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Authors

Kayhanian, Masoud
Singh, Amardeep
Suverkropp, Claus
et al.

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THE IMPACT OF ANNUAL AVERAGE DAILY TRAFFIC ON HIGHWAY RUNOFF POLLUTANT CONCENTRATIONS

Masoud Kayhanian, Member[1]

Amardeep Singh

Claus Suverkropp

Steve Borroum, Member

ABSTRACT

The objective of this study was to evaluate correlations between annual average daily traffic (AADT) and storm water runoff pollutant concentrations generated from California Department of Transportation (Caltrans) highway sites. Analyses of data collected from the Caltrans 4-year (1997-01) highway runoff characterization program revealed that, in general, pollutant concentrations from urban highways were higher than those found from non-urban highways. For a limited number of pollutants, however, the concentrations from non-urban highways were found to be higher than the concentrations from urban highways. No direct linear correlation was found between highway runoff pollutant event mean concentrations (EMCs) and AADT. However, through multiple regression analyses, it was shown that AADT has an influence on most highway runoff constituent concentrations, in conjunction with factors associated with watershed characteristics and pollutant build-up and wash off. The other noticeable factors shown

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[1] **Masoud Kayhanian, Member,** (Corresponding Author) Associate Director, Center for Environmental and Water Resources Engineering, Department of Civil and Environmental Engineering, University of California, Davis, CA 95616, Phone: (530) 752-8957, Fax: (9530) 752-8947, e-mail: mdkayhanian@ucdavis.edu.

Amardeep Singh, Formerly with Office of Water Programs. Current address: Project Engineer, URS Corporation, 2520 Venture Oaks Drive, Suite 250, Sacramento, CA 95833, Phone: (916) 679-2244, Fax: (916) 929-7263, e-mail: Amardeep_Singh@URSCorp.com.

Claus Suverkropp, Senior Scientist, Larry Walker Associates, 509 4th Street, Davis, CA 95616, Phone: (530) 753-6400, Fax: (530) 753-7030, e-mail: clausc@lwa.com

Steve Borroum, Member, Formerly, California Department of Transportation. Current address: Senior Project Manager, URS, 1380 Lead Hill Blvd, Suite 100, Roseville CA 95661, Phone: (916) 784-3900, Fax (916) 784-0211, e-mail: Steve_Borroum@urscorp.com

to influence the accumulation of pollutants on highways were antecedent dry period, drainage area, maximum rain intensity, and land use.

Keywords: Annual average daily traffic (AADT), highway runoff, linear regression model, multiple regression model, and pollutants.

INTRODUCTION

The California Department of Transportation (Caltrans) is engaged in a multi-year program of research and monitoring pertaining to the environmental effects of stormwater quality from transportation facilities. Part of Caltrans storm water quality research and monitoring program involves the characterization of highway runoff (Kayhanian et al., 2001). These monitoring studies were principally undertaken (i) to comply with the statewide National Pollution Discharge Elimination System (NPDES) storm water permit requirements, (ii) to address legal requirements, (iii) to aid in developing new treatment systems, (iv) to develop runoff load models, and (v) to fill data gaps in stormwater runoff characterization for statistical analysis. The information presented in this paper is based on a 4-year highway stormwater runoff characterization study that was undertaken during the 1997-01 rainy seasons from October through April.

Caltrans monitoring data are analyzed on a regular basis to assess runoff characteristics. One question that is frequently asked is whether a correlation exists between annual average daily traffic (AADT) and the concentrations of highway runoff pollutants. The current paper addresses this issue.

METHODS

Sampling Procedures

Representative highway sites and storm events were selected for event-based monitoring. There are a wide range of parameters that can potentially affect the quality of stormwater discharges including geographic location, climatic/ecologic conditions, hydrologic conditions, land use, and AADT. The highway sites were selected to represent the full range of physical parameters. In addition, the sites were selected as potential monitoring sites based on the ability of the sampling teams to perform the required tasks safely. The locations of monitoring sites are shown in Figure 1. As shown in Figure 1, during the four years of monitoring (1997-2001), 83 highway sites were monitored for water quality characteristics. These highway sites were located in 7 of the 12 Caltrans districts. General physical characteristics of these sites, including AADT, are summarized in Table 1.

To ensure monitoring of an appropriate number of storms, a weather-tracking procedure was established to target storms producing a minimum of 2.54 mm of rainfall (7.62 mm in Northern California). The predicted amount of rainfall, known as the quantity of precipitation forecast (QPF), was obtained from the National Weather Service in conjunction with other private weather services up to 72 hours prior to a storm event. Once a storm event with a targeted QPF was forecasted, monitoring teams were dispatched to the various sites to set up for monitoring and observe the runoff characteristics.

Stormwater runoff samples were collected using automated samplers placed at the discharge points downstream of representative drainage areas. A typical Caltrans automated sampler installation is shown in Figure 2. Flow-weighted composite samples were collected, runoff flow was measured, and rainfall amounts were recorded using automated equipment. The monitoring was conducted during the wet season, starting October 1 through April 30. On average, up to eight storm events were monitored annually at each highway site during the 4-year period. Depending on the storm intensity and duration, up to 50 sample aliquots were obtained to capture a representative composite sample during each monitoring event. A typical hydrograph, including sampling time and number of sample aliquots taken during a representative storm event, is shown in Figure 3. Sample collection procedure, sample representativeness criteria, and other aspects of monitoring methods followed the specifications presented in the Caltrans Guidance Manual: Stormwater Monitoring Protocols, second edition (Caltrans, 2000a).

The flow-weighted composite samples obtained from the entire storm event were sent to a laboratory for analysis. The results of these analytical tests are assumed to represent event mean concentrations (EMC) for runoff from a given rainfall event. Constituents and parameters analyzed under this program during the course of monitoring are summarized in Table 2. As shown, the constituents and parameters were organized as: (i) conventionals, (ii) metals (total and dissolved), (iii) nutrients, (iv) major ions and minerals, (v) microbiological, (vi) oil and grease, and (vii) pesticides. All laboratory analyses were conducted according to Standard Methods and U.S. Environmental Protection Agency (USEPA) analytical methods as specified in the Caltrans Stormwater Monitoring Protocols (Caltrans, 2000a). Extensive field and laboratory quality assurance/quality control (QA/QC) procedures were followed and analytical results were qualified as necessary based on the results of the QA/QC evaluations.

Data Evaluation

All highway stormwater runoff monitoring data were reported as specified by Caltrans data reporting protocols (Caltrans, 2000b). The data were then imported into a database containing three main tables: sample description, sampling event description, and site description. Sample description data consist of information specific to individual samples including lab results, analytical methods and date information. Event description data consist of precipitation (start and end time, maximum intensity, antecedent dry period), and runoff (total flow volume, peak flow rate, and start and end time) information. Site description data describe location of the monitoring site along with some physical characteristics of the site.

The above database was used to extract all analytical, precipitation information, and site characteristics data for highway sites for statistical analysis. For the most part, pollutant concentrations in stormwater runoff were reported above the analytical reporting limit (detected values). When analytical results containing data below reporting limits (non-detects) the entire data sets including the non-detects were used in statistical analysis. Traditionally, these non-detects were substituted with the detection limit or an arbitrary fraction of the detection limit. In this paper a more scientific approach described in Shumway et al. (2002) and known as regression on order statistics (ROS), was used to evaluate data sets containing non-detects.

Statistical Approach

Multiple linear regression (MLR) and analysis of covariance (ANCOVA) were used to address the impact of AADT on pollutant concentrations. Unless specified, thresholds for statistical significance were set at a confidence level of 95 percent ($p < 0.05$) for all analyses.

The distributions of runoff quality data for each constituent were evaluated for approximate normality using normal cumulative probability plots of untransformed and log-transformed data. These evaluations were performed using only detected data with probabilities adjusted for data below detection using the method of Helsel and Cohn (1988). The transformation providing the best R^2 regression statistic was selected as the appropriate starting point for additional analyses. Distributions with R^2 values greater than 0.975 were considered adequately normal to meet the assumptions of subsequent analyses. If the probability plot R^2 was less than 0.975, statistically significant deviation from normality was evaluated using the method of Ryan and Joiner (1976). This method is essentially equivalent to the method of Shapiro and Wilk (1968) and D'Agostino (1971). Significant deviations from normality were evaluated at 99 percent confidence level ($p<0.01$). The distributions of other continuous predictor variables (precipitation factors, antecedent conditions, AADT, and contributing drainage area) were also evaluated for approximate normality by inspection of cumulative probability plots, and were transformed to natural logarithms (event rainfall, maximum intensity, antecedent dry period, and drainage area) or cube-roots (cumulative precipitation), if appropriate.

MLR and ANCOVA methods were used to evaluate the effects of precipitation factors, antecedent conditions, AADT, contributing drainage area and surrounding land use on highway runoff quality. MLR and ANCOVA analyses were performed using only data reported above reporting limits. Pair-wise comparisons between land use categories were performed using the Tukey-Kramer post-hoc test. MLR models were developed for each constituent. The primary assumptions of MLR analysis (equal variance and normality) were assessed by inspection of residual plots. Problems due to unequal variance and non-normality of residuals were largely avoided by transforming dependent and independent variables to approximate normality prior to analysis. Generally, all significant predictor variables ($p<0.05$) were included in the MLR model unless they exhibited symptoms of multi-collinearity or co-dependence in the set of predictors. Independence of predictor variables (the absence of multi-collinearity) was assessed by evaluating correlations and partial correlations of the variables. If correlation coefficients were greater than 0.4 for a pair of predictors, or if the signs of the correlation and partial correlation coefficients "disagreed," one of the pair of predictor variables was excluded from the MLR model. Partial correlations were also used to select the independent variables for the MLR models.

The final "optimized" MLR model was used to generate a new fitted variable calculated as the cumulative effects of the significant predictor variables for each constituent. This fitted variable was then included as the single covariate in the ANCOVA models used to evaluate the effects of surrounding land use. Because of imbalances in the representation of land use categories, interaction between individual covariates in the MLR model and the categorical variables could not be assessed in a statistically rigorous way. Instead, potential interaction effects were quantitatively evaluated by inspection of bivariate plots of the dependent variable versus the MLR-fitted data. In all cases, interaction was judged to be minimal and to have no substantial effect on interpretation of the ANCOVA results.

RESULTS AND DISCUSSION

Highway Classification

A report prepared by Driscoll et al. (1990) for the Federal Highway Administration (FHWA) attempted to divide highway sites into two general categories: urban and non-urban. According to the report, the highways with AADT values greater than 30,000 are considered "urban" and those with AADT values less than 30,000 are "non-urban."

The AADT values for all 83 highway sites investigated as part of this study are shown in Table 1. The AADT values range from as low as 2,200 vehicles/per day (VPD) to as high as 328,000 VPD. Due to large variations in urban AADT values (AADT>30,000 VPD), a single classification for urban highways was found to be impractical to properly assess any correlations that may exist between pollutant concentrations and AADT. For this reason the urban highways were further divided into four categories: low, medium, medium-high, and high vehicular traffic volume. This new highway classification based on the number of vehicles per day (VPD) is shown in Table 3.

