

Forecasting Pollutant Loads From Highway Runoff

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ABSTRACT

Forecasting regression equations for estimating pollutant loads in runoff from highways are developed in this paper. Data were collected during the runoff seasons at completely paved urban highway sites in Redondo Beach, Walnut Creek, and Sacramento, California. Information was also obtained from a rural site near Placerville. Rainfall and runoff were monitored continuously. Bubbler flow meters were used with automatic sequential samplers so that storm water samples could be collected to characterize entire storm events. The constituents that were analyzed were boron, total lead, total zinc, nitrate (nitrogen), ammonia (nitrogen), total Kjeldahl nitrogen, total phosphorus, dissolved orthophosphate, oil and grease, nonfilterable residue, filterable residue, total cadmium, and chemical oxygen demand. The number of vehicles during the storm was evaluated and accepted as a satisfactory independent variable for estimating the loads of total lead, total zinc, filterable residue, chemical oxygen demand, and total Kjeldahl nitrogen. The total residue was evaluated and accepted as a satisfactory independent variable for estimating total zinc, nonfilterable residue, and chemical oxygen demand. Estimates by using these equations should be limited to highways with average daily traffic of at least 30,000 vehicles. The numbers of antecedent dry days was found not to be a satisfactory independent variable.

A method is needed to forecast expected pollutant loads in the runoff from highway surfaces. When an existing highway is upgraded or a new highway is constructed, natural runoff patterns are altered. These alterations can cause significant changes in flow rates and runoff water quality.

Runoff from highway surfaces carries potentially harmful pollutant loads to nearby surface waters. These pollutants may be deposited on the highway surfaces from vehicles traveling on the highway, from winds, and from fallout of air pollutants.

The pollutants may be dissolved in the runoff water or carried as particulate matter. An adverse impact on the receiving water may result from the toxic (heavy metals), oxygen-consuming, biostimulation (nutrients), or aesthetic (oil and grease) characteristics of the pollutant. The magnitude of the impact may be a function of the concentration of the pollutant or the total quantity (load) of the pollutant that reaches the receiving waters during a storm event or that is accumulated over a period of years.

The objectives of this research project are (a) identify those pollutants in highway runoff that may cause an adverse impact on receiving waters, and (b) develop forecasting regression equations that can be used in predicting the expected pollutant loads in highway runoff. To attain these objectives, one rural site and three urban sites were selected. The rural site was located near Placerville and the urban sites were located near Redondo Beach, Walnut Creek, and Sacramento (Figures 1 and 2).

RESEARCH PROCEDURES

Because of the complexity of interactions among pollutants, rainfall, runoff, highway design, operating vehicles, surrounding land use, and maintenance practices, regression analysis was the technique chosen for building the forecasting equations. The main thrust of the regression analysis was to find a

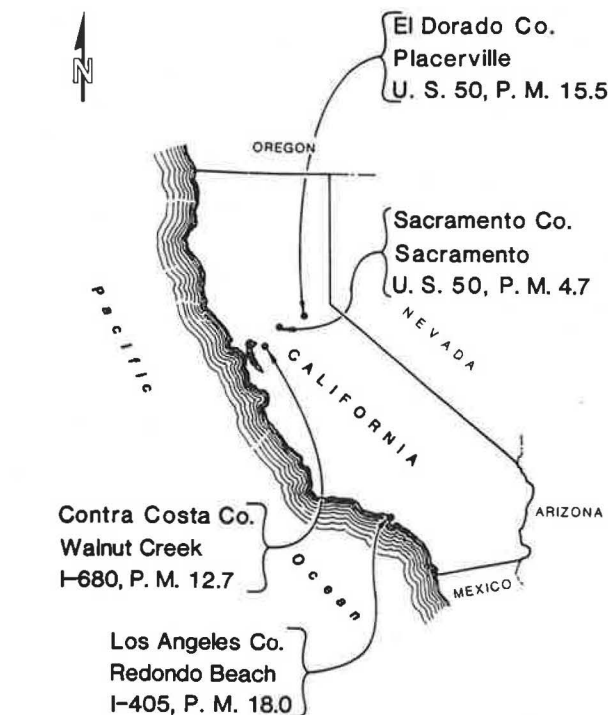


FIGURE 1 Runoff sites.

suitable independent variable that could be used to quantify the response variables. The response variables were the selected pollutants that had already been identified in past research by the California Department of Transportation (Caltrans) and others, which can be generally classified as heavy metals (toxicants), oil and grease (aesthetic), nutrients (biostimulants), and residue (particulate material).

