Environ. Eng. Res. Vol. 8, No. 4, pp. 163~176, 2003
Korean Society of Environmental Engineers

# DETERMINATION OF EVENT MEAN CONCENTRATIONS AND FIRST FLUSH CRITERIA IN URBAN RUNOFF

**Lee-Hyung Kim**†

Department of Civil and Environmental Engineering, Disaster Prevention Research Center,
Kongju National University, Chungnam-do, 314-701, Korea

(received March 2003, accepted July 2003)

**Abstract** : Non-point source pollution has become an important component in watershed planning in United States because of high mass emissions. Land use associated with vehicular activity such as parking lots and streets are especially thought to be high contributors of stormwater pollutants. In order to determine the magnitude of the first flush from freeway runoff, pollutant loading is being measured at eight freeway sites with emphasis on interpretations of event mean concentrations (EMCs) and first flush effects. The EMCs cannot be determined by simple statistical averaging of measured pollutant concentrations because of random characteristics of runoff quality and quantity. Also, it is necessary to develop a definition of first flush effects since this has not been defined clearly. Therefore, this paper will show a new EMC determination method and an appropriate definition and criteria for first flush. Using results of the monitoring and new washoff model, EMCs are determined. The EMC ranges of 95% confidence intervals are from about 102.78 to 216.37 mg/L for TSS, 104.53 to 251.79 mg/L for COD, 5.42-10.58 mg/L for oil & grease and 2.42-10.18 mg/L for TKN. The mass discharge curves that will explain the definition and criteria of first flush are classified into three types: high (>50% mass/30% runoff volume), medium and non-first flush (<50% mass/30% runoff volume). More than 80% of the events exhibited a first flush.

**Key Words** : Event mean concentrations, first flush, non-point sources, stormwater, washoff

## INTRODUCTION

The United States has made tremendous advances in the past 30 years to clean up the aquatic environment by controlling pollution from point sources. Although point source discharges have decreased during recent years, many water bodies or rivers are still impaired and are either eutrophic, with excess algae biomass and episodes of toxic algal blooms, or oxygen depleted.[1,2] Non-point sources (NPSs) are the cause of many of the problems. Non-point source pollution, unlike pollution from industrial and sewage treatment plants, comes from many diffuse sources. NPS pollution is widespread because it can occur at any time in any types of landuse. Agriculture, forestry, grazing, septic systems, recreational boating, urban runoff, construction, physical changes to stream channels, and habitat degradation are potential sources of NPS pollution. As the runoff moves, it picks up and carries away natural and anthropogenic pollutants, finally brings them into lakes, rivers, wetlands, coastal waters, and even underground drinking water sources.[3~5]

The United States Environmental Protection Agency (USEPA) developed Nationwide Urban Runoff Program (NURP) to expand knowledge

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† Corresponding author
E-mail: leehyung@kongju.ac.kr
Tel: +82-041-850-8667, Fax: +82-041-856-9388

of urban runoff pollution by instituting data collection and applied research projects in selected urban areas throughout the United States.[3,6] The realization that significant quantities of nutrients, pesticides, herbicides and heavy metals are contained in runoff caused the U.S. EPA to require that regional planning agencies develop programs to reduce pollution from urbanized areas under section 208 of the Clean Water Act. Best Management Practices (BMPs), which refers to education, regulatory procedures, treatment systems and other methods to control pollutants in runoff were required.[4,6]

Paved areas such as highways and streets in urban areas are "stormwater intensive" land uses since they are highly impervious, and have high pollutant mass accumulation from vehicular activity. Highway runoff pollutants have numerous sources such as automobile emissions, wet and dry atmospheric deposition, gross depositions such as litter, vegetation and organic residues, erosion, and road deicers. These varied sources are usually quantified using an event mean concentration (EMC), which is a flow-weighted average.[7,8] The EMC can be multiplied by the total runoff volume to determine the mass emission such as Eq. 1.

$$EMC = \frac{Discharged\ mass\ during\ an\ event}{Discharged\ volume} = \frac{\int_0^t C(t) \cdot V_{TRu}(t)dt}{\int_0^t V_{TRu}(t)dt} \tag{1}$$

Where, $C(t)$ is pollutant concentration and $V_{TRu}(t)$ is stormwater volume discharged at time t.

The difficulty of EMC determination is generally caused by uncertainties of rainfall intensity and magnitude, experimental errors and lack of sufficient data. Generally, the exponential method was used by many people because the concentrations during a storm event usually declines with time.[9~13] Multiple linear regression analysis[14] and the medium point method[2] have been used to determine EMCs by interpolating between measured concentrations. When the concentration profile does not strictly decline, as shown later, numerical or "fit" errors are introduced into the calculation.