Highway Runoff Characteristics

Characteristics of runoff for all monitored highway sites, combining urban and non-urban highways, are summarized in Table 4. Average concentrations of pollutants in runoff from urban and non-urban highways are compared in Table 5. Data were also analyzed separately for the different urban highway classifications, and the mean and median values for each category are summarized in Table 6. As shown in Table 5, there are some large apparent differences in the constituent concentrations for sites with AADT greater than 30,000 (urban highways) compared to sites with AADT less than 30,000 (non-urban highways). On average, most of the pollutant concentrations in urban highway runoff were higher than those in non-urban highway runoff. Exceptions included chemical oxygen demand (COD) total suspended solids (TSS), total dissolved solids (TDS), turbidity, ammonia, and diazinon for which the average concentrations were higher in non-urban highways than urban highway runoff. Average concentrations of total lead and total arsenic were more than ten times greater in urban highway runoff than for non-urban highways. The higher concentrations of some pollutants observed in runoff from urban highways does not fully address the issue of correlating pollutant concentrations with AADT. This aspect of the study is further discussed below.

Direct Correlation between Pollutant Concentrations and AADT

Simple linear regression analysis was performed to evaluate direct correlation between AADT and concentration of highway runoff pollutants. The results of this analysis revealed extremely low R^2 values (ranging from 0 to 0.32) for all constituents, which suggests weak or no direct correlation between AADT and pollutant concentrations. Simple linear regression analysis is a useful, but relatively crude, form of data analysis. For better understanding of the relationship being examined, and to avoid faulty conclusions produced by simple regression, all monitoring data were plotted and examined. Selected scatter plots for copper, lead, zinc, and oil and grease are shown in Figure 4. As shown, no direct correlations were evident between concentrations of these metals and AADT when data for all highways (non-urban and urban) were considered. In addition to pollutants shown in Figure 4, no clear relationships between AADT and pollutant concentrations were evident for nearly every other constituent examined.

However, when median and mean concentrations for the same pollutants were examined for medium and higher range of AADTs for urban highway, a more consistent correlation began to emerge (Figure 5).

Several other studies have also attempted to correlate AADT to pollutant concentrations in highway runoff. However, most of these studies were unable to confirm strong correlations. For example, Chuiet et al. (1982) found only a weak correlation, and a study conducted by FHWA (Driscoll et al. 1990) suggested that there is no strong and definitive relationship between differences in traffic density and the pollutant concentrations for a site. Driscoll et al. conclude that, other than the use of AADT as a surrogate measure to distinguish between urban and non-urban highways, further use of AADT to refine estimates of pollutant levels in runoff has no supporting basis. Another study, conducted by Stotz (1987) on highway runoff in Germany, also concluded that the pollutant concentration is not dependent on traffic frequency. Other investigators found somewhat better correlations between AADT and highway runoff pollutants. For example, Dorman et al. (1988) demonstrated a direct correlation between pollutants and AADT, and in another study, McKenzie and Irwin (1983) found that the concentrations of lead, zinc and COD correlate well with AADT. The limited number of studies able to demonstrate correlations between AADT and pollutant concentrations may be explained by the fact that these studies focused on pollutant concentrations from highways in urbanized areas having medium to high vehicular traffic. When the medium to high range AADT highway sites were evaluated as part of this Caltrans study, the average concentrations of about half of the pollutants investigated were found to correlate well with AADT.

The positive or negative nature of correlations of pollutants with AADT can be explained if the sources of the contaminants are taken into consideration (Kobriger and Gainopolos, 1984). For example, cadmium, copper, lead, oil and grease, and zinc are known to be related to transportation activities. Because AADT is measure of transportation activity, a positive correlation between these pollutants and AADT is expected (Laxen and Harisson 1977, Gupta et al. 1981, Moe et al. 1982, Kim and Fergusson 1994). As shown previously, results obtained from this study were inconclusive when both urban and non-urban highways are considered, and therefore the above pollutants can not be quantitatively related to AADT with any certainty. Oil and grease, however, was the only pollutant for which the average concentration had strong correlation with AADT, and quantitatively can be related to transportation activity (Figure 5). On the other hand, pollutants such as pesticides and nitrogen and phosphorus compounds (constituents commonly found in highway runoff) are expected to have little or no correlation with AADT (Young 1996). While in most part this was found to be true, contrary to expectation, fairly strong correlations between Diazinon, total Kjeldahl nitrogen (TKN), and total phosphorous pollutant concentrations and AADT were obtained when low AADT urban highways are disregarded. Interpretation of these correlations can be problematic, as the sources of pesticides and nutrients are not obviously related to transportation activities. It is, however, possible that atmospheric deposition of these pollutants is higher in urban areas than in non-urban areas.

Based on the findings of this study and information presented in most literature cited previously, AADT should only be considered as a very general indicator of pollutant concentrations when it is used as a sole predictor. Possible reasons for the lack of simple linear correlation include complicating factors such as wind, vehicular turbulence, volatilization, and oxidation (Irish et al. 1995, Wistrom and Matsumoto, 1999). These factors can limit the accumulation of pollutants on road surfaces, and thereby decrease the importance of AADT for short periods. Unusual or atypical points (known as outliers) in specific data sets may be another factor limiting the ability to demonstrate simple correlations. Examination of plotted data indicated that for some pollutants there were one or more outlier data points that were substantially higher than all other values in the data set. Although the data were processed through vigorous QA/QC, the validity of these outlier data for those specific sites is questionable. Clearly these outliers are not consistent with the remaining data, and at best suggest an unusual or atypical situation. Although inclusion of these outlier points in regression analyses may influence the correlations between pollutant concentrations and AADT, analysis of those pollutants with apparent outliers revealed that the exclusion of the outliers generally did not improve the regression correlation coefficients substantially.

In the absence of a strong correlation between AADT and pollutants, some investigators (Keri et al. 1985, Chui et al. 1982) suggest that traffic levels during storm events (vehicles during storm, VDS) is a better independent variable for estimating total runoff loads for certain pollutants. Literature reviewed by Wistrom and Matsomoto (1999), however, conclude that AADT is not generally expected to be useful as a control variable for the design, operation, and maintenance of specific runoff control structures, as traffic intensity on a particular stretch of highway is expected to be fairly constant from day to day.

From the discussion above, it appears that the AADT is not the sole factor contributing to pollutant accumulation in highway sites. In the absence of a direct relationship between AADT and highway runoff pollutants, the search for a better model shifted to multiple regression, where variables other than AADT were considered.

Multiple Linear Regression Analysis

The results of the MLR analyses are presented in Table 7, including relevant MLR model statistics and the specific effects of precipitation factors, antecedent conditions, AADT, and drainage area on Caltrans highway runoff quality. A summary of the patterns in significant covariate effects is provided in Table 8.

The effects of precipitation factors (event rainfall and maximum rainfall intensity), antecedent conditions (cumulative seasonal precipitation and antecedent dry period), AADT, and contributing drainage area on constituent concentrations in storm runoff from highways were evaluated using MLR. Models were developed for 33 of 36 constituents, with statistically significant adjusted R^2-values ranging from 0.085–0.648 ($p<0.05$). The results of these analyses indicate that all of these factors have statistically significant effects on pollutant concentrations in runoff, and that these effects are generally consistent for most pollutants. The dominant (most frequently observed) statistically significant effects of precipitation factors, antecedent conditions, contributing drainage area, and AADT on runoff quality are summarized as follows:

- A statistically significant negative coefficient for *Event Rainfall* was observed for nearly all pollutants modeled, indicating that concentrations tend to decrease as total event rainfall increases.

- A statistically significant positive coefficient for *Maximum Rainfall Intensity* indicates that higher rainfall intensities tend to result in greater pollutant concentrations in runoff. A significant negative slope suggests that higher rainfall intensities tend to have a diluting effect. *Maximum Rainfall Intensity* tended to be correlated with *Event Rainfall* and was statistically significant for only a few constituent MLR models. In most cases where the coefficient was positive (total zinc, oil and grease, TSS, total phosphorous, and bacteria), the constituents were associated with particulates, indicating that higher rainfall intensities have the effect of mobilizing these particulate-associated parameters. The four constituents with negative coefficients (dissolved copper and zinc, hardness and total dissolved solids) were all dissolved parameters, indicating that the diluting effect is more common for parameters not associated with particulates.
- *Antecedent Dry Period* had a statistically significant effect in the MLR models for most constituents, and significant coefficients for this factor were nearly all positive. The significant positive slope indicates that longer antecedent dry periods tend to result in higher pollutant concentrations in storm runoff, and is consistent with the "buildup" of pollutants during dry periods.
- The effect of the seasonal first flush (e.g. the first significant storm event in a season) was assessed by evaluating the effect of *Cumulative Seasonal Precipitation* on runoff quality. The statistically significant negative slope of the coefficient for *Cumulative Seasonal Precipitation* indicates that pollutant concentrations in runoff are highest in the early wet season and tend to decrease thereafter. *Cumulative Seasonal*

Precipitation had a statistically significant effect in the MLR models for most constituents, and significant coefficients for this factor were negative in every case.

- A significant positive slope for the *Drainage Area* parameter indicates that sites with larger contributing drainage areas tend to have higher pollutant concentrations in runoff, while a negative slope indicates that larger drainage areas tend to reduce pollutant concentrations in runoff. *Drainage Area* had a statistically significant effect in approximately half of the MLR models. Significant coefficients for *Drainage Area* were predominantly positive for particulate-associated constituents (with the exception of fecal coliform) and negative for dissolved parameters.
- A statistically significant positive slope for *AADT* indicates that higher *AADT* tends to result in higher pollutant concentrations in runoff. *AADT* had a statistically significant effect in two thirds of the significant MLR models, and significant coefficients for *AADT* were nearly all positive. A significant negative slope was observed for only one constituent (NO_2-N), and this result was based on relatively few detected data compared to most other constituents.

The relative importance of the effects of AADT was assessed in two ways: (i) by comparing the numbers of constituents significantly affected by AADT, drainage area, and precipitation related factors, and (ii) by comparing the relative magnitude of the effects. Evaluation of the relative magnitude of the effects of significant independent factors on listed pollutant concentrations was based on comparisons of the absolute values of the standardized regression coefficients, which express the effects of variables in the same scale regardless of differences in the original scales of the variables (Figure

6). Based on these comparisons, the effects of AADT, event rainfall, cumulative seasonal precipitation, and antecedent dry period on pollutant concentrations were all similar in magnitude. On average, these four parameters were statistically significant factors in 73 percent of the MLR models. Contributing drainage area and rainfall intensity tended to have smaller effects and were significant for fewer pollutants (45 and 33 percent of MLR models, respectively).

Analysis of Covariance: Evaluating the Effect of Predominant Land Use

Effects on highway runoff quality attributable to differences in contributing land use were assessed using ANCOVA methods. Note that these comparisons are based on results adjusted to account for the statistically significant effects of precipitation factors, antecedent conditions, AADT, and drainage area on runoff quality.

Results of ANCOVA analyses of the effects of predominant land use on runoff quality are presented in Table 9. For approximately half of the constituents evaluated (16 of 29), contributing land use was determined to have a statistically significant effect on pollutant concentrations. However, the most consistent pattern observed was that runoff quality from *Agricultural (Agr)*, *Commercial (Comm)*, *Industrial (Ind)*, *Residential (Res)*, and *Transportation (Trans)* land use categories was generally similar for most pollutants when the effects of AADT, precipitation, antecedent conditions and drainage area were considered. It is important to note that *Transportation* and *Residential* land uses dominate compared to other land use categories, and that very few sites were sampled for the *Mixed (Mxd)*, *Agricultural*, and *Open* land use categories. This imbalance in sampling design contributes to pseudoreplication effects and overestimation of the significance of the effect of under-represented land use categories on runoff quality, and is in part responsible for the finding of significant effects of contributing land use.

