Chapter 15

Discharge Characterization of Urban Storm Water Runoff Using Continuous Simulation

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Introduction

The extent to which stormwater pollutant loads are affected by build up and wash off of pollutants is widely debated. Physical, chemical, biological, and sociological processes controlling pollutant build up and wash off are exceedingly complex and difficult to predict. Not only do these effects vary between locations but they vary between constituents as well. Representations of build up and wash off in estimating storm water pollutant loads is usually limited to emulating the physical processes. Various stormwater management models such as SWMM (Huber and Dickenson, 1988) and P8 (Walker, 1990) use deterministic models of build up and wash off to aid in storm water quality assessments. SWMM users are referred to a variety of studies on build up to aid in the selection of empirical parameters in build up function. However, calibration of necessary parameters may be extremely difficult.

Empirical relationships can provide site specific information on the build

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up and wash off of catchment pollutants. From an empirical viewpoint there is evidence to suggest that build up and wash off are important factors in determining annual and seasonal loads in certain areas. For instance, some regional stormwater monitoring programs have reported that event mean concentrations decrease as a rainy season progresses (Montoya, 1989). Conclusions have been drawn from these observations that build up (and subsequent wash off) is occurring. Very few stormwater monitoring programs have measured actual build up and wash off specifically. However, most programs do measure event mean concentration and total runoff volume. Simultaneous observations of concentration and volume allow quantification of *event mass* which is a direct measure of event “wash off”. Significant build up and wash off effects can be identified empirically through multiple linear regression of event mass *versus* serial rainfall statistics including cumulative rainfall to date, days since last storm, and event rainfall volume. Knowledge of how runoff mass is related to serial rainfall parameters can be used to reflect build up and wash off in continuous simulation models thereby producing more accurate estimates of time series of runoff event pollutant mass.

15.1 Methodology

15.1.1 Concentration vs Mass in Quantifying Wash Off

Build up and wash off are mass transport processes. Using event mass observations is the only sure way of assessing build up and wash off magnitude. Event mean concentration (EMC) is dependent upon runoff volume and should not be relied upon directly to quantify mass transport processes. The fact that EMCs show trends over a rainy season may be an artifact of storm size and not, as some have suggested, evidence of build up or wash off. Short duration storms typically have higher event mean concentrations due to first flush phenomena in which the most highly concentrated runoff occurs within the first few hours. Event masses of short duration storms may be equal to or less than storms of greater duration (and lower mean concentration) for that reason. Therefore, using event mean concentration to quantify wash off can excessively weight smaller, shorter storms over larger, longer storms.

15.1.2 Treatment of Non-Detected Data

Accurate description of urban runoff greatly depends on the quantity of detectable concentration data (*i.e.* numerical results reported above the detection limit), as well as total number of data points (sampling events). Even with low method detection limits, certain constituents may not be detectable for some or all events.

The treatment of non-detected data applies to event mean concentrations

below detection from which event masses are calculated. The process by which non-detected values are included begins with a ranking of all observations including non-detected values. Detected values are fit to either a normal or lognormal distribution. In the case of metals concentration data, EMC distributions are generally better described using a lognormal fit.

In cases where analyses are to be performed that would include non-detected values, a single value may be assigned to the non-detected values for each constituent. The value to assign each non-detected point is determined by the median rank of the non-detected EMCs. Assignment of a single value to the non-detected values corresponding to the median rank of the non-detected values insures equal weight to all censored values when performing analyses. Basic statistics and population distribution parameters may be inferred from the equation of the regression line without assigning values to non-detected observations. Figure 15.1 shows a typical lognormal probability plot of a data set containing >50% undetected values with a single detection limit. This method has been shown to be accurate for large data sets containing as little as 40% detected data, (Gilliom and Helsel, 1986).

15.1.3 Multiple Linear Regression of Event Mass with Serial Rainfall Parameters

Multiple regression analysis of discharge mass vs. serial rainfall parameters serves two purposes. First, regression results provide a measure of the effects of build up and wash off for each individual constituent. Second, regression creates deterministic models (regression equations) to drive the continuous simulation (see Figure 15.2).

The multiple linear regression process includes collecting monitoring event EMCs and total event runoff volumes. These quantities are combined to produce the monitoring event masses (see Figure 15.2). The corresponding serial rainfall parameters (rainfall depth, rainfall intensity, cumulative rainfall to date, and days since last storm) are determined for each event from the rainfall time series. (Since runoff volume is often assumed to be a linear function of rainfall depth, identical results will be obtained if runoff volume is used in place of rainfall depth in the regression modelling process.)