Often the pollutant concentration declines over time, which tends to create greater emission rates 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 (BMPs). 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 concentrations. Regression models, stochastic, and deterministic simulation models have all been used.[11] The main difference between the models is the assumption of the origin of pollutants. Most of the models commonly use concentrations or loads of pollutants as variables that are dependent upon runoff volume, rainfall intensity, traffic intensity, antecedent dry days, surrounding land use, etc. Generally, it is difficult to consider all factors because of many different site-specific conditions such as presence or absence of street sweeping, soil saturation, wind direction, etc. Regression models have been criticized as poor predictors of future events or other regions. The existence of first flush has been debated. Hence, there have been many defining criteria for the first flush effect. Thornton and Saul[15] defined the first flush as the initial period of storm flow during a storm event. Geiger[16] defined that a first flush occurs when the slope of normalized cumulative mass emission plotted versus normalized cumulative volume is greater than 45%. Several other investigators have also used the Geiger's definition.[2,14,17,18] Vorreiter and Hickey[19] proposed using only the first 25% of runoff volume in defining first flush. Deletic[10] used standard statistical methods including a multiple regression model, and restricted first flush to the first 20% of runoff. Saget et al.[20] and Bertrand-Krajewski et al.[8] defined that a first flush occurs 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 proportion of imperviousness area is high. Large watersheds may have long travel time, so that the early runoff from areas far from the sample location is mixed with later runoff from areas adjacent to the sample location.

This research investigates the existence of first flush as a function of site-specific variables as well as stormwater characteristics. The objectives of this study is to show determination approaches for EMCs and mass loading with data interpolation method and to suggest the clear definition and criteria of first flush.

# METHODS

## Descriptions of Sites and Monitored Events

Figure 1 shows the eight monitoring sites. All were selected to include primarily highway runoff. The sites were sampled over two rainy seasons. Monitoring was performed by collecting 4L grab samples. Generally five 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 the runoff. Rainfall and runoff rates were also measured with automated monitoring equipment. EMCs were calculated by integrating the product of runoff rate and concentration. A large suite of water quality parameters was measured, including oxygen demand parameters, metals, nutrients and ions.[21] Of those water quality parameters, 10 parameters will be shown in this paper.

Table 1 summarizes the sites and event descriptions. It includes site area, date, average daily traffic (ADT), antecedent dry days (ADD), 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 about 69 days. The smallest catchment area is 1,700 $m^2$ at site URS6-20F and the largest area is 48,100 $m^2$ at site CDM7-10.

## Derivation of New Wash-off Model

The new wash-off model is derived using continuous mass balance considering runoff volume, rainfall volume and time. Each pollutant has a total mass on the watershed that existed before rainfall and a remaining mass that exists after a rainfall. The wash-off mass is the difference between total and remaining mass. The mass input from processes during the storm event is neglected in the initial derivation, but is added later. The initial mass will also be related to the antecedent dry periods. Eq. 2 is the "dynamic mass balance equation" for this system and it accounts for all mass everywhere in the system at time $t$.

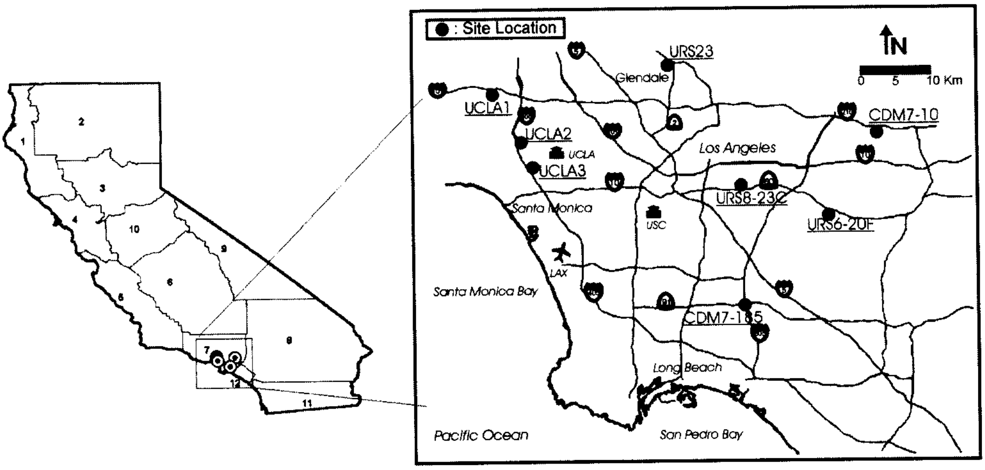


Figure 1. Study areas in Southern California, USA.