The general conclusion from these analyses is that contributing land use appears to significantly affect concentrations of many pollutants in highway runoff, but that additional data are needed to conclusively establish the specific effects for different land uses. Although the results of analyses for the effects of land use vary by constituent, an example of a fairly typical case is illustrated in Figure 7 for total copper concentrations in highway runoff. Comparisons of raw data and residuals from the MLR model for total copper illustrate that runoff quality varies significantly for different land uses. Both plots suggest that runoff from *Mixed* and *Open* land uses typically have higher copper concentrations. However, the plot of MLR residuals demonstrates that copper concentrations in runoff from other land uses are similar when variations in event rainfall, antecedent dry period, cumulative precipitation, drainage area, and AADT are accounted for. The relatively large error bars (95 percent confidence limits for the mean) for the *Industrial* land use reflects the small data set for this category.

PRACTICAL APPLICATION OF THE RESULTS

Comparative Analysis

To illustrate whether Caltrans runoff quality is different or similar to that documented in other studies, the results of Caltrans highway runoff quality data were compared with the Nationwide Urban Runoff Program (NURP) study (USEPA 1983) and other national highway runoff characterization studies (Barrett et al. 1993, and Wu et al., 1998).

Qualitative comparisons of highway runoff quality for constituents monitored by both Caltrans and NURP (Figure 8) show that the coefficients of variation (COVs) for trace metals and conventional pollutants (copper, lead, zinc, chemical oxygen demand, and total suspended solids) are similar, while the COVs for nutrients (nitrate, nitrite, phosphorus, and TKN) are somewhat larger for Caltrans highway runoff data than for NURP land use categories. Figure 9 compares the median EMCs for all of the Caltrans highway runoff data with median EMCs for the median and 90th percentile ranked sites from the NURP results. As shown, median copper, lead, and zinc EMCs were generally lower for Caltrans highway runoff than for NURP. The largest difference was observed for the Caltrans median lead EMC, which was dramatically lower than the NURP median EMC. Median Caltrans highway EMCs for COD, TSS, and nutrients were generally similar to the median NURP EMCs for these constituents.

In previous analyses (Kayhanian and Borroum, 2000; Kayhanian et al., 2001), representative concentrations of pollutants in California highway stormwater runoff were compared to values reported for highways in Texas and North Carolina (Barrett, et al. 1993, and Wu et al., 1998). In general, concentrations of most pollutants for California highways were found to be within the range of values reported elsewhere. However, the median concentrations of COD and NO_3-N were reported to be higher for California highways. Site characteristics and environmental conditions were thought to play a major role contributing to the higher pollutant concentrations observed for California highways because most Caltrans monitoring studies were conducted in Southern California, where there are more industrial activities, higher traffic, and more asphalt surface per unit drainage area. More in-depth analysis of the relationship between these characteristics and other potential sources of these pollutants are not supported by the currently available data set.

Modeling and Addressing Management Issues

The development of MLR-based runoff quality models has a number of practical applications. Two of the most important applications include estimating mass loads and using the model as a tool to address runoff management issues. For instance, the equations derived from multiple regression models in Table 7 can be used to estimate the pollutant event mean concentrations under different conditions. For example, the expected event mean total copper concentration in runoff from a specific (or predicted) storm event and location can be estimated as:

$$\text{Total copper, } \mu\text{g/L} = e^{2.944-(0.233 \bullet X_1)+(0.127 \bullet X_2)-(0.247 \bullet X_3)+(0.077 \bullet X_4)+(5.66 \bullet X_5)} \qquad (1)$$

where,

X_1 = Ln(Event Rainfall, cm),
X_2 = Ln(Antecedent Dry Period, days),
X_3 = (Cumulative Precipitation, cm)$^{1/3}$,
X_4 = Ln(Drainage Area, ha), and
X_5 = AADT•10^{-6} (vehicles/day)

These estimated EMCs can in turn be used to estimate the mass loading on a site-specific, regional, or watershed basis. When applying a loading model, an appropriate EMC for the regional location must be used. Applying one EMC on statewide basis is a common problem among modelers and practitioners and may generate large errors when calculating loads. For illustration purposes, the regional variation in zinc EMC for large urban areas versus less urbanized sampling locations is shown in Figure 10. As shown, applying a single mean zinc concentration (215.8 µg/L) for highway runoff on statewide basis would result in an overestimate of the zinc mass loading for primarily rural areas such as Redding, Eureka, and Marysville. Applying the same zinc concentration for the highly urbanized highways in Los Angeles and San Diego would underestimate the zinc loading in these areas. Using the appropriate EMC for each category of highway classifications would allow more accurate prediction of loads from Caltrans right-of-ways. This type of modeling tool may also be applied to evaluate and fulfill total maximum daily load (TMDL) requirements on a regional basis.

The analyses performed in this paper may also provide tools relevant to best management practices (BMPs). For instance, the increase of pollutant concentrations in proportion to the AADT indicates the need to prioritize high traffic sites for management and treatment of stormwater runoff. Similarly, the association of longer antecedent dry periods with higher pollutant concentrations suggests that a more regular street sweeping or drain inlet cleaning may reduce the pollutants in runoff and thereby decrease the need for potentially higher performance and costly BMPs.

CONCLUSIONS

The following conclusions can be drawn from this study:

- In general, the average pollutant concentrations in runoff from urban highways (AADT>30,000 vehicle per day) were found to be two to ten times higher than those found in non-urban (AADT<30,000 vehicle per day) highways. However, average concentrations of some pollutants (COD, TSS, TDS, turbidity, NH_3, and diazinon) were found to be higher in runoff from non-urban highways than the runoff from urban highways, suggesting sources other than the transportation related activities.

- No simple linear correlations were found between highway runoff pollutant event mean concentrations (EMCs) and AADT, including for those pollutants that are known to be related to transportation activities (e.g., Pb, Cu, Zn, and oil and grease).
- AADT is not the only factor capable of influencing the accumulation and runoff of pollutants from highways. Other factors with significant effects include antecedent dry period, seasonal cumulative rainfall, total event rainfall and maximum rain intensity, drainage area, and land use. When the effects of these other factors were also considered, AADT was found to have a significant effect on concentrations of most constituents in highway runoff.
- The effects of AADT, total event rainfall, seasonal cumulative rainfall, and antecedent dry period on pollutant concentrations in highway runoff were significant for more than 70 percent of constituents evaluated using multiple linear regression analysis. The effects of drainage area and maximum rainfall intensity were smaller and less frequently significant.
- AADT and other factors evaluated in this paper can be used as a practical tool for planning and prioritizing efforts for managing runoff quality in highly urbanized areas. Based on these results, contributing land use effects on runoff quality seem to be less consistent and less important than AADT and the other parameters evaluated in this paper. Consequently, land use characteristics may be less valuable in predicting runoff quality and in planning and prioritizing management activities.

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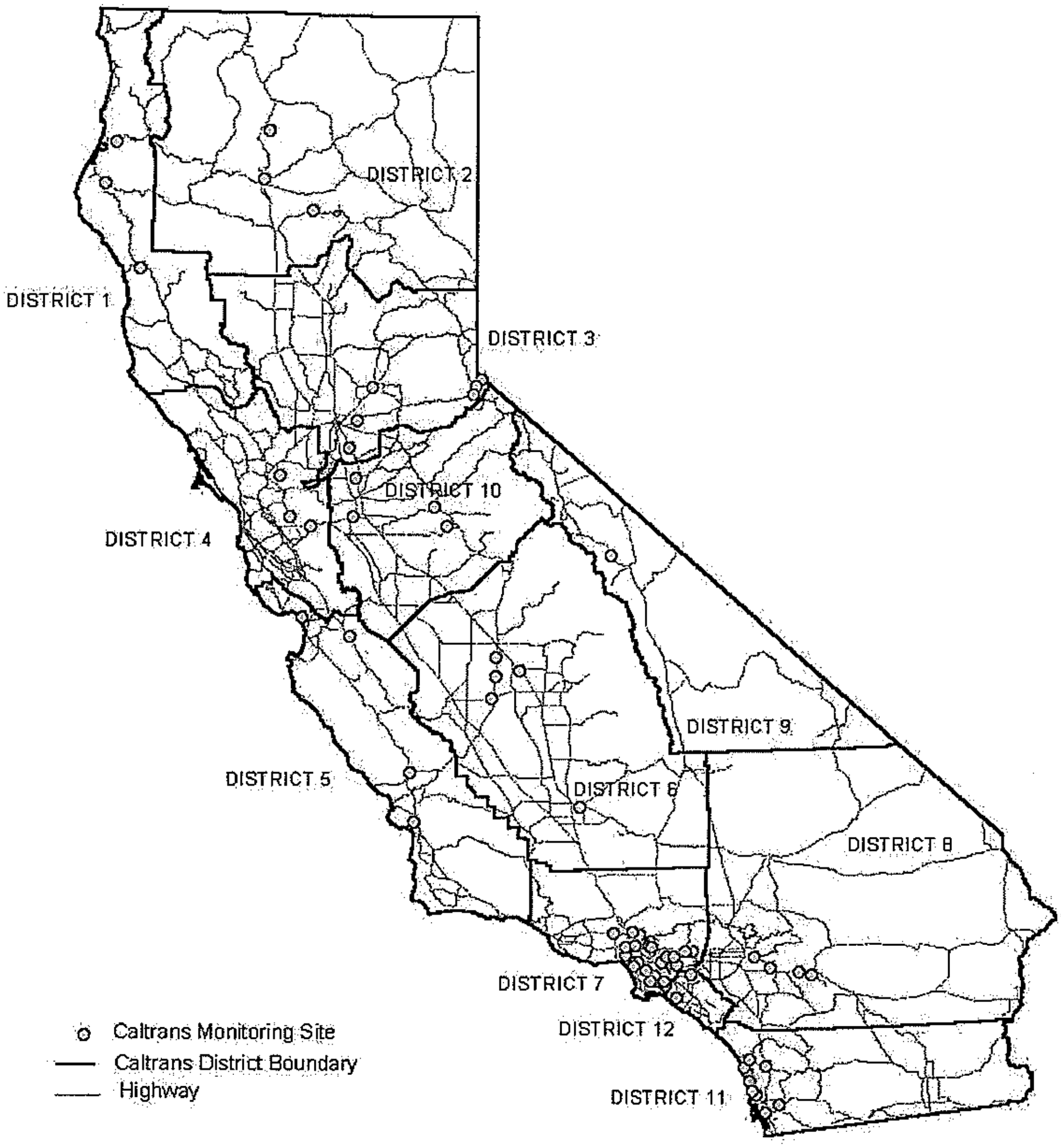