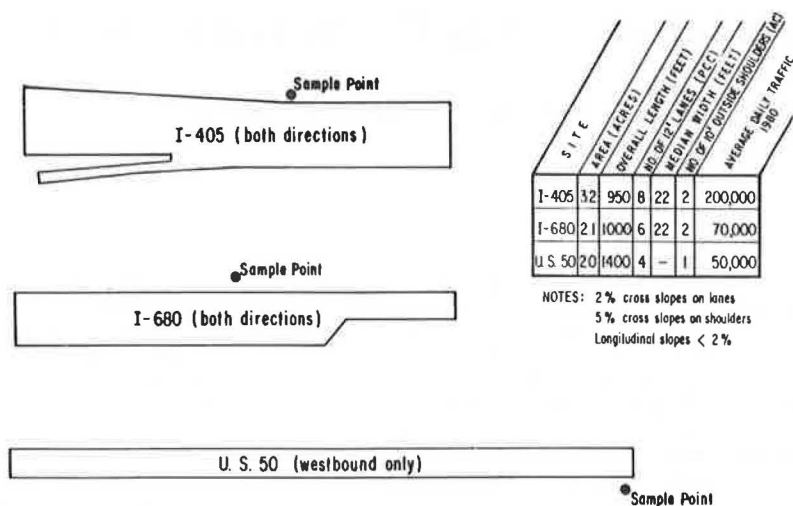


FIGURE 2 Simplified plan views and runoff sites.

Data Sources

Three sets of data were used for developing the forecasting regression equations. The first was collected by Caltrans from 1975 through 1978 (1). The data consist mainly of instantaneous flow observations and water quality measurements of manually obtained samples. These data were screened to select constituents for additional sampling in the current study. They were also used for preliminary investigations. The runoff sites were at I-405 in Redondo Beach, I-680 in Walnut Creek, and US-50 in Placerville (Figure 1). The second set of data was collected by Caltrans specifically for this study at I-405 in Redondo Beach and I-680 in Walnut Creek during the 1980-1981 wet season. The data consist mainly of continuous flow observations and discrete water quality measurements of composited samples of entire storms. These data were used to build the tentative regression equations.

The third set of data was collected by Caltrans, but was analyzed and reported by Envirex, Inc. (2-4) in cooperation with FHWA. The runoff site was at US-50 in Sacramento. Data were collected from 1979 through 1981. The data consist mainly of continuous flow observations and discrete water quality measurements of composited samples of entire storms. These data were used to evaluate the tentative regression equations based on Redondo Beach and Walnut Creek data.

Flows were measured and recorded continuously at all sites using Parshall flumes. Water quality samples were collected using automatic sequential discrete samplers. An electronic probe sensed the start of runoff from each storm and transmitted a signal that activated the samplers. The samplers were programmed to collect samples either at 15-min intervals or after every 100- or 300-ft³ of flow through the Parshall flume (5). Similar results were obtained by using either the time or volume incremental method of sampling.

Selection of Constituents to Sample: Dependent Variable

Seven storms were evaluated to determine whether significant concentrations of any of 31 constituents existed in the storm water before it entered the receiving waters, where further dilution would reduce concentration levels or the addition of a pollutant

could increase concentration levels. The significance criteria were based on the maximum observed concentration, which had to be within 50 percent of critical concentration reported by the U.S. Environmental Protection Agency (6) or the California Water Resources Control Board (7).

Lead (Pb), zinc (Zn), cadmium (Cd), and oil and grease were chosen for study because they are vehicle related. Total residue (TR) was selected because it is associated both with vehicles and with local air particulate deposition. Nitrate-nitrogen, ammonia-nitrogen, total Kjeldahl nitrogen (TKN), total phosphorus, and orthophosphate were studied because these constituents may collect on traveled surfaces and shoulders. Boron was studied because of its potential impact on vegetation. Cadmium was selected for the 1980-1981 sampling program; however, cadmium testing at the Walnut Creek site was discontinued after the first major storm on December 10, 1980, because values dropped below detection limits after the initial runoff. Analysis of the 1975-1978 data revealed a "first flush" pattern: sulfate, iron, chromium, copper, manganese, and nickel concentrations were not within 50 percent of the critical concentrations listed in Table 1.