Significant ($p < 0.05$) correlations of event mass loads with cumulative annual precipitation, days since last storm, rainfall intensity, and rainfall volume are generated for each constituent (and each watershed). The regression results may indicate that event mass per unit area or mass per unit impervious area produces better correlation with hydrologic conditions than event mean concentration. If this is the case, the possibility exists to combine data from multiple watersheds into a single data set on the basis of mass per unit (impervious) area.

Figure 15.1
Typical lognormal regression with data containing a large percentage of non-detected values.

Figure 15.2
Schematic of continuous simulation including multiple linear regression.

15.1.4 Continuous Simulation Modelling of Watershed Response

The continuous simulation method is preferable to event methods because of its ability to incorporate significant serial and cross correlations of parameters known to affect urban runoff mass loads, particularly in areas where annual rainfall patterns are seasonal. The ability of continuous simulation to reflect decreasing mass loads from watersheds as a wet season progresses and mass build up between storms is a major advantage over event modelling approaches. Furthermore, continuous simulation results provide estimates of the frequency and variability of mass loadings important to the assessment of water quality-based compliance criteria.

In the continuous analysis process, multiple regression relationships between event mass per unit impervious area and time-based rainfall observations were produced from monitoring event EMCs and the runoff volumes used to simulate event masses in response to the actual historical precipitation record. Figure 15.2 is a schematic of the continuous analysis process including multiple linear regression.

15.1.5 Test Case: Sacramento, CA

Location, Geography, and Hydrology

Sacramento, CA sits at the confluence of two major Northern California Rivers, the Sacramento and the American. The American River water is of high quality and is fed most of the year by Sierra snowmelt. The Sacramento drains a very large watershed including the American River watershed. At the extreme southern end of the Sacramento River watershed, the city of Sacramento lies downstream of the entire watershed. Over half of Sacramento urban runoff drains to the American River. The remaining urban runoff flows directly to the Sacramento River.

Rainfall patterns in Sacramento (and most of the west coast) consist of a distinct wet season extending from October to April in which over 90% of the rainfall occurs. The months from May through August are nearly completely dry.

Data Availability

For practical purposes, only those constituents having at least 5 total data points, a minimum of 40% detected values, and at least four detected values are considered to have sufficient data. This is consistent (for the most part) with the data assessment methodology used in NURP (USEPA, 1983).

Runoff water quality data are available for Sacramento area stormwater

discharges dating from the early 1970's. There have been several independent studies of Sacramento stormwater quality since then, including studies performed by the California Regional Water Quality Control Board (Montoya, 1987), and in-depth studies by Brown & Caldwell Consultants and HDR Engineering for the Sacramento permittees, under terms of the area wide stormwater NPDES permit program. In 1983, USEPA published the results of its multi-year Nationwide Urban Runoff Program (NURP), including stormwater monitoring data from 28 cities throughout the United States.

The Sacramento NPDES Stormwater Permit Program has produced the most extensive stormwater quality database to date for the Sacramento area. At the time of this analysis, the program had completed its second year. In the first year (1990-1991), three American River sites and three Sacramento River sites were sampled, along with four urban stormwater discharge points. In the second year (1991 - 1992), the program was expanded to include five American River sites, three Sacramento River sites, and five urban runoff sites. The river and urban runoff sites generally have been sampled synoptically, with analysis of grab and composite samples for a wide range of chemical, physical and biological parameters.

After assuring data compatibility and quality, a reliable and up-to-date data set of runoff concentrations was obtained. Model input data included event rainfall, EMCs for fourteen constituents (seven metals and seven conventional constituents), and event runoff volume for four urban watersheds for five storm events during 1990-92. Non-parametric tests of all available monitoring data revealed that monitoring data from the early 1980's are not compatible with more recent NPDES monitoring data for most constituents and were, therefore, excluded from the modelling effort. The previous stormwater monitoring data were significantly higher in concentration and mass load for all constituents.

Median event mean concentrations from Sacramento were compared with those generated by EPA during the Nationwide Urban Runoff Program (NURP). As shown in Table 15.1, the Sacramento and NURP concentrations are somewhat comparable for BOD, phosphorous and nitrate/nitrite nitrogen, whereas the NURP data is higher for metals and TSS. The most striking disparity lies with the lead concentrations, where NURP is more than eight times higher than the Sacramento program.

Runoff volume data are required by this analysis for three purposes: 1) to enable calculation of event mass loads from concentration data, 2) to estimate effective impervious area for each watershed, and 3) to estimate dry season runoff volume. Existing pump run time and stream stage data are adequate for these purposes. Estimates of runoff volumes for watersheds served by stormwater pumps are developed from observations of pump run times and pump capacities. Estimates of runoff volume for watersheds drained by gravity are obtained through continuous stage readings and stage-discharge curves.