Figure 1
Caltrans Highway Monitoring Sites

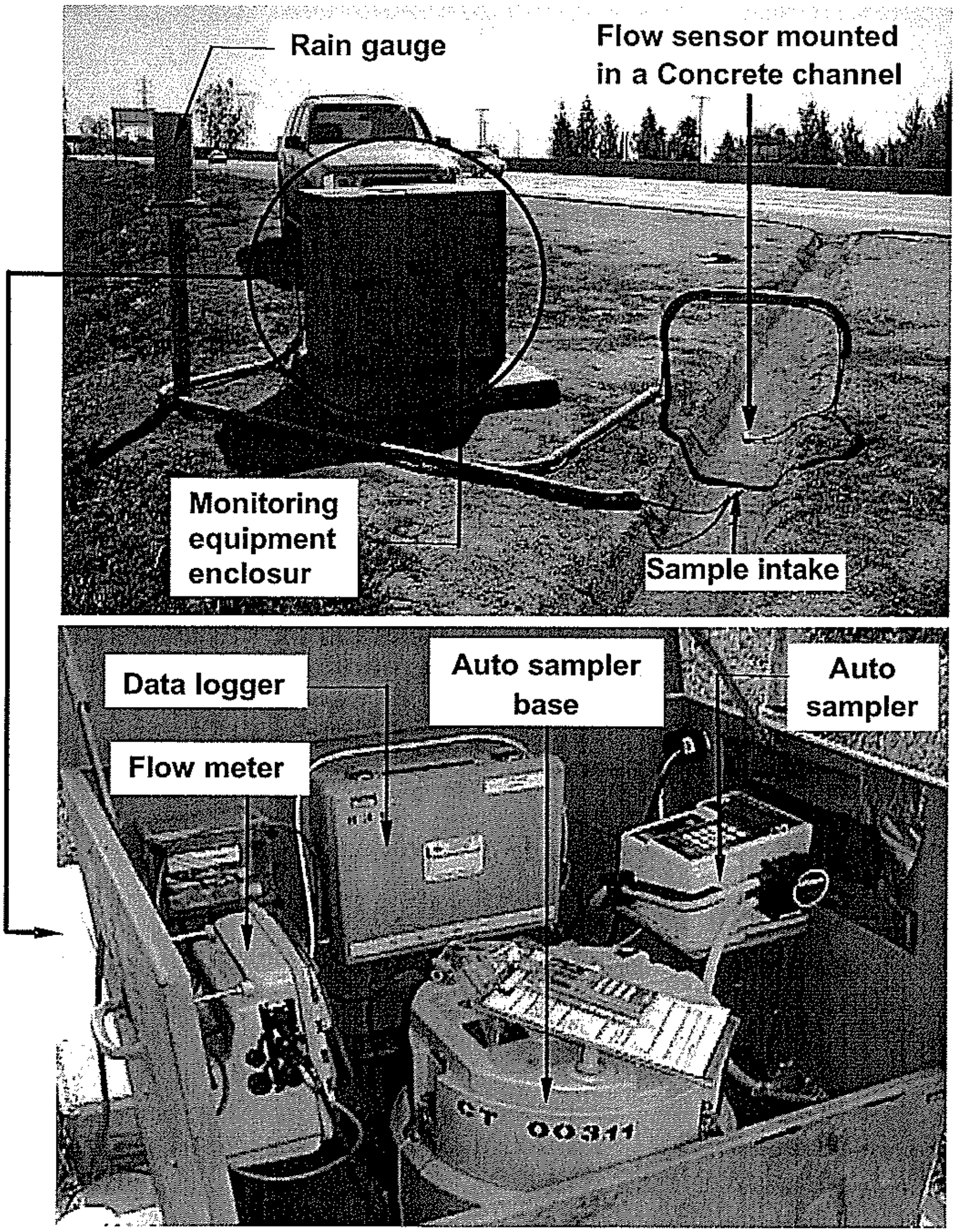

Figure 2
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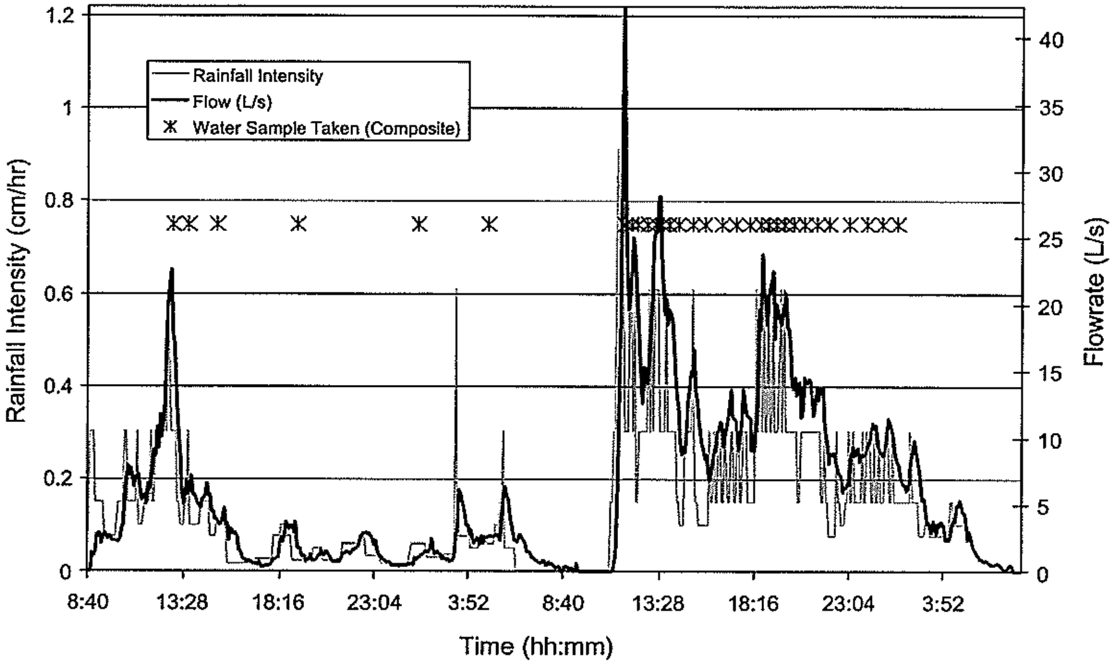

Figure 3
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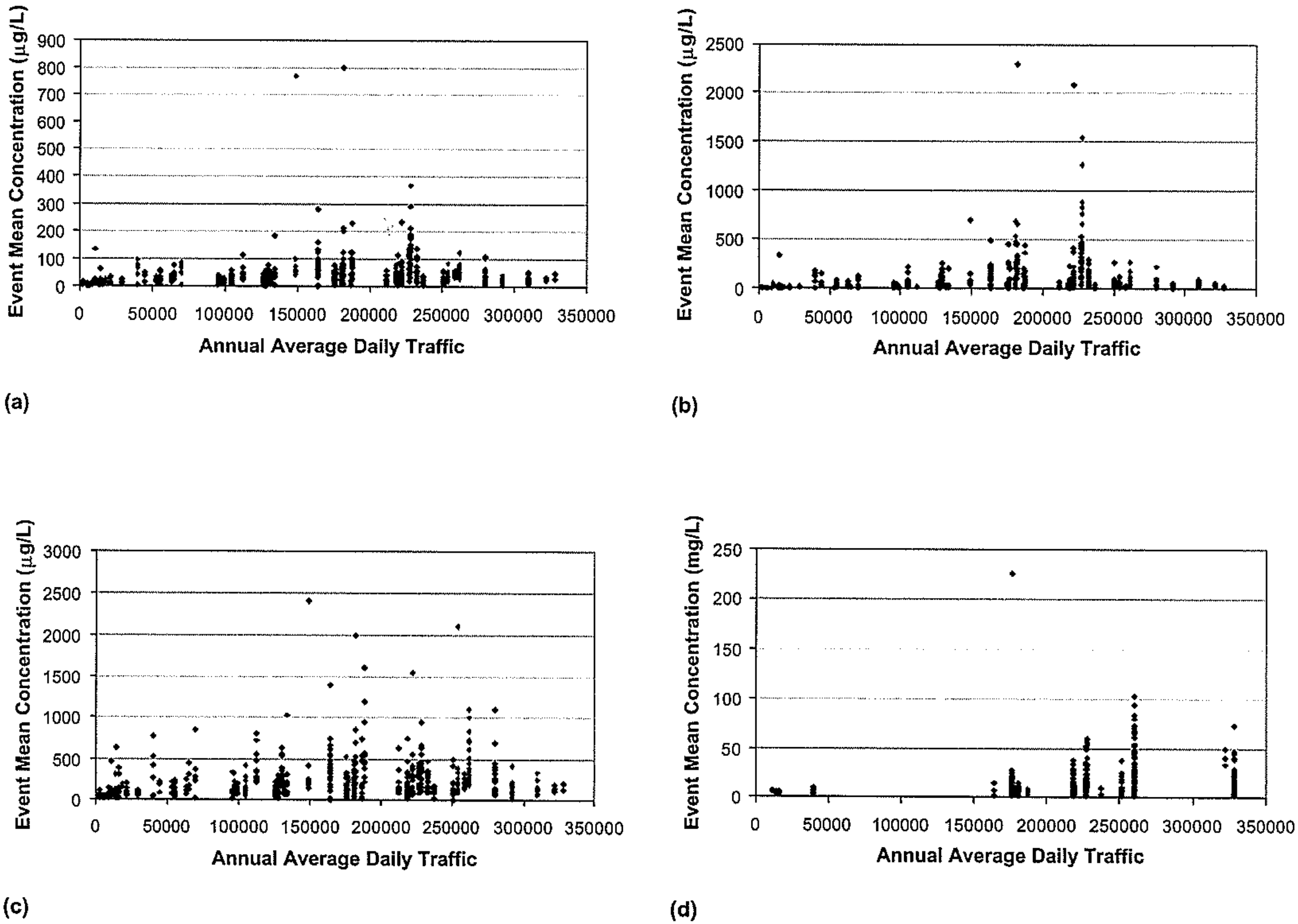


Figure 4

Scatter Plots of EMC Concentrations for (a) total Cu, (b) total Pb, (c) total Zn, and (d) Oil and Grease

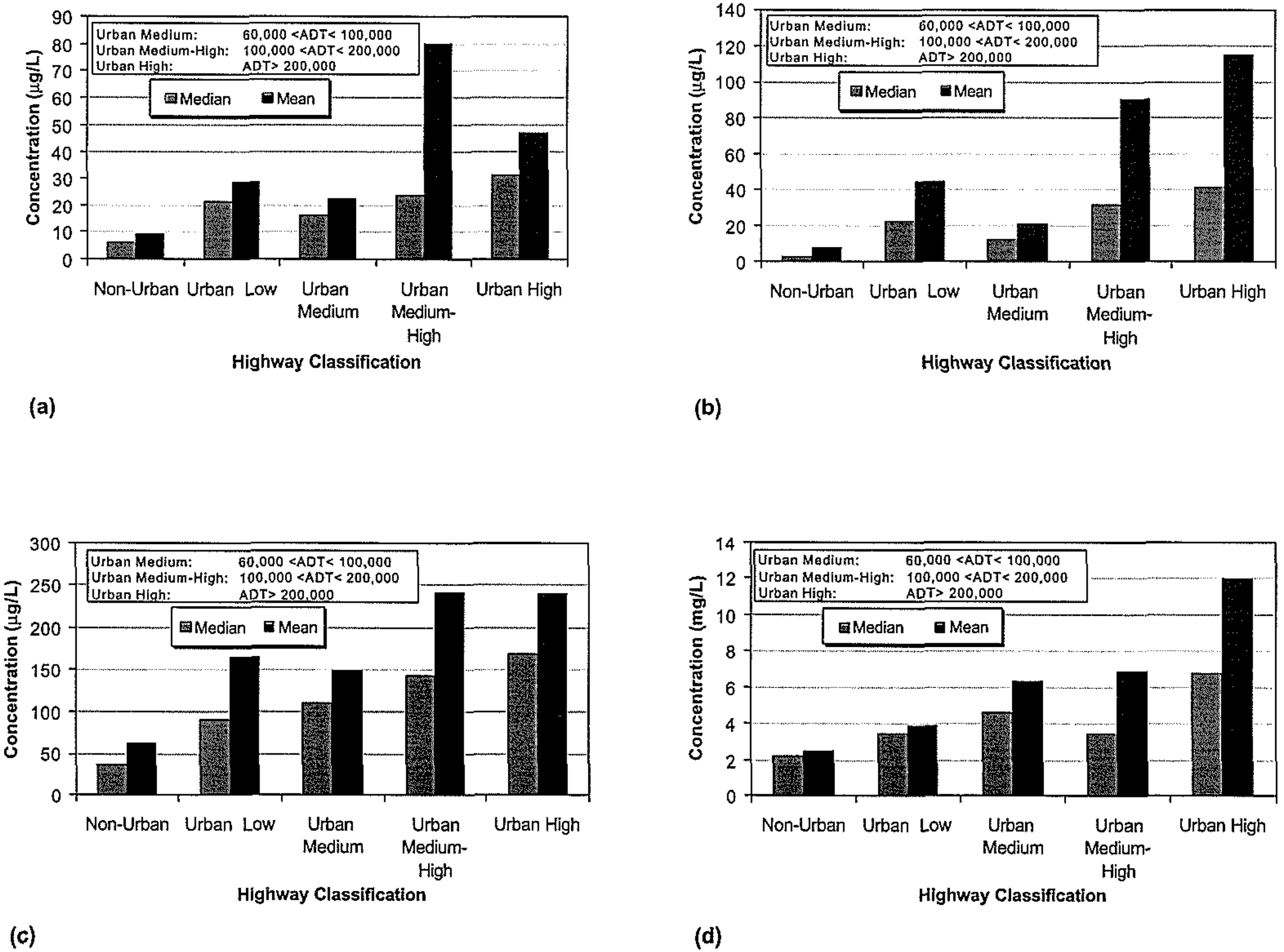


Figure 5

Correlation Between AADT and Selected Pollutant Concentrations, (a) total Cu, (b) total Pb, (c) total Zn, and (d) oil and grease

