flow. When the median values are above the diagonal line, there is proportionally more mass washed off in the earlier runoff than in the later runoff, indicating a first flush effect. TSS, represented in the lower right of Fig. 9, shows the largest effect.

Notched box plots are used in both cases, and all events for all sites are represented in the figures. Both

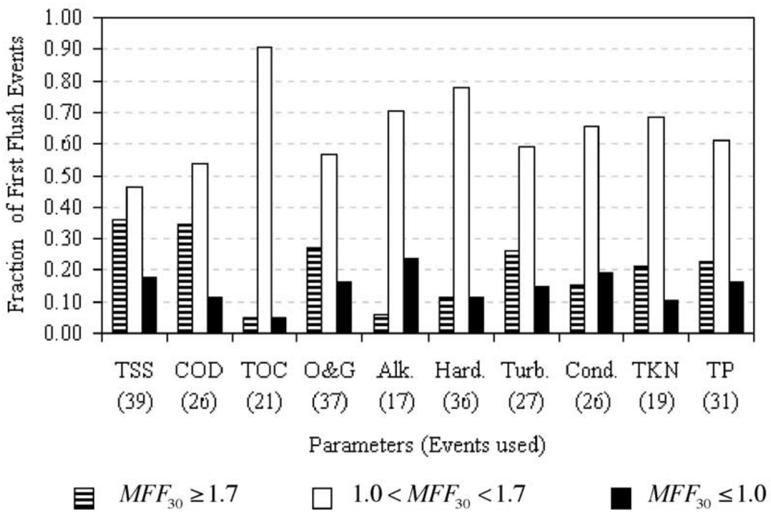
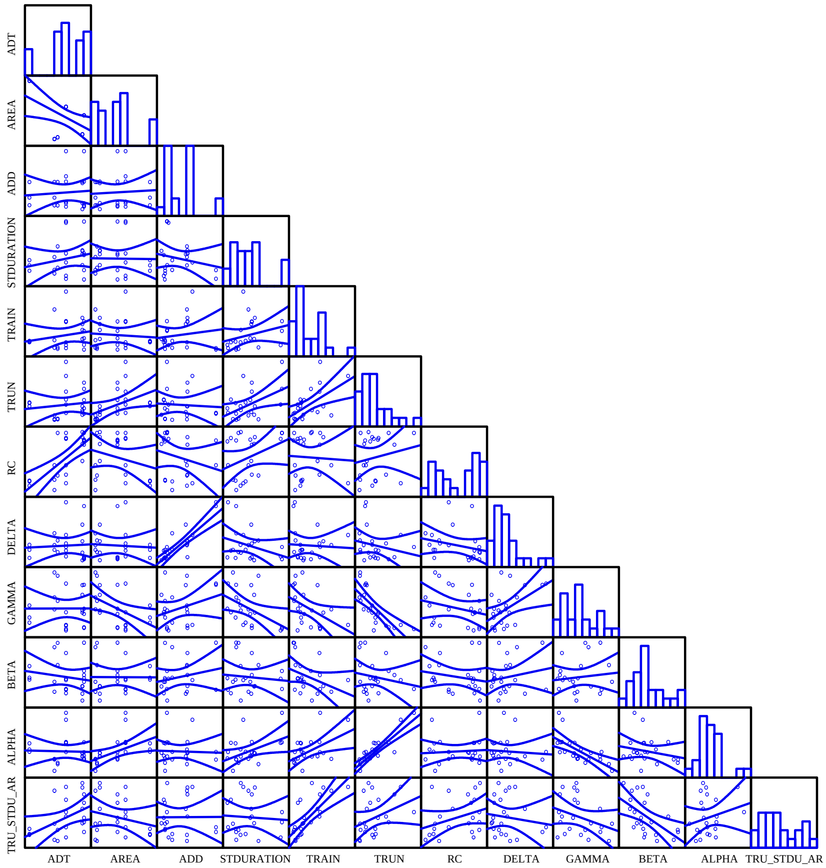


Fig. 10. Frequency of first flush events of different magnitudes.