EPA NURP data analysis reports significant correlation of pollutant

Table 15.1
Median Event Mean Concentrations from the Sacramento NPDES Program (all five watersheds combined), EPA/NURP, Fresno (NURP), and Santa Clara Valley (residential).

Constituent	Combined Median EMCs	EPA/NURP ^a Median EMCs	Fresno NURP EMCs	Santa Clara Valley Median EMCs
Arsenic	0.002		0.001	
Cadmium	(0.0002)		0.001	0.0013
Chromium	0.0051		0.0085	0.014
Copper	0.014	0.034	0.014	0.031
Lead	0.017	0.144	0.17	0.037
Nickel	0.0042		0.011	0.025
Zinc	0.108	0.160	0.09	0.200
Total Suspended Solids	30	100		
Total Dissolved Solids	94.8			
BOD	7.4	9		
Oil & Grease	1.07			
Phosphorous, total	0.30	0.33	0.45	
Nitrate/Nitrite Nitrogen	0.88	0.68	0.006	
Ammonia	0.52		0.035	

Notes: All concentrations are shown as mg/l.
 Concentrations shown in parentheses are lower than the analytical detection limit due to the inclusion of "Not Detected" data.
^a Table 6-17, NURP.

mass with impervious area. The results of this study corroborate that finding for Sacramento. Event mass per impervious area values from the various watersheds are combined into a single data set for the purpose of describing typical pollutant loads from Sacramento watersheds. Loadings are computed for a "combined" watershed data set, as well as for the individual watersheds.

Multiple Regression Analysis

Tables 15.2 a,b,c present the results of the multiple regression analysis for two Sacramento area watersheds, Sump 111, Chicken/Strong Ranch, and the combined watershed data set. (Note: The analysis is done only on constituents for which sufficient acceptable data exist. The "combined" data set includes more observations and therefore more constituents pass the criteria for sufficient acceptable data.) The column "Log Trans.?" signifies whether the dependent variable (pollutant mass) was log transformed. The column "Significant?"

signifies whether the regression is considered to be statistically significant (“p” for the regression coefficients is less than 0.05). The column headed by “r” signifies the value of the linear correlation coefficient.

Table 15.2a
Most Significant Multiple Regression Results for Sump 111
(Hydrologic factors vs. Mass in lbs per impervious acre), (n=5)

	Parameter(s)	Log Trans.?	Significant?	"r"
Cadmium	Rainfall	N	Y	0.99
	Cum. Ppt.		Y	
Chromium	Rainfall	N	N	0.71
Copper	Rainfall	N	Y	0.977
	Cum. Ppt.		Y	
Lead	Rainfall	N	Y	0.996
	Cum. Ppt.		Y	
Zinc	Rainfall	N	Y	0.979
	DSL		Y	
Total P	Rainfall	N	N	0.9
	Cum. Ppt.		N	
Nitrate + Nitrite N	Rainfall	N	N	0.86
	Cum. Ppt.		N	

Note: Rainfall = Rainfall Volume;
Cum. Ppt. = Cumulative Precipitation;
DSL = Days Since Last Storm

Table 15.2b
Most Significant Multiple Regression Results for Chicken/Strong Ranch
(Hydrologic factors vs. Mass in lbs/impervious acre), (n=5)

	Parameter(s)	Log Trans.?	Significant?	"r"
Arsenic	Rainfall	N	Y	0.98
Copper	DSL	N	Y	0.98
Lead	Rainfall	Y	Y	0.96
Zinc	Rainfall	Y	Y	0.92
Total P	Rainfall	N	N	0.90
Nitrate N	Rainfall	Y	N	0.92

Note: Rainfall = Rainfall Volume; DSL = Days Since Last Storm

Table 15.2c
Most Significant Multiple Regression Results for the Combined
NPDES Data (Hydrologic factors vs. lbs/impervious acre), (n = 18)

	Parameter(s)	Log Transform?	Significant?	"r"
Arsenic	Rainfall	N	Y	0.54
Cadmium	Rainfall	N	Y	0.63
	Cum.Ppt.		Y	
Chromium	Rainfall	N	Y	0.74
Copper	Rainfall	N	Y	0.83
	Cum. Ppt.		Y	
Lead	Rainfall	N	Y	0.81
	DSL		Y	
Nickel	DSL	N	Y	0.79
Zinc	Rainfall	N	Y	0.57
TSS	Rainfall	N	Y	0.80
	DSL		Y	
TDS	Rainfall	N	Y	0.87
BOD	DSL	N	Y	0.999
Oil & Grease	Rainfall	N	Y	0.85
	Cum. Ppt.		Y	
Total P	Rainfall	N	Y	0.9
	DSL		Y	
Nitrate\ Nitrite N	Rainfall	N	Y	0.76
Ammonia	Rainfall	N	Y	0.82