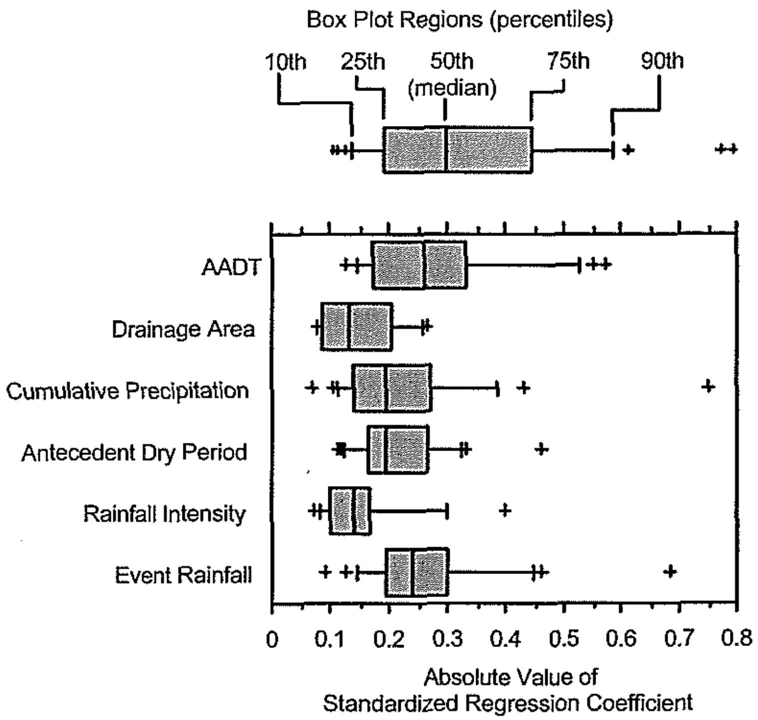


Figure 6
Comparison of Independent Variable Effects

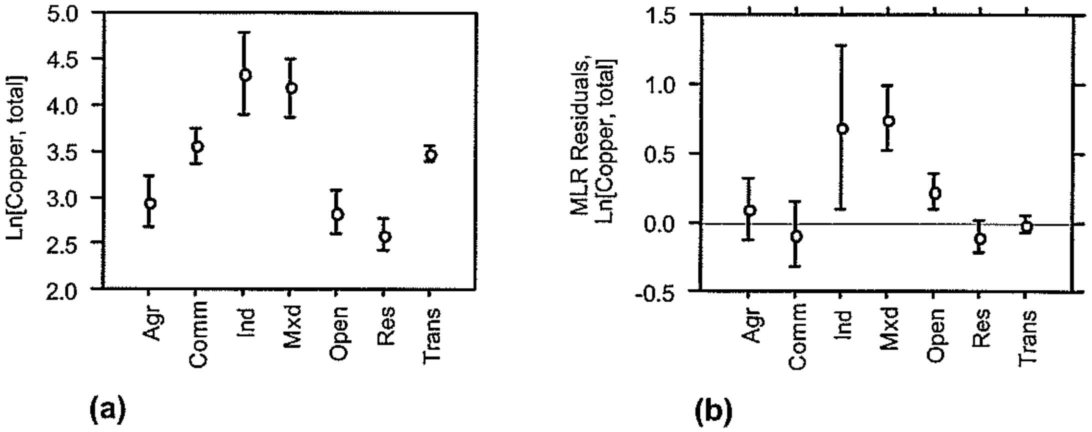


Figure 7
Effect of Contributing Land use on Highway Runoff Quality for Total Copper
(a) Means with 95% for raw data, and (b) Means with 95% for MLR model residuals

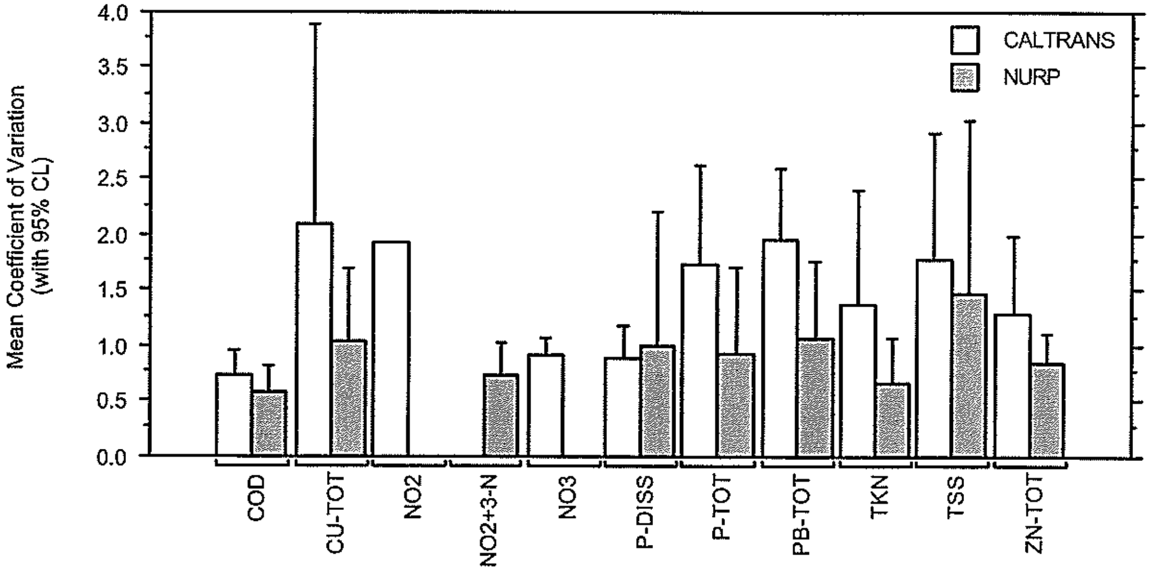
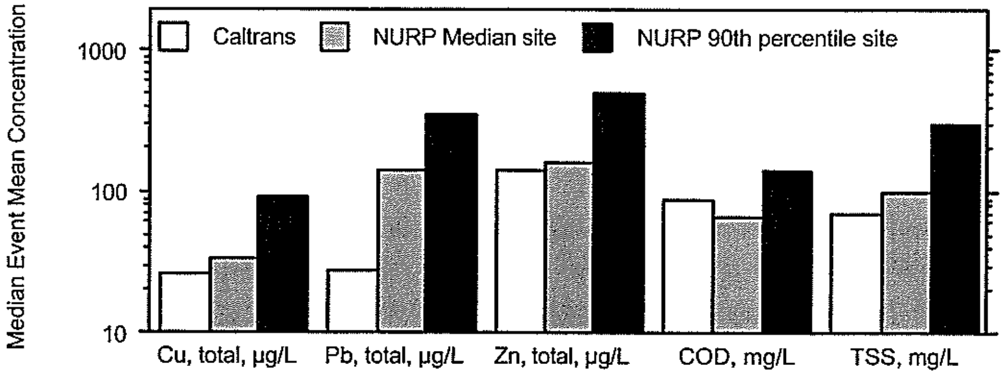
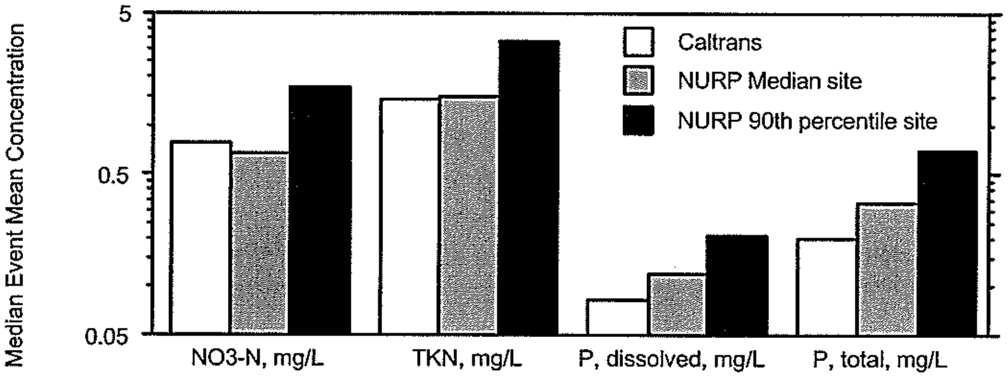


Figure 8
Comparisons of EMC Variability, Caltrans and NURP Results



(a) Trace metals and conventional pollutants



(b) Nutrients

Figure 9
Comparisons of Caltrans median EMCs to NURP Results for (a) Trace Metals and Conventional Pollutants, and (b) Nutrients