DEVELOPMENT OF POLLUTANT LOAD FORECASTING EQUATIONS

Analysis of the 1975-1978 data (1) revealed that insufficient information was collected during storm events. To determine pollutant loads in either pounds or kilograms of each specific pollutant per storm event, the storm hydrograph and the pollutant concentrations (pollutograph, a plot of pollutant concentrations versus time) during the runoff period must be known. Continuous flow recorders and automatic samplers were used to collect these data. Samples for oil and grease were collected manually by field personnel during storm events to obtain representative samples.

Number of Vehicles Before the Storm as an Independent Variable

Hypothesis testing of regression equations by using number of vehicles before the storm as an independent variable and the constituent load as a dependent variable showed no statistical significance.

TABLE 1 Constituents to be Considered for Further Study

Constituent	Criterion	Critical Value
Boron ^a	Crops	750 µg/liter
Sulfate	Water supply	250 mg/liter
Iron	Water supply	300 µg/liter
Lead ^a	Water supply	50 µg/liter
Zinc ^a	<i>Salmo gairdneri</i>	10 µg/liter
Nitrate-nitrogen ^a	Aquatic growth	300 µg/liter
Total Kjeldahl nitrogen ^a	Aquatic growth	600 µg/liter
Ammonia ^a	Aquatic life	20 µg/liter
Total phosphorus ^a	Aquatic growth	10 µg/liter
Dissolved orthophosphate ^a	Aquatic growth	10 µg/liter
Oil and grease ^a	Water supply	Virtually free from oil and grease
Total residue ^a	Water supply	250 mg/liter for CL
Total nonfilterable residue ^a	Water supply	Variable
Chemical oxygen demand ^a	Treatment plant effluent	50 mg/liter
Conductivity ^a	Aquatic life	1,000 µmhos
pH ^a	Special treatment required	
Cadmium ^a	Salmonid	0.4 µg/liter
Chromium	Water supply	50 µg/liter
Copper	<i>Salmo gairdneri</i>	2.0 mg/liter
Manganese	Water supply	50 µg/liter
Nickel	Water supply	100 µg/liter

^aConstituent was selected for 1980-1981 sampling program because the observed concentrations were within 50 percent of the critical value shown.

The results of sweeping/flushing studies performed at the US-50 site in Sacramento by Envirex Inc. (2-4) showed that the active freeway lanes do not retain significant amounts of pollutants. Furthermore, the Envirex dustfall transect study in Sacramento indicated that particulates were blown off the traveled lanes to the shoulders and beyond. Evidently, during the antecedent dry period, the freeways are continuously swept by the traffic-generated turbulence; thus, it was not surprising that the correlation of pollutant loads with amount of traffic before the storm [average daily traffic (ADT) times dry days] showed no statistical significance. During dry periods, there apparently is a greater adherence of materials to the engine, undercarriage, and wheel walls of vehicles, whereas during a storm or wet periods, there is more splashing and washing of these materials from the vehicles.

Number of Vehicles During the Storm as an Independent Variable

A study of Lead Emissions and Washoff (5,8) showed that a significant fraction of lead emitted from

vehicles during a storm correlated well with lead in runoff. Further studies using the number of vehicles during the storm (VDS), as the independent variable were made by using Equation 1. Equation 1 is the general form of the line:

$$CL = a + b(VDS) \quad (1)$$

where CL is the cumulative constituent load, and a and b are the regression coefficients. Vehicles were counted on an hourly basis in this research project to match, as closely as possible, the times from start to end of runoff. Vehicle counts were obtained from the Traffic Operations Branches of the respective Caltrans districts in which the sampling was performed.

The ideal forecasting equation is a regression equation in which the independent variable is easily sampled and quickly and inexpensively measured. When a highway project requires that nonpoint source pollution via runoff be addressed, the relatively inexpensive tests of TR, nonfilterable residue (NR), and filterable residue (FR) could be performed and estimates of the other constituents could be obtained from the prediction equations. Subsequent evaluation studies led to the formulation of Equation 2 in which no transformations (normalizing) were applied to the data.

$$CL = a + b(TR) \quad (2)$$

where CL is cumulative constituent load, and a and b are regression coefficients (a represents an initial load in grams, and b is the fraction of constituent washed off the highway during a storm).