Note: Rainfall = Rainfall Volume; Cum. Ppt. = Cumulative Precipitation; DSL = Days Since Last Storm

15.2 Results

The regression results can be used to assess the degree to which hydrologic factors affect mass loads for each constituent. Test case arsenic and chromium mass per impervious area are consistently correlated exclusively with rainfall volume. This implies that there exists a constant source of these elements throughout the urban area which is unaffected by build up or wash off processes. Sacramento copper mass per impervious area is consistently correlated with either cumulative precipitation or days since last storm. This implies that the copper washed from the watershed by a rainfall event depletes copper available

for wash off in subsequent events. While some hydrologic factor affects each of the other constituents, no clearly consistent relationships between watersheds is shown. No significant correlations of Sacramento event mass with rainfall intensity were observed.

15.2.1 Annual Mass Loadings

Table 15.3 shows the expected values of annual mass loads in lbs/impervious acre along with the calculated coefficient of variation. The coefficient of variation is calculated using a first order error analysis.

In general, most of the models exhibited acceptable levels of uncertainty. However, the results for lead and zinc for Chicken/Strong Ranch and lead and ammonia for the combined data set have higher than acceptable variances. Other sources of uncertainty may exist that are overlooked by the sensitivity analysis including errors due to sparse data sets. The coefficient of variation calculations are based on the uncertainty associated with the estimation of the regression model coefficients (standard errors).

Figures 15.3-15.7 show comparisons of steady state methods to multiple

Table 15.3
Mean Wet Season Mass Loads in Lbs/Impervious Acre per Year

	Sump 111		Chicken/Strong Ranch		Combined ^a	
	Mean	CV	Mean	CV	Mean	CV
Arsenic			0.010	0.079	0.0059	0.15
Cadmium	0.0019	0.060			0.0013	0.15
Chromium	0.022	0.070			0.013	0.087
Copper	0.037	0.10	0.017	0.082	0.021	0.12
Lead	0.053	0.074	0.08	0.96	0.049	0.084
Nickel					0.0055	0.13
Zinc	0.50	0.11	0.56	0.50	0.40	0.12
TSS					99	0.21
TDS					245	0.10
Oil & Grease				18.2	0.074	
BOD					10.6	0.032
Total P	0.78	0.068	0.7	0.14	0.65	0.082
NNN	3.8	0.11	6.6	0.15	3.3	0.062
Ammonia					1.54	0.11

^a All 5 NPDES Monitoring Locations

Figure 15.3
Comparison of continuous simulation wet weather copper mass loads with NURP derived copper loading estimates

Figure 15.4
Comparison of continuous simulation wet weather lead mass loads with NURP derived lead loading estimates

Figure 15.5
Comparison of continuous simulation wet weather zinc mass loads with NURP derived zinc loading estimates

Figure 15.6
Comparison of continuous simulation wet weather total suspended solids mass loads with NURP derived total suspended solids loading estimates

Figure 15.7
Comparison of continuous simulation wet weather total phosphorus mass loads with NURP derived total phosphorus loading estimates

simple method currently used to estimate annual pollutant loads for NPDES storm water permit applications. The first column in each case is the annual mass load per acre as calculated using NURP methods and concentrations. The second column are annual loads calculated using NURP methods and adjusting the concentrations to Sacramento concentrations. The third column shows annual load estimates generated through multiple linear regression and continuous simulation.

15.3 Conclusions

- 1) Build up and wash off effects can be identified through multiple linear regression with serial rainfall parameters such as cumulative rainfall to date and/or days since last storm. Consistent significant correlation of event mass with cumulative rainfall to date or days since last rain suggests that build up and wash off processes may dominate for a particular constituent. Consistent significant correlation of event mass with rainfall volume or intensity suggests that there exists a dominant continuous supply of the constituent throughout the watershed.

- 2) Annual pollutant load estimates can be improved by consideration of build up and wash off processes. Steady state methods of estimating annual pollutant loads for constituents correlated with serial rainfall parameters can produce excessive estimates. For those constituents strongly correlated with rainfall volume (zinc) the estimates produced using steady state methods may be low or high depending upon the regression model.
- 3) Continuous simulation can be used to reproduce observed wash off and build up in modelling watershed response.
- 4) Regression models of event mass vs serial rainfall parameters may produce overestimates when a constituent is strongly correlated with rainfall depth and larger storms have not been included in the event mass data set.

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