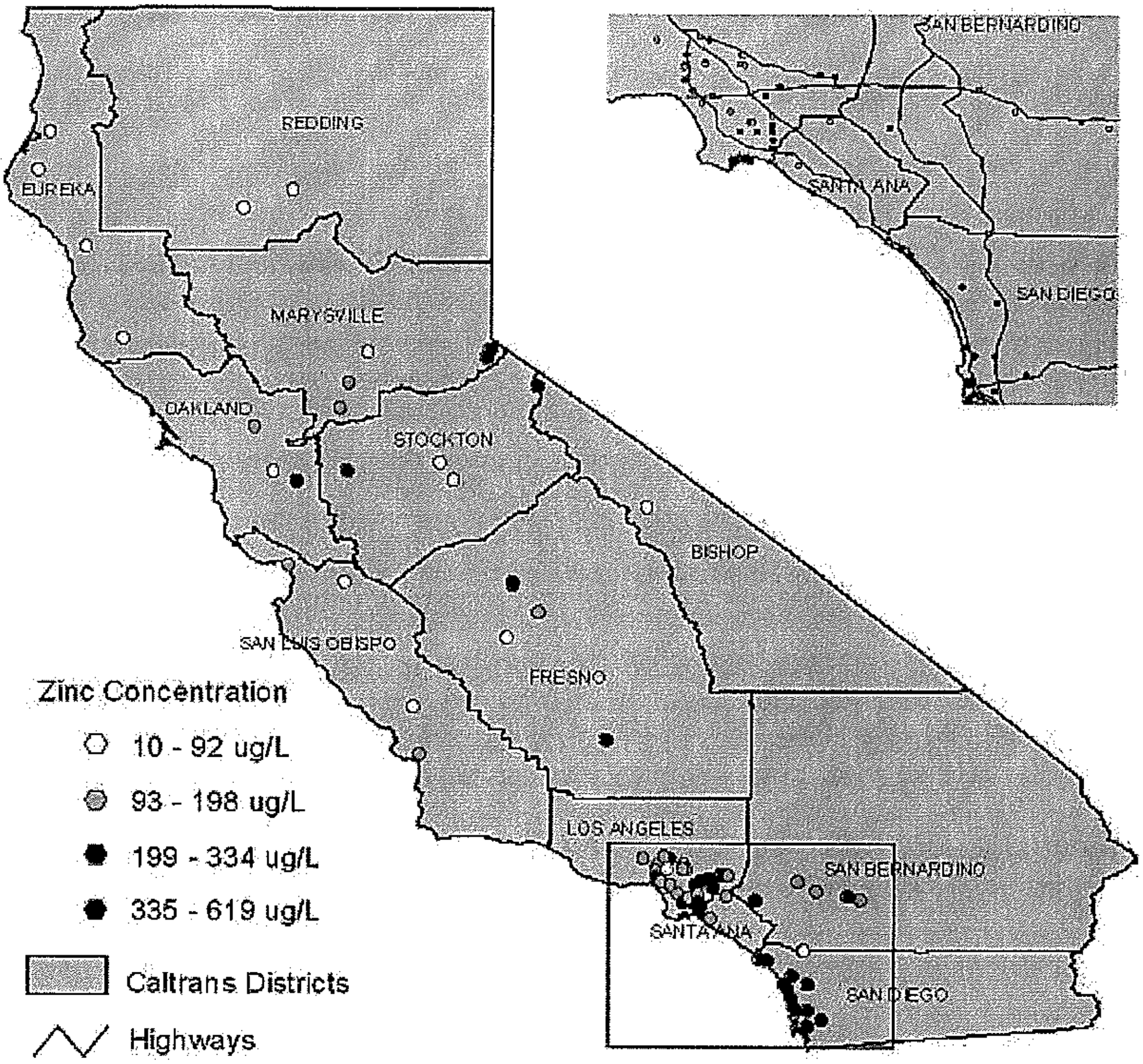


Figure 10
Variations in Total Zinc EMCs for Monitoring Locations

Table 1
AADT Values and other General Characteristics of the Monitoring Sites

Highway (1)	County (2)	Drainage Area (ha.) (3)	Land Use (4)	AADT (5)
580	Alameda	0.1	Transportation	134,000
680	Contra Costa	0.1	Transportation	132,000
50	El Dorado	0.3	Residential	37,000
50	El Dorado	0.1	Open	14,100
50	El Dorado	0.3	Open	11,600
180	Fresno	0.7	Transportation	41,000
41	Fresno	0.2	Transportation	118,000
299	Humboldt	0.1	Residential	8,500
36	Humboldt	0.2	Residential	2,600
395	Inyo	0.3	Residential	5,500
58	Kern	17.3	Transportation	40,000
198	Kings	0.1	Agriculture	14,000
405	Los Angeles	0.4	Transportation	219,000
210	Los Angeles	4.8	Residential	181,000
605	Los Angeles	4.1	Agriculture	149,000
210	Los Angeles	12.6	Agriculture	97,000
210	Los Angeles	0.4	Transportation	176,000
91	Los Angeles	0.4	Transportation	187,000
105	Los Angeles	0.1	Transportation	218,000
210	Los Angeles	12.8	Residential	105,000
105	Los Angeles	0.2	Transportation	176,000
105	Los Angeles	0.2	Transportation	176,000
105	Los Angeles	0.1	Transportation	218,000
110	Los Angeles	1.4	Commercial	292,000
60	Los Angeles	0.2	Transportation	228,000
60	Los Angeles	0.3	Transportation	227,100
405	Los Angeles	2.1	Residential	310,000
605	Los Angeles	0.1	Transportation	280,000
605	Los Angeles	0.0	Transportation	280,000
91	Los Angeles	1.0	Commercial	233,000
5	Los Angeles	0.1	Transportation	222,000
605	Los Angeles	0.1	Transportation	222,000
210	Los Angeles	0.2	Transportation	96,000
91	Los Angeles	1.6	Industrial	164,000
210	Los Angeles	0.4	Transportation	99,000
210	Los Angeles	1.5	Residential	128,000
101	Los Angeles	1.3	Transportation	328,000
405	Los Angeles	1.7	Transportation	260,000
405	Los Angeles	0.4	Transportation	322,000
10	Los Angeles	1.5	Residential	223,000
170	Los Angeles	1.0	Residential	180,000
210	Los Angeles	2.9	Residential	126,000
10	Los Angeles	0.5	Residential	267,000
170	Los Angeles	0.9	Residential	180,000

Table 1 continued

Highway (1)	County (2)	Drainage Area (ha.) (3)	Land Use (4)	AADT (5)
710	Los Angeles	2.9	Residential	219,000
210	Los Angeles	2.8	Commercial	100,000
118	Los Angeles	0.8	Residential	111,000
5	Los Angeles	1.1	Transportation	251,000
605	Los Angeles	0.1	Transportation	130,000
132	Mariposa	0.3	Residential	2,100
101	Mendocino	0.4	Residential	6,400
299	Mendocino	0.9	Transportation	1,800
142	Orange	0.4	Transportation	16,000
405	Orange	0.4	Transportation	237,000
80	Placer	0.2	Open	74,000
10	Riverside	0.2	Transportation	70,000
111	Riverside	0.6	Transportation	13,600
10	Riverside	0.5	Residential	18,300
10	Riverside	0.2	Residential	63,000
99	Sacramento	0.1	Open	47,500
50	Sacramento	0.3	Commercial	127,000
25	San Benito	0.1	Residential	2,200
10	San Bernardino	0.4	Transportation	95,000
805	San Diego	1.1	Transportation	212,000
8	San Diego	0.2	Transportation	175,000
5	San Diego	2.1	Transportation	254,000
15	San Diego	5.4	Commercial	262,000
78	San Diego	1.0	Transportation	112,000
5	San Diego	1.9	Transportation	188,000
5	San Diego	1.7	Mixed	182,000
5	San Diego	0.9	Transportation	181,000
15	San Diego	1.3	Transportation	259,000
805	San Diego	0.8	Transportation	177,000
12	San Joaquin	0.3	Transportation	14,300
5	San Joaquin	0.2	Mixed	65,000
46	San Luis Obispo	0.5	Residential	21,300
227	San Luis Obispo	0.1	Commercial	10,500
1	Santa Cruz	2.4	Residential	55,000
680	Solano	0.6	Transportation	53,000
36	Tehama	0.6	Transportation	2,100
5	Tehama	0.6	Transportation	29,000
99	Tulare	0.1	Agriculture	44,500
120	Tuolumne	0.3	Residential	4,900

Table 2

Chemical Constituents, Analytical Methods, and Reporting Limits

Constituent (1)	Abbreviation (2)	Analytical Method (3)	Reporting Limit (4)	Unit (5)
Conventional				
Chemical Oxygen Demand	COD	EPA 410.4	10	mg/L
Hardness	Hard.	EPA 130.2	2	mg/L as $CaCO_3$
Total Dissolved Solids	TDS	EPA 160.1	1	mg/L
Total Suspended Solids	TSS	EPA 160.2	1	mg/L
Turbidity	Turb.	EPA 180.1	0.05	NTU
Metals (Total and Dissolved)				
Arsenic[a]	As	EPA 200.8	0.5	µg/L
Cadmium	Cd	EPA 200.8	0.5	µg/L
Chromium	Cr	EPA 200.8	1	µg/L
Copper	Cu	EPA 200.8	1	µg/L
Lead	Pb	EPA 200.8	1	µg/L
Nickel	Ni	EPA 200.8	2	µg/L
Zinc	Zn	EPA 200.8	5	µg/L
Nutrients				
Ammonia (N)	NH_3	EPA 300.2	0.1	mg/L
Nitrate (N)	NO_3	EPA 300.0	0.1	mg/L
Nitrite (N)	NO_2	EPA 300.0	0.1	mg/L
Ortho-phosphate (P)	Ortho-P	EPA 365.2	0.05	mg/L
Total Kjeldahl Nitrogen	TKN	EPA 351.3	0.1	mg/L
Total Phosphorus	TP	EPA 365.2	0.05	mg/L
Major Ions and Minerals				
Calcium (Ca)	Ca	SM 3111B	1	mg/L
Magnesium, Total and Dissolved	Mg	SM 3111B	1	mg/L
Sodium, Total and Dissolved	Na	SM 3111B	1	mg/L
Sulfate	SO_4	EPA 300	2	mg/L
Microbiological				
Total Coliform	TC	EPA 9211E	2	MPN/100/mL
Fecal Coliform	FC	EPA 9221B	2	MPN/100/mL
Oil and Grease	O&G	EPA 1664	5	mg/L
Pesticides				
Diazinon		EPA 8141	0.05	µg/L
Chlorpyrifos		EPA 8141	0.05	µg/L
Glyphosate		EPA 8321	0.05	µg/L

[a] Arsenic is not a metal. For the purpose of this paper Arsenic is organized under metal pollutant.

Table 3
Classification of Non-Urban and Urban Highways Based on AADT

Classification (1)	AADT Values (2)
Non-Urban Highways	AADT<30,000
Urban Highways	
Low	60,000>AADT>30,000
Medium	100,000>AADT>60,000
Medium-High	200,000>AADT>100,000
High	AADT>200,000

Table 4
General Characteristics of Runoff from Urban and Non-Urban Highways

Constituent (1)	Unit (2)	Sample Size (3)	Non-Detects (4)	Range (5)	Mean (6)	Median (7)
Conventionals						
Chemical Oxygen Demand	mg/L	61	1	2.4 – 480	123.8	106
Hardness	mg/L as CaCO3	792	3	2 – 448	49.5	37.3
pH	PH	664	0	5.1 – 10.1	7.3	7.3
Temperature	°C	170	0	4.8 – 18.7	13.0	13.2
Total Dissolved Solids	mg/L	397	16	5 – 8780	184.1	68
Total Suspended Solids	mg/L	809	9	1 – 5100	148.1	65.8
Turbidity	NTU	42	0	1.1 – 2620	310.1	141.5
Metals-Total						
Arsenic	µg/L	343	143	0.5 – 2300	8.4	1.1
Cadmium	µg/L	586	184	0.15 – 13	0.9	0.6
Chromium	µg/L	586	32	1 – 100	8.8	5.8
Copper	µg/L	692	75	1 – 9500	51.3	20.2
Lead	µg/L	694	54	0.5 - 2300	79.6	21.8
Nickel	µg/L	639	110	1 – 317	10.1	6.0
Zinc	µg/L	693	16	2.5 – 2400	203.4	118.3
Metals-Dissolved						
Arsenic	µg/L	397	199	0.5 – 15.9	1.1	0.7
Cadmium	µg/L	761	495	0.02– 6.1	0.2	0.1
Chromium	µg/L	761	166	0.6 – 22	2.4	1.9
Copper	µg/L	814	82	1 – 121	13.5	9.9
Lead	µg/L	816	257	0.2 – 414	5.4	1.7
Nickel	µg/L	761	226	0.6 – 52	3.6	2.4
Zinc	µg/L	815	13	3 – 1017	72.7	46.1
Nutrients						
Ammonia-N	mg/L	61	0	0.08 – 6.4	1.1	0.8
Nitrate-N	mg/L	760	43	0.01 – 14.7	1.1	0.7
Nitrite-N	mg/L	94	58	0.05 – 1.7	0.1	0.1
Ortho-P	mg/L	514	121	0.01 – 1.03	0.1	0.1
Total Kjeldahl Nitrogen	mg/L	844	104	0.1 - 57	2.0	1.3
Total Phosphorus	mg/L	787	108	0.01 – 10	0.3	0.2
Major Ions						
Calcium, total	mg/L	43	6	4.5 – 66.8	12.7	8.4
Magnesium, Total	mg/L	50	28	1 – 21.8	3.2	2.1
Sodium, Total	mg/L	12	2	1 - 56	11.0	4.3
Sulfate	mg/L	55	11	0.23 – 57	4.2	1.6
Microbiological						
Total Coliform	MPN/100/mL	540	12	2 – 900000	21970	2014
Fecal Coliform	MPN/100/mL	959	112	2 – 205000	6083	356
Oil and Grease	mg/L	851	68	1 - 226	10.6	5.7
Pesticides						
Diazinon	µg/L	101	33	0.013 – 2.4	0.3	0.1
Chlorpyrifos	µg/L	93	59	0.03 – 1	0.1	0.02
Glyphosate	µg/L	20	7	6.4 – 220	27.8	7.8