Table 1. Monitoring site descriptions

| Sites | Watershed Area ($m^2$) | ADT (Cars/day) | Event Date (mm/dd/yy) | Antecedent Dry Days (days) | Storm Duration (hrs: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 |
| | | | 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 | 3,900 | 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 | 220000 | 01/25/00 | 25.00 | | | |
| | | | 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 | 1,700 | 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 | 2,500 | 229,000 | 01/26/01 | 33.00 | 12:48 | 0.53 | 6.59 |
| | | | 02/19/01 | 5.50 | 7:12 | 0.43 | 10.66 |

$$Mass_{Initial} = Mass_{retained}(t) + Mass_{washed-off}(t) \tag{2}$$

The mass retained can be represented using a hypothetical concentration corresponding to the mass divided by the rainfall retained on the watershed, which is assumed constant. The washed off pollutant mass can be calculated by integrating the product of the runoff concentration $C(t)$ and the runoff rate $Q_{Ru}(t)$. Thus, the remaining mass can be expressed:

$$C(t) \cdot V_{ret} = C(t) \cdot k \cdot V_{Ra} \tag{3}$$

$V_{ret}$ = Volume of rainfall retained on the watershed, $m^3$

$k$ = Fraction of total rainfall retained on the watershed, $V_{ret} / V_{Ra}$

$C(t)$ = Time varying concentration washed-off from watershed area at time $t$, $g/m^3$

$$Mass_{Initial} - k \cdot V_{Ra} \cdot C(t) = \int_0^t C(t) \cdot Q_{Ru}(t)dt \qquad (4)$$

$Q_{Ru}(t)$ = Runoff flow rate from watershed area, $m^3$/sec

$\alpha_1$ = Runoff coefficient

$V_{Ra}$ = Total rainfall volume = $\int_0^T \text{Rainfall}(t)\ dt, m^3$

$V_{TRu}$ = Total runoff volume = $\int_0^T Q_{Ru}(t)\ dt, m^3$

Differentiating and rearranging Eq. 4 with $V_{Ra} = V_{TRu}/\alpha_1$.

$$\frac{d[C(t)]}{C(t)} = -\frac{\alpha_1}{k \cdot V_{TRu}} \cdot Q_{Ru}(t)dt \qquad (5)$$

Integrating Eq. 5, we obtain:

$$\ln[C(t)] = -\frac{\alpha_1}{k} \cdot \frac{\int_0^t Q_{Ru}(t)dt}{V_{TRu}} + \ln(\beta) \qquad (6)$$

$\beta$ = Integration constant

By letting $\frac{\alpha_1}{k} = \alpha$ and $\frac{\int_0^t Q_{Ru}(t)dt}{V_{TRu}} = Q_{nRu}(t)$, equation 6 becomes:

$$\ln[C(t)] = -\alpha \cdot Q_{nRu}(t) + \ln(\beta) \qquad (7)$$

Where, $Q_{nRu}(t)$ =Normalized cumulative volume, $0 \le Q_{nRu}(t) \le 1.0$

Taking the exponential of both sides, Eq. 7 becomes:

$$C(t) = \beta \cdot Exp[-\alpha \cdot Q_{nRu}(t)] \qquad (8)$$

Finally, as stated earlier, the mass input during a storm event should be considered as another concentration term ($\gamma$), which is originated from automobiles, etc. Thus,

$$C(t) = \beta \cdot Exp[-\alpha \cdot Q_{nRu}(t)] + \gamma \qquad (9)$$

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

$$M(t) = C(t) \cdot Q_{Ru}(t) \qquad (10)$$

$M(t)$ = Pollutant mass emission rate at time, $t$

By rearranging Eq. 10 and letting $[Q_{nRu}(t) - Q_{nRu}(t-1)] = \beta_1 \cdot Q_{nRu}(t)$, we obtain:

$$C(t) = \frac{M(t)}{Q_{Ru}(t)} = \frac{\int_{t-1}^t M(t)dt}{\int_{t-1}^t Q_{Ru}(t)dt} = \frac{\int_{t-1}^t M(t)dt}{\int_0^t Q_{Ru}(t)dt - \int_0^{t-1} Q_{Ru}(t)dt}$$
$$= \frac{1}{\beta_1 \cdot Q_{nRu}(t)} \cdot \frac{\int_{t-1}^t M(t)dt}{V_{TRu}} \qquad (11)$$

The left side of Eq. 11 is a new concentration term that is a key premise of the model. Let $\int_{t-1}^t M(t)dt \Big/ V_{TRu} = NewConc.[Q_{nRu}(t)]$. Eq. 11 can be expressed such as follows:

$$C(t) = \frac{1}{\beta_1 \cdot Q_{nRu}(t)} \cdot \{NewConc.[Q_{nRu}(t)]\} \qquad (12)$$

By equating Eq. 9 and 12, we obtain:

$$\beta \cdot Exp[-\alpha \cdot Q_{nRu}(t)] + \gamma = \frac{1}{\beta_1 \cdot Q_{nRu}(t)} \cdot \{NewConc.[Q_{nRu}(t)]\} \qquad (13)$$

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

$$NewConc.[Q_{nRu}(t)] = \beta^* \cdot Q_{nRu}(t) \cdot Exp[-\alpha \cdot Q_{nRu}(t)] + \gamma^* \cdot Q_{nRu}(t) \qquad (14)$$

In Eq. 14, a parameter is needed to describe the initial condition, which is related to antecedent dry periods. The new washoff model is expressed in Eq. 15.