RESULTS

Linear regression equations were tested and evaluated by using number of vehicles during the storm as an independent variable to quantify the loads of the following constituents: Pb, Zn, FR, chemical oxygen demand (COD), and TKN. In addition, linear regression models were tested and evaluated by using the total residue as an independent variable to quantify the loads of the following constituents: Zn, NR, and COD.

The equations for each constituent are shown in Figures 3 through 10. Each figure shows a plot of the tentative equation (Line A), which was based on observations from Redondo Beach and Walnut Creek, in addition to the pooled equation (Line B), which in-

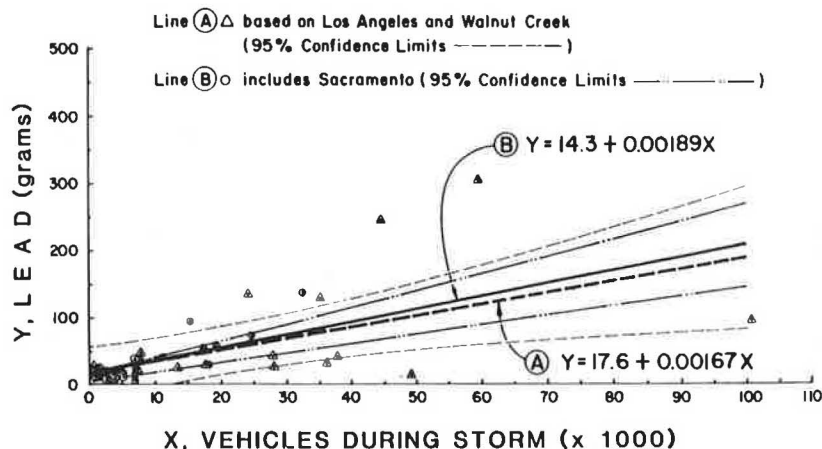


FIGURE 3 Lead versus vehicles during storm.

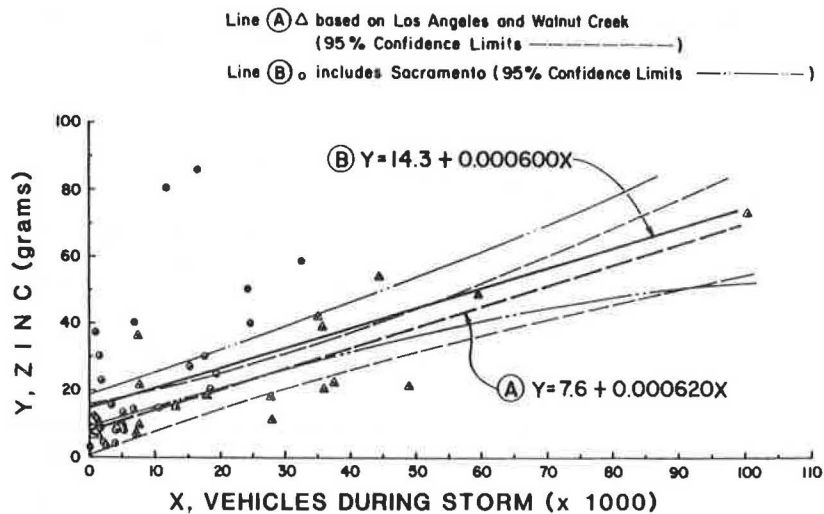


FIGURE 4 Zinc versus vehicles during storm.