Table 5
Average Constituent Concentrations for Urban vs. Non-urban Highway Sites

Constituent (1)	Unit (2)	Average Concentration		Ratio Urban/Non-Urban (5)
		Non-urban (AADT < 30,000) (3)	Urban (AADT > 30,000) (4)	
Conventionals				
Chemical Oxygen Demand	mg/L	145.5	119.0	0.8
Hardness	mg/L as CaCO3	30.3	52.5	1.7
pH	pH units	7.0	7.4	1.1
Temperature	°C	11.7	13.5	1.2
Total Dissolved Solids	mg/L	297.2	135.6	0.5
Total Suspended Solids	mg/L	168	144.7	0.9
Turbidity	NTU	567.2	135.2	0.2
Metals-Dissolved				
Arsenic	µg/L	0.6	1.2	2.0
Cadmium	µg/L	No data	0.3	No data
Chromium	µg/L	1.7	2.6	1.5
Copper	µg/L	6.5	14.7	2.3
Lead	µg/L	1.2	6.1	5.1
Nickel	µg/L	3.6	3.6	1.0
Zinc	µg/L	35.3	79.1	2.2
Metals-Total				
Arsenic	µg/L	0.7	11.6	16.6
Cadmium	µg/L	0.2	1.1	5.5
Chromium	µg/L	5.5	9.4	1.7
Copper	µg/L	9.4	59.0	6.3
Lead	µg/L	8.2	92.5	11.3
Nickel	µg/L	8.6	10.4	1.2
Zinc	µg/L	63.4	228.8	3.6
Nutrients				
Ammonia (N)	mg/L	2.3	1.0	0.4
Nitrate (N)	mg/L	0.6	1.1	1.8
Nitrite (N)	mg/L	No data	0.1	No data
Ortho-phosphate (P)	mg/L	0.1	0.12	1.2
Total Kjeldahl Nitrogen	mg/L	2.0	2.1	1.1
Total Phosphorus	mg/L	0.2	0.3	1.5
Major Ions				
Calcium (Ca)	mg/L	No data	13.0	No data
Magnesium,	mg/L	No data	3.6	No data
Sodium	mg/L	No data	15.8	No data
Sulfate	mg/L	No data	4.2	No data
Microbiological				
Total Coliform	MPN/100/mL	11,700	22,000	1.9
Fecal Coliform	MPN/100/mL	3,800	6,700	1.8
Oil and Grease	mg/L	2.5	10.9	4.4
Pesticides				
Diazinon	µg/L	0.4	0.2	0.5
Chlorpyrifos	µg/L	0.06	0.1	1.7
Glyphosate	µg/L	No data	20.5	No data

Table 6
Average Constituent Concentrations for Urban Highway Runoff Sites

Constituent (1)	Unit (2)	Urban Highway Pollutant Concentration			
		Low (3)	Medium (4)	Medium-High (5)	High (6)
Conventionals					
Chemical Oxygen Demand	mg/L	215.8 (166.5)	143.4 (110)	107.9 (88.2)	103.2 (91)
Hardness	mg/L as CaCO3	57.2 (34.5)	77.2 (55.3)	46.8 (38.2)	50.2 (38.2)
pH	PH	7.2 (7.3)	7.2 (7.2)	7.4 (7.4)	7.4 (7.4)
Temperature	°C	11.9 (11.1)	10.6 (10.1)	14.4 (14.8)	13.6 (13.9)
Total Dissolved Solids	mg/L	338.2 (85.5)	95.3 (89)	93.4 (80)	108.7 (87)
Total Suspended Solids	mg/L	360.0 (76.5)	149.0 (49)	129 (71)	127.8 (71)
Turbidity	NTU	261.4 (301)	No data	No data	97.3 (31.1)
Metals-Dissolved					
Arsenic	µg/L	1.4 (0.7)	0.61 (0.35)	1.03 (0.78)	1.6 (1.1)
Cadmium	µg/L	0.16 (0.06)	0.28 (0.19)	0.26 (0.14)	0.28 (0.18)
Chromium	µg/L	2.9 (1.7)	1.7 (1.4)	2.7 (2.2)	2.7 (2.3)
Copper	µg/L	12.7 (10.5)	12.2 (9.8)	13.9 (11.0)	16.7 (12.8)
Lead	µg/L	5.4 (0.7)	1.6 (0.7)	5.33 (2.10)	8.3 (2.66)
Nickel	µg/L	3.6 (2.5)	4.2 (2.9)	3.1 (2.1)	4.2 (2.9)
Zinc	µg/L	50.8 (31.6)	74.5 (42.5)	81.9 (54.6)	80.2 (53.1)
Metals-Total					
Arsenic	µg/L	2.6 (1.4)	1.30 (0.98)	23.7 (1.63)	2.4 (1.8)
Cadmium	µg/L	0.8 (0.5)	0.79 (0.66)	1.05 (0.77)	1.15 (0.79)
Chromium	µg/L	11.1 (8.0)	6.4 (5.0)	10 (6.6)	9.4 (6.7)
Copper	µg/L	29.2 (21.5)	22.7 (16.4)	80.1 (24.1)	47.2 (31.5)
Lead	µg/L	44.9 (22.5)	21.2 (12.3)	90.3 (31.9)	115.4 (41.5)
Nickel	µg/L	10.2 (7.8)	7.8 (6.2)	8.7 (5.2)	13.0 (7.56)
Zinc	µg/L	164.6 (90.5)	149.2 (110)	240.9 (142.7)	239.8 (168.5)
Nutrients					
Ammonia-N	mg/L	No data	0.91 (0.78)	1.2 (1.04)	0.86 (0.40)
Nitrate-N	mg/L	0.8 (0.5)	1.22 (0.88)	1.13 (0.82)	1.18 (0.83)
Nitrite-N	mg/L	0.2 (0.2)	0.28 (0.11)	0.10 (0.06)	0.1 (0.08)
Ortho-P	mg/L	0.14 (0.09)	0.10 (0.08)	0.11 (0.08)	0.12 (0.10)
Total Kjeldahl Nitrogen	mg/L	2.2 (5.2)	1.8 (1.2)	1.99 (1.35)	2.2 (1.6)
Total Phosphorus	mg/L	0.8 (0.2)	0.21 (0.16)	0.32 (0.17)	0.34 (0.20)
Major Ions					
Calcium, total	mg/L	No data	31.5 (15.2)	11.6 (9.2)	11.6 (8.0)
Magnesium, Total	mg/L	No data	5.3 (1.2)	3.9 (3.4)	3.3 (2.7)
Sodium, Total	mg/L	No data	4.8 (4.3)	No data	26.8 (19.5)
Sulfate	mg/L	No data	No data	2.98 (1.22)	6.4 (2.6)
Microbiological					
Total Coliform	MPN/100/mL	6,282 (1600)	11,858 (110)	20,213 (1791)	25,100 (3,000)
Fecal Coliform	MPN/100/mL	949 (500)	8,230 (1,200)	5,040 (246)	8,036 (500)
Oil and Grease	mg/L	3.9 (3.5)	6.3 (4.6)	6.9 (3.5)	12.0 (6.8)
Pesticides					
Diazinon	µg/L	0.15 (0.11)	0.19 (0.07)	0.2 (0.07)	0.38 (0.11)
Chlorpyrifos	µg/L	0.23 (0.08)	0.12 (0.02)	0.05 (0.01)	0.11 (0.02)
Glyphosate	µg/L	No data	No data	24.4 (9.5)	15.3 (8.6)

[a] Numbers in parenthesis are medians.

Table 7
Multiple Linear Regression (MLR) Model Parameters and Coefficients

	Model Statistics			*Significant Model Coefficients*						
Constituent (dependent variable)[a] (1)	**N (2)**	**Adjusted Model R-Squared (3)**	**RMS Residual (4)**	**y-Int. (5)**	**Ln[Event Rainfall, cm] (6)**	**Ln[Max Intensity , cm/hr] (7)**	**Ln[Antecedent Dry Period, days] (8)**	**CubeRoot [Cumulative Precipitation, cm] (9)**	**Ln[Drainage Area, hectares] (10)**	**AADT*10^{-6} (vehicles/day) (11)**
Conventionals										
Ln(COD)	52	0.169	0.820	5.259	—	—	—	(-0.379)	—	—
Ln(Hardness)	597	0.300	0.576	3.585	(-0.189)	(-0.107)	0.076	(-0.150)	—	2.45
pH	499	0.183	0.568	7.344	(-0.248)	0.133	(-0.061)	—	0.111	1.71
Temperature	9			No significant model						
Ln(TDS)	309	0.303	0.645	4.238	(-0.308)	(-0.109)	0.105	(-0.124)	—	2.38
Ln(TSS)	592	0.186	0.999	4.472	(-0.213)	0.101	0.155	(-0.321)	0.157	2.19
Ln(Turbidity)	19			No significant model						
Metals-Total										
Ln(As-Total)	189	0.196	0.548	0.865	(-0.201)	—	—	(-0.187)	—	2.075
Ln(Cd-Total)	479	0.281	0.684	(-0.129)	(-0.131)	—	0.129	(-0.343)	0.081	2.893
Ln(Cr-Total)	574	0.213	0.688	1.709	(-0.205)	—	0.110	(-0.197)	—	1.73
Ln(Cu-Total)	626	0.501	0.654	2.944	(-0.230)	—	0.127	(-0.247)	0.077	5.66
Ln(Pb-Total)	619	0.346	1.209	2.441	—	—	0.148	(-0.340)	0.130	9.21
Ln(Ni-Total)	560	0.257	0.649	2.386	(-0.238)	—	0.161	(-0.235)	—	—
Ln(Zn-Total)	591	0.454	0.717	4.650	(-0.198)	0.080	0.164	(-0.286)	0.113	5.37
Metals-Dissolved										
Ln(As-Diss)	176	0.205	0.546	0.492	(-0.121)	—	0.093	(-0.176)	(-0.090)	—
Ln(Cd-Diss)	254	0.103	0.762	(-1.411)	—	—	0.207	(-0.131)	—	—
Ln(Cr-Diss)	480	0.132	0.504	1.042	(-0.178)	—	—	(-0.097)	—	1.02
Ln(Cu-Diss)	597	0.485	0.520	1.943	(-0.222)	(-0.081)	0.204	(-0.204)	(-0.036)	2.96
Ln(Pb-Diss)	548	0.037	1.131	0.444	0.133	—	0.120	—	—	2.38