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

In order to use the model as a predictive tool, it is necessary to predict the total runoff volume, which can be based upon meteorological data for weather. Eq. 15 has four parameters that are related to antecedent dry periods, rainfall intensity and runoff coefficient. $\delta$ is an initial concentration related to antecedent dry periods. $\alpha$, $\beta^{*}$, and $\gamma^{*}$ are affected by total rainfall. The new model can be applied for data interpolation after a storm event to determine EMCs and mass loading. Also, the model can be used for pollutant predictions after sufficient experience is obtained to calculate generalized coefficients.

## RESULTS AND DISCUSSION

The typical rainfall in study area is shown on Figure 2. It has monthly rainfall and cumulative rainfall during study periods and average rainfall during 43 years. The study areas have rainy season during the winter (Dec. to Feb.) and dry season during the summer. The large dry season creates the possibility for a "seasonal first flush".

The variations of the runoff coefficients are shown on Figure 3. The runoff coefficients are ranged from 0.35 to 0.95 depending on rainfall intensity, antecedent dry days and catchment area. The mean value was determined to 0.87. It is higher, approaching unity for large rainfall events, and lower in small rainfall events. This is expected and is caused by depression storage and the limited infiltration that occurs in paved areas. For very small rainfall events, evaporation, depression storage and infiltration may be significant. Antecedent dry periods are also important because it will affect infiltration.

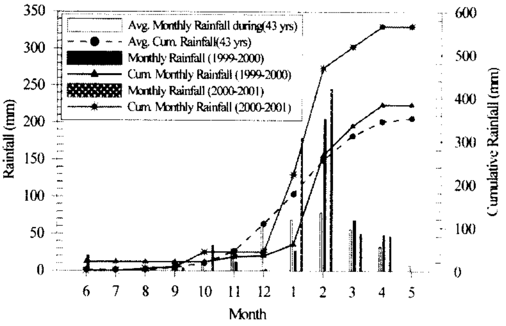


Figure 2. Average monthly and cumulative precipitation in research area.

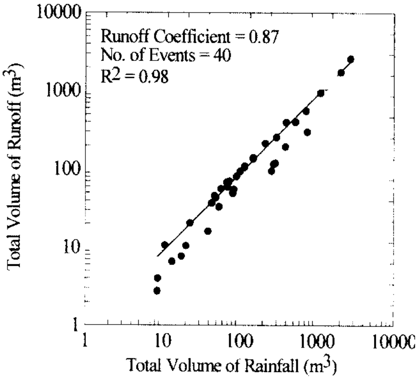


Figure 3. Runoff coefficient during research periods.

### Comparison of Monitoring and Modeling Results

The new washoff model was applied for all events as mentioned earlier to predict concentration profiles. The model can predict the various functional types such as linear, exponential and Gamma distributions. The existing models such as exponential and power types have limitations for presenting various types of distributions. However, the new model has flexibility to fit various types of concentration and it fits well. Figure 4 shows concentration distributions of monitored and modeled. It shows good agreement for most types of concentration distributions. 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 models accuracy.

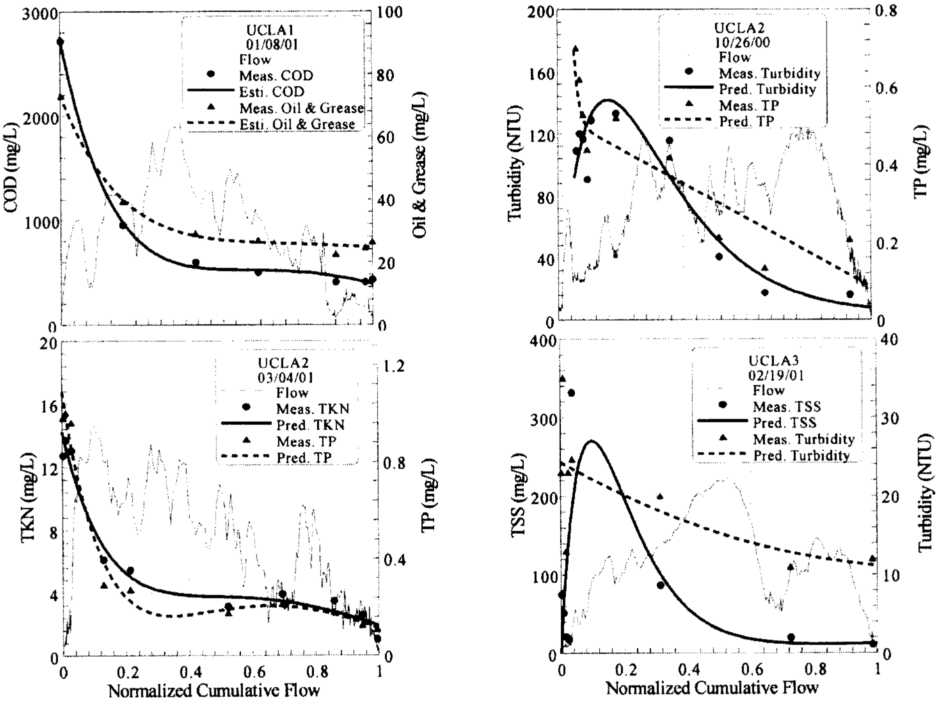


Figure 4. Concentration versus normalized flow for measured and predicted results.