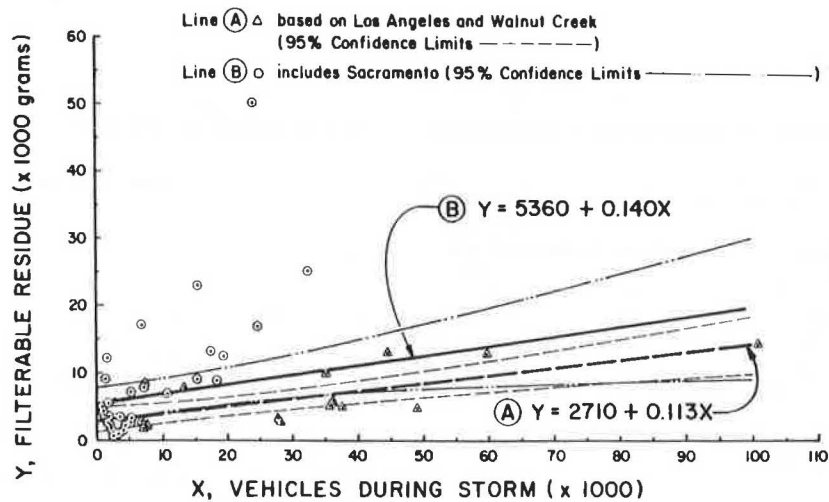


FIGURE 5 Filterable residue versus vehicles during storm.

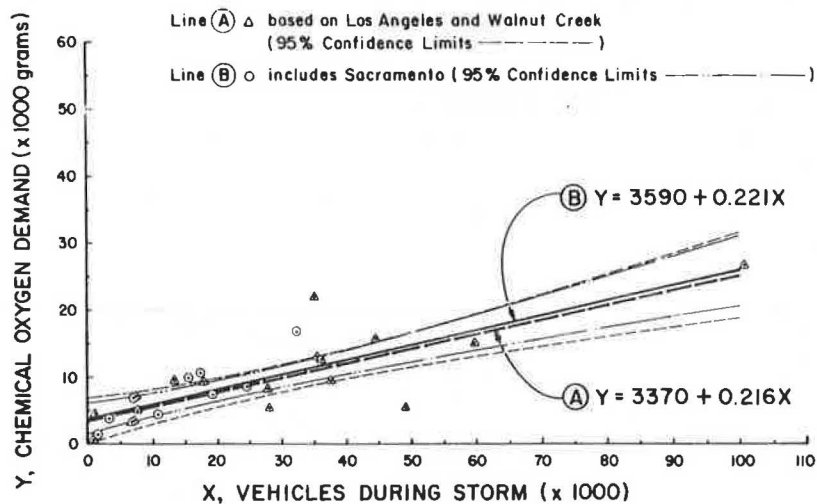


FIGURE 6 Chemical oxygen demand versus vehicles during storm.

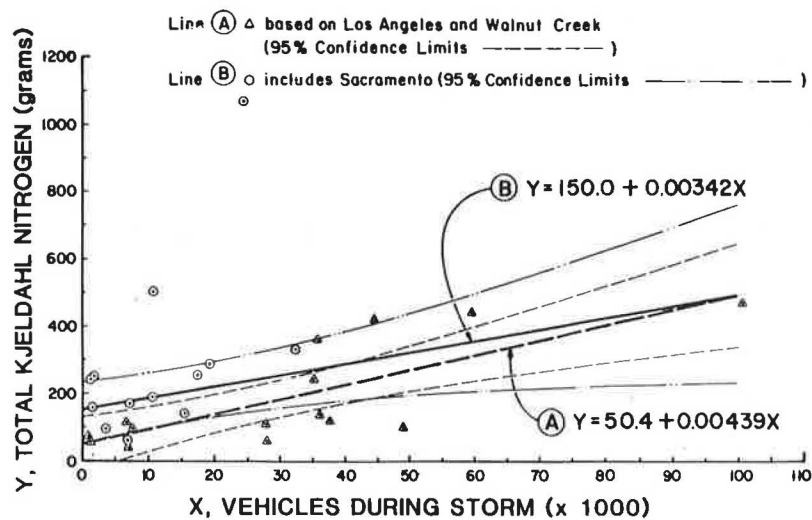


FIGURE 7 Total Kjeldahl nitrogen versus vehicles during storm.