	ADT	AREA	ADD	STDURATION	TRAIN	TRUN	RC	δ	γ*	β*	α	ARV
ADT		-0.51	0.08	0.22	0.19	0.13	0.71	0.06	0.00	-0.16	-0.03	0.46
AREA	0.01		0.06	-0.01	-0.07	0.45	-0.25	-0.06	-0.49	-0.01	0.50	-0.22
ADD	0.72	0.78		-0.20	0.14	-0.06	-0.24	0.86	0.30	0.20	-0.04	0.01
STDURATION	0.32	0.95	0.36		0.27	0.49	0.35	-0.31	-0.47	-0.09	0.46	-0.06
TRAIN	0.38	0.74	0.51	0.21		0.58	-0.05	-0.06	-0.45	-0.36	0.52	0.75
TRUN	0.57	0.03	0.78	0.02	0.00		0.18	-0.21	-0.75	-0.19	0.88	0.36
RC	0.00	0.25	0.27	0.10	0.82	0.41		-0.25	-0.25	-0.19	0.08	0.33
δ	0.79	0.77	0.00	0.14	0.80	0.33	0.25		0.52	0.19	-0.08	-0.14
γ*	0.99	0.02	0.17	0.02	0.03	0.00	0.26	0.01		0.12	-0.68	-0.33
β*	0.46	0.98	0.35	0.67	0.09	0.40	0.38	0.39	0.58		-0.22	-0.57
α	0.89	0.01	0.86	0.03	0.01	0.00	0.73	0.73	0.00	0.32		0.23
ARV	0.03	0.30	0.98	0.78	0.00	0.10	0.12	0.53	0.13	0.00	0.28	

Note: ADT (Average Daily Traffic, cars/day), ADD (Antecedent Dry Days, days), STDURATION (Storm Duration, hours), TRUN (Total Volume of Runoff, m^3), RC (Runoff Coefficient, -) and ARV (Average Runoff Velocity, m/hr)

Fig. 11. Correlation matrix and table for COD.

graph types are useful for visualizing the potential for BMPs to remove material form the first flush. The fractional mass diagrams show the opportunity for treatment in each fraction of runoff volume. The cumulative diagrams are useful in visualizing the performance of BMPs that might treat the first fraction of a storm event. A BMP that treats the first 10% of the volume treats proportional more mass. When a first flush exists, BMPs that can capture and store the first runoff, while bypassing later, less contaminated runoff are more effective.

The concepts shown in Figs. 8 and 9 have been quantified using a mass first flush ratio (MFF) (Ma et al., 2002), as follows:

$$\mathrm{MFF} = \frac{\dfrac{\int_0^{t_1} C(t)Q(t)\mathrm{d}t}{M}}{\dfrac{\int_0^{t_1} Q(t)\mathrm{d}t}{V}} = \frac{\dfrac{\int_0^{t_1} C(t)Q(t)}{\int_0^{t_1} Q(t)\mathrm{d}t}}{\dfrac{M}{V}} \tag{17}$$

Where M and V are the total washed-off mass and volume, and t_1 is a particular time in the storm. The calculation can be performed so that the washed-off pollutant mass can be determined at any point in the storm. For example, the MFF_{10} ratios for the O and G and TSS cited earlier would be 1.9 and 1.7.

Fig. 10 shows the storms classified into three categories of first flush. The first are high first flush, when 50% or more of the washed-off mass occurs in the first 30% of flow ($\mathrm{MFF}_{30} \geq 1.7$), medium first flush, when 30 to 50% of the mass is washed off in the first 30% of the flow($1.0 < \mathrm{MFF}_{30} < 1.7$), and non-first flush, when 30% or less mass in washed off in the first 30% of flow ($\mathrm{MFF}_{30} \leq 1$). These results are useful in visualizing the impact of first flush on BMP performance. A "first flush friendly" BMP, meaning a BMP that can treat a high percentage or all of the initial flow, would be advantageous for 80% of the events for TSS, 90% for COD, and 95% for TOC.

3.6. Model parameter estimation

As stated earlier, the new washoff model has four different coefficients, which are α, β^*, γ^*, and δ. All coefficients have a different meaning such as washoff rate for α, coefficient affected by runoff for β^*, coefficient representing additional pollutant sources during a rainfall event for γ^*, and initial concentration affected by antecedent dry days for δ.