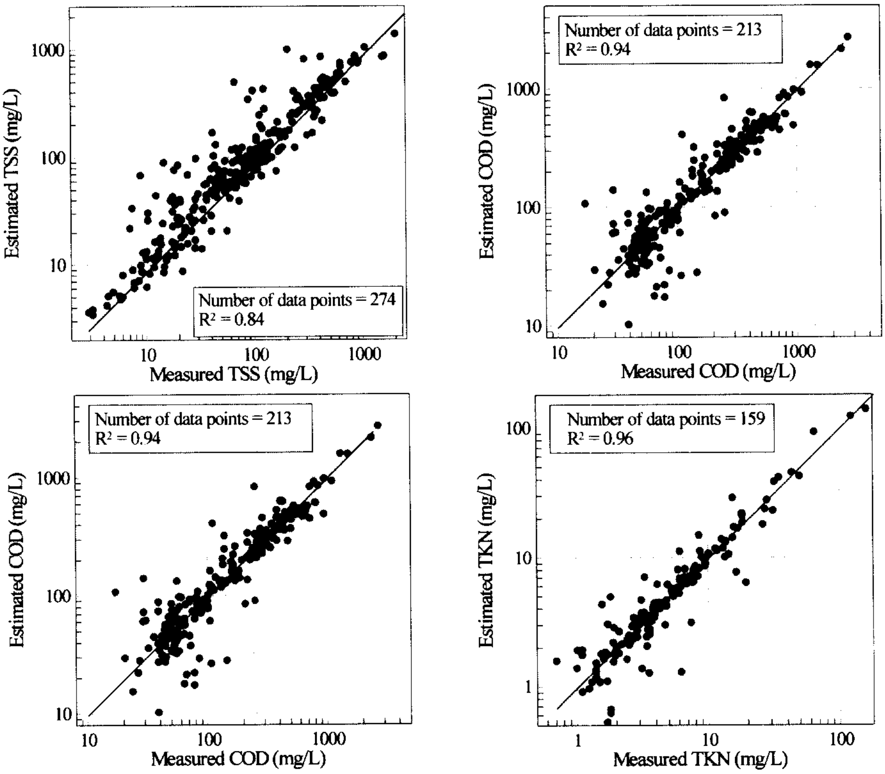


Figure 5. Relationships between measured and estimated concentrations.

Figure 5 shows the comparison of the monitored and modeled results. The $R^2$ for water quality constituents are between 0.84 and 0.98 and the residuals (not shown) are generally equally distributed and unbiased. The model can be used to estimate EMCs for an entire event, or could be integrated over a subset of the storm to obtain flow-weighted average concentrations. In this way the concentration in one part of the storm can be compared to concentrations in other parts of the storm.

## Determination and Comparison of EMCs and Mass Loading

Generally, EMCs of the equation are available to evaluate effects of stormwater runoff on receiving waters. The EMCs usually vary among storm events due to factors such as rainfall intensity and antecedent dry periods, etc. As stated earlier, the existing EMC determination methods such as the medium point and exponential methods are limited. The medium point method is easy to apply, but can introduce large error if only a few samples were collected. The exponential model may not fit the observed data, which results in large errors. The key problem of the EMC dertermination method is how to express the concentration changes, *C(t)*, reasonably. It is interesting and useful to compare EMCs calculated in different ways. Three methods for estimating EMCs were used: 1) predicting concentration using the new washoff model; and 2) generating the concentrations from an exponential model, and 3) the medium point method suggested by Larsen.[2] The results are shown in Figure 6. The notched box plots shows minimum, median, maximum, standard deviations, upper/lower 95% confidence intervals and outliers for each parameter. The median values are similar, but the 50% interquartile ranges are smaller for new model than other methods, suggesting less variability in the new method. Reductions in variability are even greater if the maximum and minimum values