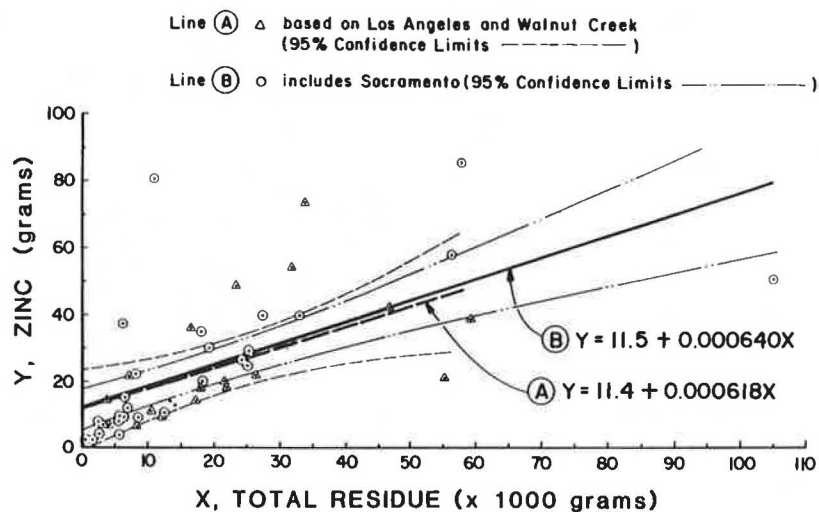


FIGURE 8 Zinc versus total residue.

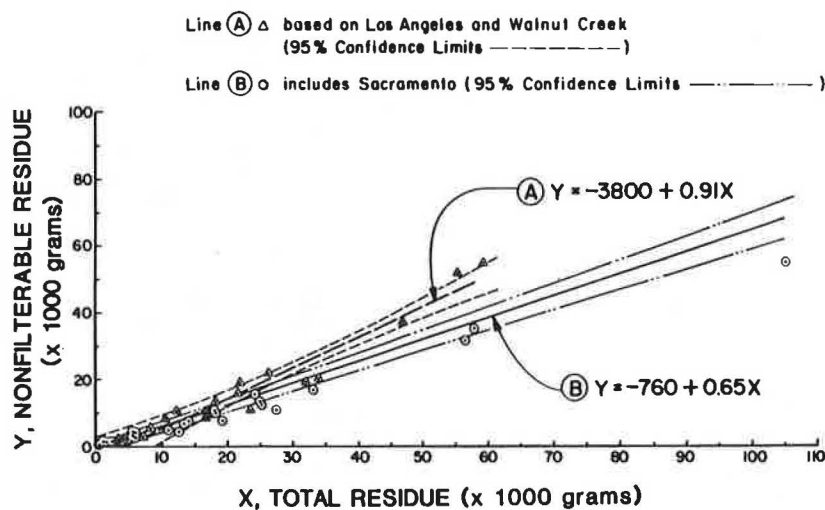


FIGURE 9 Nonfilterable residue versus total residue.

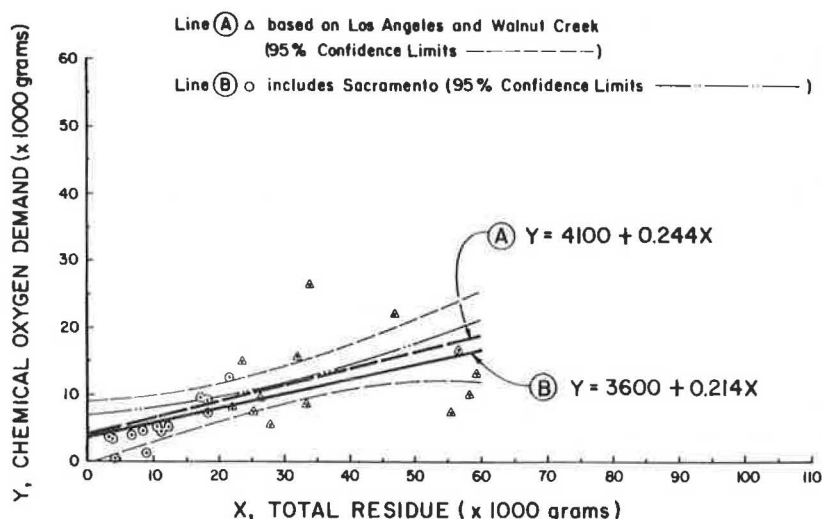


FIGURE 10 Chemical oxygen demand versus total residue.

cluded observations from Sacramento. The 95 percent confidence limits are plotted for each line. The equations are statistical representations that were based on continuous observations for each storm event of constituents found in runoff from urban highways in California.