The new model can be directly used for a previously monitored rainfall event to calculate EMCs and to estimate the mass loading. A set of unique parameters can be calculated; however, for broad application and predicting runoff from future storms, each coefficient of the model should be generalized. According to the derivations, we can anticipate the factors that affect each parameter. Fig. 11 shows a Pearson correlation matrix and associated scatter gram for model parameters and COD (see Fig. 7 for explanation). The model parameters are compared to average daily traffic (ADT), catchment area, ADD, storm duration, total runoff, runoff coefficient, and average runoff velocity (total rainfall divided by area and storm duration). For all pollutant parameters, α shows strong positive relationship with total runoff, but γ^* shows negative relationship with total runoff. δ is strongly and positively related to ADD. However, β^* is generally related with rainfall, runoff coefficient, and storm duration and shows negative relationship with "average runoff velocity".

Table 3
Summaries of model parameters

Parameters	δ	γ^*	α	β^*
TSS	240.8Ln(ADD)−164.8	−83.74Ln(TRun)+489.1	0.007(Trun)+3.83	−1475Ln(ARV)−9539
COD	305.9Ln(ADD)−135.5	−259.1Ln(TRun)+1480.1	0.035(Trun)+2.30	−3016Ln(ARV)−22138
TOC	2.32(ADD)+12.9	−72.61Ln(TRun)+488	1.044(Trun)+0.54	−196.4Ln(ARV) −1106
Oil and grease	14.24Ln(ADD)−1.61	−39.76Ln(TRun)+194	0.0046(Trun)+3.82	−526Ln(RC)−353.67
Alkalinity	28.98Ln(ADD)+5.1	−64.72Ln(TRun)+485.3	0.023(Trun)+2.06	−786963(ARV)+828
Hardness	8.52(ADD)+44.2	−0.219Ln(TRun)+131.8	0.003(Trun)+4.55	−4270(RC)+2620
TKN	1.75(ADD)−10.6	−26.17Ln(TRun)+148.9	1.173(Trun)−0.02	−68.9Ln(ARV)−523
TP	19.81(ADD)+430.9	−117Ln(TRun)+955.4	1.35Ln(Trun)−0.54	−6325(RC)+2930

The best-fit model parameters for all eight water quality parameters for all storms are shown in Table 3. The model using these parameters could be to create ideal mass emission rates for the various conditions that affect BMP design for highways. For example, the mass emission rates can be determined for a range of ADD, total rainfall, and other affecting conditions. These emission rates can then be used to evaluate BMP designs.

4. Conclusions

This research has presented a new semi-empirical model for describing stormwater runoff. The model uses four parameters which gives it flexibility to fit first flush as well as non-first flush events. The model's parameters are correlated to measurable or predictable storm events such as total runoff volume, antecedent dry days, and storm duration. The model shows good fit for eight water quality constituents. Future uses of the model include improving estimates of event mean concentrations from sparse data and designing BMPs to take advantage of the first flush. The following specific conclusions are made:

1. The median values of EMCs calculated to EMCs using the exponential or medium point methods are similar, but the 50% interquartile ranges are smaller for the new model than for other methods, showing that the new model produces more precise estimates. The reductions in variability are even greater if one considers the maximum and minimum values.
2. Washed-off mass loading and EMCs are presented for eight water quality parameters. Generally, the differences between minimum and maximum washed-off mass and EMCs are large because of event and site characteristics, such as rainfall intensity, area, runoff coefficient, and antecedent dry periods.
3. The EMCs are negatively correlated to storm duration, total rainfall, total runoff volume of runoff, and average rainfall intensity. Large storms have smaller EMCs because of dilution effects or exhaustion of pollutant mass.
4. The fractions of washed-off mass are very high in first 30% of runoff, which shows a first flush. The washed-off mass stabilizes after 30% of the runoff volume and it is apparent that treatment capacity in the early part of a storm (i.e., less than 30% of the runoff volume) is more valuable that treatment capacity in the later part of the storm.
5. Using the criteria of "high" first flush and "medium" first flush, as 50% of the mass in the first 30% of the volume, and 30 to 50% in the first 30% volume, respectively, more than 30% of the storms showed high first flush for TSS and COD, and more than 45% showed a medium first flush. The frequency of first flushes is tabulated for the other parameters, which is generally less frequent. A "first flush friendly" BMP, meaning a BMP that can treat a high percentage or all of the initial flow, would be advantageous for 80% to 90% of the events for TSS, COD, and TOC.

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