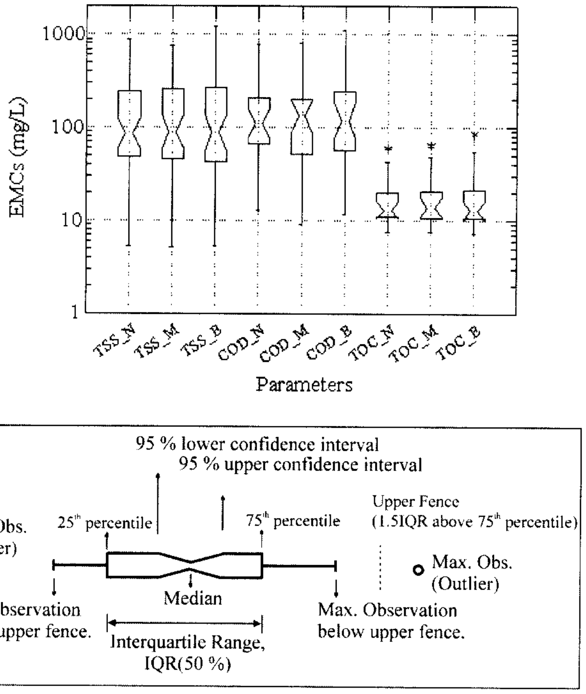


Figure 6. Comparison of event mean concentrations (N=New model, M=Medium point method, and E=Exponential model).

Table 2. Statistical summaries of event mean concentrations and mass loading

| Parameters | | Basic Statistics | | | | | | Confidence Interval | |
|---|---|---|---|---|---|---|---|---|---|
| | | No. of Events | Min. | Max. | Median | Mean | StDev. | 95% Upper | 95% Lower |
| TSS | EMC | 39 | 5.21 | 874.23 | 87.54 | 159.57 | 175.22 | 216.37 | 102.78 |
| | Mass Loading | | 0.06 | 17.27 | 0.83 | 2.43 | 3.91 | 3.71 | 1.14 |
| COD | EMC | 26 | 13.51 | 776.71 | 102.87 | 178.16 | 182.30 | 251.79 | 104.53 |
| | Mass Loading | | 0.10 | 3.23 | 0.98 | 1.19 | 0.91 | 1.56 | 0.83 |
| TOC | EMC | 21 | 7.36 | 59.26 | 12.82 | 18.09 | 13.27 | 24.13 | 12.05 |
| | Mass Loading | | 0.03 | 0.85 | 0.14 | 0.22 | 0.23 | 0.33 | 0.12 |
| TKN | EMC | 19 | 1.93 | 33.85 | 3.15 | 6.30 | 8.06 | 10.18 | 2.42 |
| | 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 & Grease | EMC | 37 | 0.52 | 34.57 | 5.23 | 8.00 | 7.73 | 10.58 | 5.42 |
| | Mass Loading | | 0.01 | 0.39 | 0.05 | 0.08 | 0.08 | 0.11 | 0.05 |
| Hardness | EMC | 36 | 8.36 | 291.58 | 44.63 | 70.83 | 59.82 | 90.49 | 51.17 |
| | Mass Loading | | 0.00 | 5.68 | 0.52 | 0.82 | 1.02 | 1.16 | 0.49 |
| Alkalinity | EMC | 17 | 8.98 | 75.54 | 21.82 | 26.88 | 18.58 | 36.43 | 17.32 |
| | Mass Loading | | 0.05 | 0.49 | 0.22 | 0.24 | 0.13 | 0.31 | 0.18 |

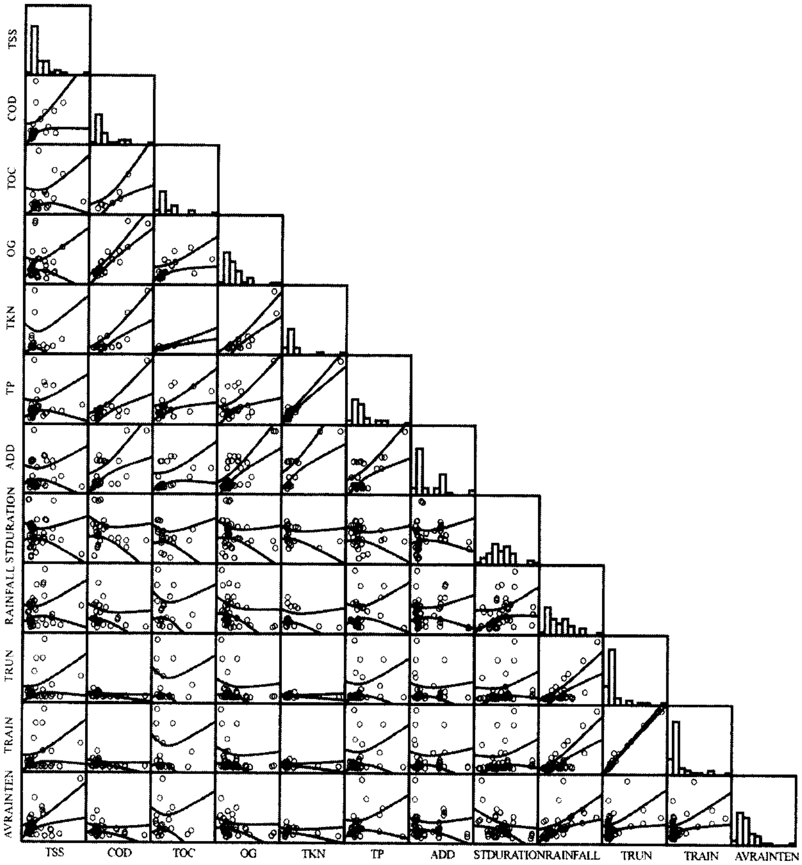
* Units of EMC and mass loading are mg/L and $g/m^2$.
EMC's and mass loading are calculated using the new model.