The equations may be applied for 100-percent-paved highways that have the same general site characteristics as the sites from which the observations were obtained. Figure 2 shows a simplified plan view of each of the completely paved test sites. Longitudinal slopes were generally less than 2 percent, so that the times of travel of runoff, which originated at the farthest point on the drainage catchment, to the sampling location were less than 30 min.

The constituents for which no linear relationships were found by using Equation 1 are boron, cadmium, nitrate-nitrogen, ammonia-nitrogen, total phosphorus, dissolved orthophosphate, NR, TR, and oil and grease. In addition, no correlations were found by using Equation 2 for the following constituents: boron, cadmium, lead, nitrate-nitrogen, TKN, ammonia-nitrogen, total phosphorus, dissolved orthophosphate, FR, and oil and grease.

Summary of Evaluations

Use of the number of vehicles during the storm as a variable (Equation 1) was found to be acceptable by t-testing the equality of slopes of the equations for total Pb, total Zn, FR, COD, and TKN. Total residue (Equation 2) was found to be acceptable by t-testing the equality of the slopes of the equations for total Zn, NR, and COD.

Analysis of laboratory test results from the runoff at each of the four sites (1-5,9,10) revealed that none of the pollutants that were studied produced levels of contaminants that exceeded the water quality criteria in Table 1 or that created detrimental impacts when they eventually reached nearby receiving waters.

EXPLANATION AND PROCEDURE FOR USING THE FORECASTING EQUATIONS

Before the regression equations are used to compute constituent loadings, there are three criteria to examine: (a) there must be a sensitive receptor nearby (e.g., a stream that supports aquatic life or

is a municipal water supply); (b) the ADT must exceed 30,000 vehicles; and (c) the average annual rainfall in the area should be between 18 and 24 in.

Because the drainage details are not known in the advance stages of a highway project, the following assumptions and procedures are used to forecast constituent loads and flow-weighted concentrations:

1. The future vehicle fleet and fuels used are approximately the same as in the years of actual data collection (1979-1981).
2. The highway is in an urban setting in an arid or semiarid region of the United States.
3. The median, traveled lanes, and shoulders are 100 percent paved.
4. The assumed drainage area is the actual proposed width of pavement times an assumed length. The drainage area should be between 2 and 4 acres to correspond to the drainage areas used for the research sites. The actual site configurations and characteristics are as follows (see Figure 2 also):

Physical Characteristics	Los Angeles	Walnut Creek	Sacramento
Area (acres)	3.2	2.1	2.0
Lane miles	1.4	1.0	1.1
Gutter miles	0.70	0.56	0.27

5. Runoff from the assumed drainage area is conveyed via open channels to a single point of discharge. (Runoff quantity and quality from the unpaved area adjacent to the paved area was excluded from this study.)

6. A runoff coefficient of 0.90 is used to compute the cumulative runoff volume because the drainage area is completely paved.

7. The hydrologic records are analyzed to determine (a) the expected number of storms per year with sufficient duration and intensity occurring during both the a.m. and p.m. peak traffic to wash off the gutter load and contributions to pollutant runoff from traffic traveling through the site and (b) the expected precipitation per storm in (a). Precipitation data can be obtained from hydrologic data available from the U.S. Geological Survey, National Oceanographic and Atmospheric Administration, or state water resource agencies (11). Rainfall intensity may be a key factor at some sites; however, this study considered the volume of runoff that results from both the intensity and duration of a

storm. Various situations will require appropriate analysis and the application of hydrologic data.

8. Because the storm duration includes both the a.m. and p.m. peak traffic, the projected ADT is used to compute constituent loads by using the following linear regression equations, which were evaluated and found to be acceptable:

$$Pb = 14.3 + 0.00189(ADT) \quad (3)$$

$$Zn = 14.3 + 0.00060(ADT) \quad (4)$$

$$FR = 5360 + 0.140(ADT) \quad (5)$$

$$COD = 3590 + 0.221(ADT) \quad (6)$$

$$TKN = 150 + 0.00342(ADT) \quad (7)$$

where Pb, Zn, FR, COD, and TKN are the cumulative loads in grams per storm. The intercepts represent initial dry loads in grams, and the slopes represent the washoff rate of constituent in grams per ADT during a storm. The intercepts for FR and COD indicate that a first flush of particulate matter can be expected to consist of some organic materials.