Table 7 continued

	Model Statistics			*Significant Model Coefficients*						
Constituent (dependent variable) (1)	**N (2)**	**Adjusted Model R-Squared (3)**	**RMS Residual (4)**	**y-Int. (5)**	**Ln[Event Rainfall, cm] (6)**	**Ln[Max Intensity, cm/hr] (7)**	**Ln[Antecedent Dry Period, days] (8)**	**CubeRoot [Cumulative Precipitation, cm] (9)**	**Ln[Drainage Area, hectares] (10)**	**$AADT*10^{-6}$ (vehicles/day) (11)**
Ln(Ni-Diss)	456	0.271	0.583	1.428	(-0.221)	—	0.186	(-0.183)	(-0.040)	—
Ln(Zn-Diss)	591	0.185	0.843	3.411	—	(-0.122)	0.231	(-0.197)	(-0.053)	2.22
Nutrients										
Ln(NH3-N)	57	0.557	0.642	1.353	—	—	—	(-0.775)	—	—
Ln(NO3-N)	585	0.381	0.608	0.202	(-0.373)	—	0.119	(-0.264)	0.044	1.60
Ln(NO2-N)	34	0.309	0.569	(-0.955)	—	—	—	—	—	(-4.12)
Ln(OrthoP-Diss)	371	0.173	0.595	(-2.173)	(-0.187)	—	0.121	(-0.120)	(-0.043)	—
Ln(TKN)	607	0.440	0.585	1.159	(-0.285)	—	0.141	(-0.405)	—	1.34
Ln(P-Total)	521	0.296	0.676	-1.101	(-0.216)	0.084	0.109	(-0.301)	0.090	2.25
Major Ions										
Ln(Ca)	33	0.392	0.450	2.237	(-0.427)	—	—	—	—	2.209
Ln(SO4)	44	0.648	0.773	(-2.464)	(-0.730)	—	—	—	—	21.39
Microbiological										
Ln(Total Coliform)	278	0.194	1.687	7.547	—	0.192	0.321	(-1.030)	—	7.88
Ln(Fecal Coliform)	595	0.085	2.046	5.591	—	0.247	0.347	—	(-0.159)	—
Ln(Oil & Grease)	336	0.552	0.712	0.846	(-0.560)	0.322	0.254	—	—	5.61
Pesticides										
Ln(Diazinon)	30	0.186	0.895	(-0.369)	—	—	(-0.328)	—	—	—
Ln(Chlorpyrifos)	21	0.156	0.557	-2.586	(-0.506)	—	—	—	—	—
Ln(Glyphosate)	12						No significant model			

Note: Threshold for statistical significance is $p < 0.05$ for all comparisons and effects

[a] The unit of constituents (dependent variable) are the same as those appeared in Tables 4, 5, and 6.

Table 7 continued

	Model Statistics			Significant Model Coefficients						
Constituent (dependent variable) (1)	**N (2)**	**Adjusted Model R-Squared (3)**	**RMS Residual (4)**	**y-Int. (5)**	**Ln[Event Rainfall, cm] (6)**	**Ln[Max Intensity, cm/hr] (7)**	**Ln[Antecedent Dry Period, days] (8)**	**CubeRoot [Cumulative Precipitation, cm] (9)**	**Ln[Drainage Area, hectares] (10)**	**AADT*10^{-6} (vehicles/day) (11)**
Ln(Ni-Diss)	456	0.271	0.583	1.428	(-0.221)	—	0.186	(-0.183)	(-0.040)	—
Ln(Zn-Diss)	591	0.185	0.843	3.411	—	(-0.122)	0.231	(-0.197)	(-0.053)	2.22
Nutrients										
Ln(NH3-N)	57	0.557	0.642	1.353	—	—	—	(-0.775)	—	—
Ln(NO3-N)	585	0.381	0.608	0.202	(-0.373)	—	0.119	(-0.264)	0.044	1.60
Ln(NO2-N)	34	0.309	0.569	(-0.955)	—	—	—	—	—	(-4.12)
Ln(OrthoP-Diss)	371	0.173	0.595	(-2.173)	(-0.187)	—	0.121	(-0.120)	(-0.043)	—
Ln(TKN)	607	0.440	0.585	1.159	(-0.285)	—	0.141	(-0.405)	—	1.34
Ln(P-Total)	521	0.296	0.676	-1.101	(-0.216)	0.084	0.109	(-0.301)	0.090	2.25
Major Ions										
Ln(Ca)	33	0.392	0.450	2.237	(-0.427)	—	—	—	—	2.209
Ln(SO4)	44	0.648	0.773	(-2.464)	(-0.730)	—	—	—	—	21.39
Microbiological										
Ln(Total Coliform)	278	0.194	1.687	7.547	—	0.192	0.321	(-1.030)	—	7.88
Ln(Fecal Coliform)	595	0.085	2.046	5.591	—	0.247	0.347	—	(-0.159)	—
Ln(Oil & Grease)	336	0.552	0.712	0.846	(-0.560)	0.322	0.254	—	—	5.61
Pesticides										
Ln(Diazinon)	30	0.186	0.895	(-0.369)	—	—	(-0.328)	—	—	—
Ln(Chlorpyrifos)	21	0.156	0.557	-2.586	(-0.506)	—	—	—	—	—
Ln(Glyphosate)	12			No significant model						

Note: Threshold for statistical significance is $p < 0.05$ for all comparisons and effects

[a] The unit of constituents (dependent variable) are the same as those appeared in Tables 4, 5, and 6.

Table 8
Summary of Significant Effects for Multiple Linear Regression Models

Covariate Factor (predictor variable) (1)	Dominant effect on pollutant concentrations[a] (2)	Ratio of models exhibiting significant dominant effect[b] (3)	Exceptions[c] (4)	Comments (5)
Event Rainfall	Concentrations decrease with higher total event rainfall.	23 of 24 models had a significant negative coefficient	*Positive*: dissolved Pb; *Not significant*: total Pb, dissolved Zn, COD, NH_3, NO_2, fecal and total coliform, diazinon	Very consistent predictor. Same pattern for nearly all models.
Maximum Rainfall Intensity	Concentrations increase with higher maximum intensity	7 of 11 models had a significant positive coefficient	*Negative*: dissolved Cu and Zn, hardness, TDS	*Not significant* is the most common result. Maximum intensity is correlated with event rainfall. Generally appears not to be a good predictor variable.
Antecedent Dry Period	Concentrations increase with longer antecedent dry period	23 of 25 models had a significant positive coefficient	*Negative*: pH, diazinon; *Not significant*: total As, dissolved Cr, Calcium, COD, SO_4, NH_3, NO_2, and chlorpyrifos	Very consistent predictor. Same pattern for nearly all significant models.
Seasonal Cumulative Precipitation	Concentrations decrease as cumulative rainfall increases	24 of 24 models had a significant negative coefficient	*Positive*: none *Not significant*: dissolved Pb, calcium, oil and grease, pH, SO_4, turbidity, NO_2, fecal coliform, chlorpyrifos and diazinon	Very consistent predictor. Same pattern for all significant models.
Drainage Area	Concentrations are higher for larger drainage areas	9 of 15 models had a significant positive coefficient	*Negative*: dissolved As, Cu, Ni, and Zn, dissolved orthophosphate, and fecal coliform	Positive for total metals, total P, and TSS. Negative or not significant for dissolved metals and dissolved ortho-P.
AADT	Concentrations are higher for sites with higher traffic	22 of 23 models had a significant positive coefficient	*Negative*: NO_2 *Not significant*: dissolved As, Cd, and Ni, total Ni, COD, NH_3, ortho-P, fecal coliform, chlorpyrifos and diazinon	Very consistent predictor. Same pattern for nearly all significant models.

[a] Summarized for MLR models including only whole storm or first flush data. "Dominant Effect" is the most frequently observed sign of significant coefficients for the factor in MLR models. In all cases, the relationship between covariate and dependent variables (after transforming to approximate normality) is approximately linear.

[b] Threshold of statistical significance is $p<0.05$.

[c] Constituents for which the predictor had a significant effect opposite to the dominant effect for the predictor.

Table 9
Effect of Land Use on Highway Runoff Quality

Constituent (1)	p-value (2)	Significant pairwise comparisons of contributing land use categories[a] (Tukey-Kramer post-hoc test) (3)
Conventionals		
Ln(COD)	ID	ID
Ln(Hardness)	<0.0001	Ag > (Comm, Ind, Mxd, Open, Res, Trans); Trans > Res
pH	0.0002	(Ag, Comm, Ind, Mxd, Res, Trans) > Open
Temperature	ID	ID
Ln(TDS)	0.0640	Not Significant
Ln(TSS)	<0.0001	(Ag, Comm, Ind, Mxd, Res, Trans) > Open; Ind > (Ag, Res, Trans)
Ln(Turbidity)	ID[b]	ID
Metals-Total		
Ln(As-Total)	0.5854	Not Significant
Ln(Cd-Total)	0.0335	Mixed > Open
Ln(Cr-Total)	0.0002	Ind > (Open, Res, Trans)
Ln(Cu-Total)	<0.0001	Mxd > Ag; (Mxd, Ind) > (Comm, Res, Trans)
Ln(Pb-Total)	<0.0001	(Ag, Ind, Mxd, Res, Trans) > Open; Mxd > (Ag, Comm, Res, Trans)
Ln(Ni-Total)	0.0002	Comm > Res
Ln(Zn-Total)	<0.0001	Mxd > (Ag, Comm, Res, Trans)
Metals-Dissolved		
Ln(As-Diss)	0.1209	Not Significant
Ln(Cd-Diss)	0.1752	Not Significant
Ln(Cr-Diss)	0.0108	No significant pairwise comparisons
Ln(Cu-Diss)	<0.0001	(Ind, Mxd, Open) > (Comm, Res) Mxd > Trans
Ln(Pb-Diss)	0.0193	No significant pairwise comparisons
Ln(Ni-Diss)	0.0017	Ag > Res
Ln(Zn-Diss)	0.3211	Not Significant
Nutrients		
Ln(NH3-N)	0.4647	Not Significant
Ln(NO3-N)	0.0470	No significant pairwise comparisons
Ln(NO2-N)	ID	ID
Ln(OrthoP-Diss)	0.0639	Not Significant
Ln(TKN)	0.1724	Not Significant
Ln(P-Total)	0.0011	Mxd > (Res, Trans)
Major Ions		
Ln(Ca)	0.0557	Not Significant
Ln(SO4)	0.9508	Not Significant
Ln(Oil & Grease)	0.0962	Not Significant
Microbiological		
Ln(Fecal Coliform)	0.7021	Not Significant

Table 9 Continued

Constituent (1)	p-value (2)	Significant pairwise comparisons of contributing land use categories[1] (Tukey-Kramer post-hoc test) (3)
Ln(Total Coliform)	0.8050	Not Significant
Pesticides		
Ln(Chlorpyrifos)	ID	ID
Ln(Diazinon)	ID	ID
Ln(Glyphosate)	ID	ID

Note: Threshold for statistical significance is $p < 0.05$ for all comparisons and effects

[a] Land Use designations: Ag=Agriculture, Comm=Commercial, Ind=Industrial, Mxd=No dominant land use determined, Open=Open, Res=Residential, Trans=Transportation

[b] ID=insufficient data