were considered. For example, the maximum TSS EMC calculated using the exponential method is 1,200 mg/L. The maximum using the medium point method is 750 mg/L, which compares more favorably to the maximum calculated using the new model, 890 mg/L. The large values calculated with the exponential model occur when the fit is poor. The medium point method is easy to apply, but it potentially inaccurate if there are few monitored samples. According to new model, 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 0.5 mg/L to 34 mg/L. The large range shows the difficulty of predicting EMCs for even a single land use type. Table 2 shows the statistical summaries for EMCs. The EMC ranges of 95% confidence intervals are from about 102.78 to 216.37 mg/L for TSS, 104.53 to 251.79 mg/L for COD, 5.42-10.58 mg/L for oil & grease and 2.42-10.18 mg/L for TKN.

Washed-off mass was calculated using the continuous model and the measured runoff flow rate with one-minute intervals. Concentrations at one-minute intervals were generated using the washoff model. Table 2 summarizes the statistical analysis for washed-off mass loading for each water quality parameter. The ranges of washed-off mass loading are from about 0.06 $g/m^2$ to 17.27 $g/m^2$ for TSS and about 0.1 to 3.23 $g/m^2$ for COD. The volume of runoff can affect on mass loading and EMCs because of dilution effect during a storm event. 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. As shown in the table, large amounts of pollutant are washed-off during storm events, which may affect receiving waters. This process could be expanded to an entire watershed to estimate freeway loadings in a TMDL analysis.

## Factors Affecting EMCs and Mass Loadings

The relationships of pollutant EMCs and factors affecting are shown in Figure 7. The EMCs are negatively correlated to storm duration, total rainfall, total volume of runoff and



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

Figure 7. Relationships of EMCs and affecting parameters.

rainfall, and average rainfall intensity. Large storms have smaller EMCs because of dilution effects or exhaustion of pollutant mass.

## First Flush Criteria

The existence and importance of first flush has been debated. If first flush exists, it can be important in BMP design, since the BMP can be used to treat more early runoff volume and bypass the later runoff.

Figure 8 shows two ways of displaying first flush. The results were obtained by fitting the model to each storm event and then using the model results to calculate mass emission rates. Both 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. The left side of Figure 8 shows COD and oil & grease mass emission rates for successive normalized runoff volumes. This method of plotting shows that the first 10% of the normalized volume carries the greatest mass of pollutants. The right side of Figure 8 shows a first flush ratio or in this case the mass first flush ratio (MFF). For COD, the $MFF_{10}$ is 2.7, which means that 27% of the normalized COD mass is washed off in the first 10% of normalized runoff. The MFF ratio declines as the storm

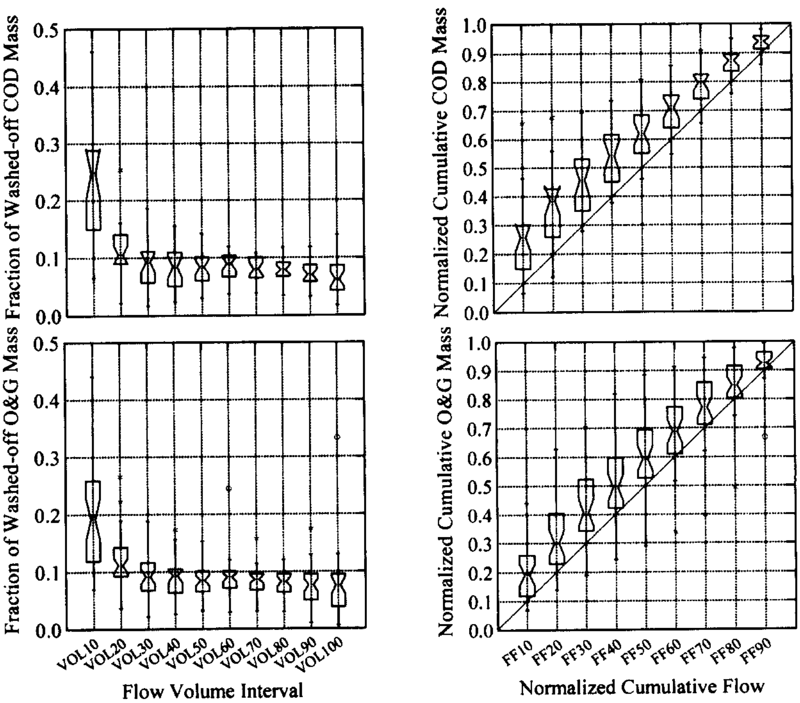


Figure 8. Washed-off pollutant mass and volume.

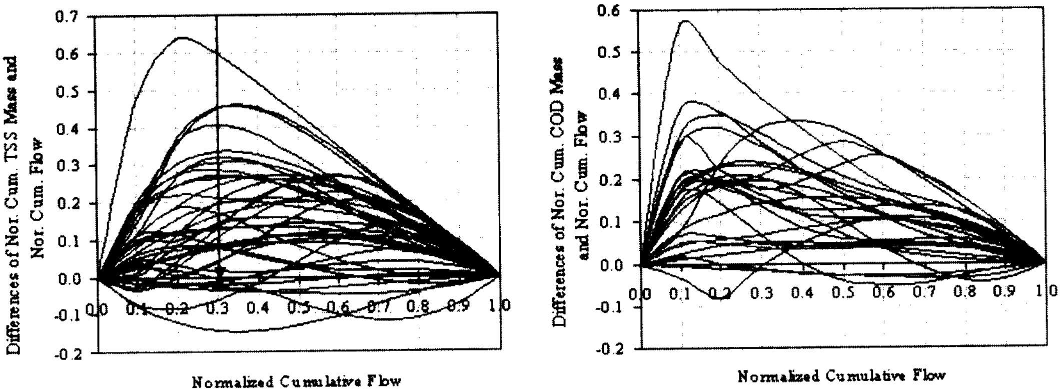


Figure 9. Differences of normalized cumulative mass and flow for TSS and COD.

proceeds and the $MFF_{20}$ and $MMF_{30}$ decline to 2.4 and 1.5, respectively.

The washed-off mass generally decreases with time, and a point of diminishing returns can be envisioned for BMPs that are sized based on flow rate, or total volume treated. Each subsequent volume fraction provides less opportunity for removal. After 30% of the runoff volume, the washed-off mass does not show large differences. It is apparent that treatment capacity in the early part of a storm (i.e., less than 30%) is more valuable.

Figure 9 shows another way of describing first flush. The difference between the normalized washed off mass (curved line) and the normalized flow (diagonal line) is plotted. The first flush and non-first flush or "last flush" are clearly shown with the figures. Negative num-

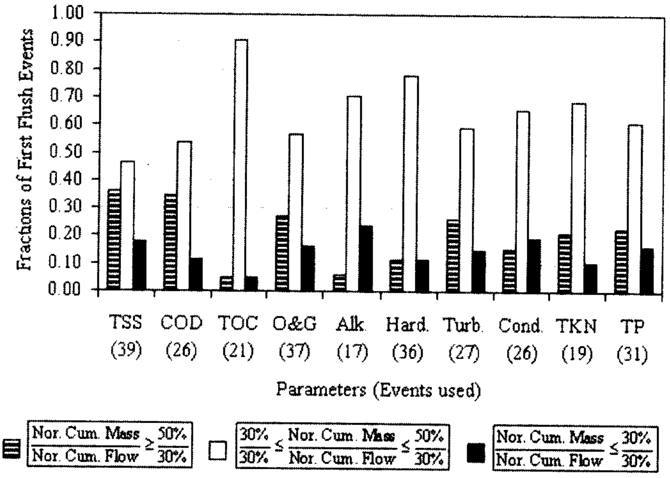


Figure 10. Fractions of first flush events.

bers indicate a last flush. The maximum value of the function is the point of maximum first flush, or the point where the normalized washed off mass most TSS and COD are shown and all events are plotted. The maximums vary significantly, but generally the maximums are in the 20 to 30% range of normalized runoff. The non-first flush effects are clearly shown in the figures. Therefore, the figures are also a reasonable approach for determining the first flush criteria and first flush effects.

The ranges of first flush observed are shown in Figure 9. The numbers in parenthesis below the parameters represent the number of observed rainfall events. The events are divided into $MFF_{30}$ ratios greater than 1.67 (high), between 1 and 1.67 (medium) and less than 1.0 (non-first flush). Most events are between 1 and 1.67. About 80% events for TSS, 90% events for COD and 95% events for TOC are had some type of first flush.

## CONCLUSIONS

This paper has presented a new model for describing stormwater runoff. The model uses four parameters which gives its 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. 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 additional conclusions are made:

(1) 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.

(2) 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.

(3) The fractions of washed-off mass are very high in first 30% of runoff, which suggests 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%) is more valuable that treatment capacity in the later part of the storm.

(4) 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.

## ACKNOWLEDGEMENT

This study was supported in part by the California Department of Transportation (Caltrans). The authors are grateful to their continuous support.

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