9. To forecast an annual load, each of the daily loads (item 8) is multiplied by the expected number of 1-day events per year (item 7a) to arrive at an annual load.

10. The flow-weighted concentration is computed by dividing the daily event load in item 8 by the 1-day cumulative runoff volume (use item 7b).

11. The following linear regression equations use total residue to calculate constituent loads in grams per storm:

$$Zn = 11.5 + 0.00064(TR) \quad (8)$$

$$COD = 3600 + 0.214(TR) \quad (9)$$

$$NR = -760 + 0.65(TR) \quad (10)$$

The intercepts represent the initial dry loads in grams, and the slopes represent the fraction of constituent found in the TR that is washed from the pavement during the storm. Because TR is an independent variable for which no easy future value can be obtained, the following procedure is suggested. Substitute the values of total Zn computed from Equation 4 and COD computed from Equation 6 (which are based on ADT during storm) in Equations 8 and 9. Solve these two equations for the independent variable, TR. Use the average of the two calculated values of TR to compute the NR load using Equation 10. Then, compute the flow-weighted concentration as in item 10.

12. The final step of the procedure is to check the computed loads and flow-weighted concentrations. The check is to ensure that the computed values are bounded by the field observations. Table 2 shows the limits of the observed concentrations and loads.

Final water quality assessment must be made by applying values of the pollutant loads and concentrations to the receiving waters and by determining the resulting impacts. To assess the effects of the constituent load on nearby receiving waters, the load must be routed through the drainage system and, ultimately, to the receiving water. Along the way, runoff from other sources may be encountered. To conduct an environmental assessment, these other sources must be included along with dilution factors for the highway runoff in terms of the receiving waters.

Inclusion of mitigation measures in transportation projects to reduce the influence of pollutants from paved highway surfaces should be based on findings from analyses that are performed in accordance

TABLE 2 Limits of Observed Concentrations and Loads of Single Events

Constituent	Concentration (mg/liter)		Load (gr)	
	Low	High	Low	High
Total lead	0.17	4.10	4.0	304
Total zinc	0.10	1.80	2.0	84
Filterable residue	16	461	428	50,167
Chemical oxygen demand	23	724	382	26,344
Total Kjeldahl nitrogen	0.1	14.0	34	1,070
Nonfilterable residue	18	2,660	143	55,259

with the procedures described in this paper. The following list should be considered in determining mitigation measures:

1. A potential mitigation measure is to route direct runoff through grass-covered drainage courses to remove particulate matter, heavy metals, trace organics, toxicants, and oxygen-consuming materials (12).

2. Where mitigation measures are needed, proper designs should be based on pollutant loading analyses to provide a cost-effective measure to protect the aquatic receptor.

3. Inclusion of mitigation measures that do not improve water quality on projects should be avoided to reduce unnecessary costs.

CONCLUSIONS

The following conclusions were reached from this research project:

1. Urban highways in California that are operated under normal conditions (i.e., no accidents or chemical spills) do not produce large amounts of pollutant constituents during storm runoff events. The findings of the research indicate that for highway segments that drain between 2 and 4 acres of completely paved areas, and have six to eight traveled lanes, the constituent pollutant loads in runoff water are sufficiently low so that costly treatment facilities are not needed to meet water quality objectives.

2. Equations to estimate the cumulative loads of the following pollutants were found to be statistically significant at the 5 percent level on a storm event basis when correlated with the number of vehicles during the storm (pollutants included COD, FR-dissolved solids, total Pb, TKN, and total Zn) and with total residue (pollutants included COD, NR-suspended solids, and total Zn).

The number of dry days between storm events and the corresponding cumulative traffic volume before the storm were found to be not statistically significant for quantifying cumulative constituent loads. Apparently, traffic-generated turbulence tends to continuously sweep the traveled lanes and shoulders that were studied in this project.

After the initial pavement and gutter loads are washed off, vehicles traveling on the highway will continue to release pollutant constituents. Pollutants will also be reaching the highway surface from atmospheric fallout and surrounding land-use activities. Because constituents are continuously being added to the runoff, the use of an exponential wash-off equation is not adequate. Instead, a linear approximation is appropriate.

3. No statistically significant correlations at the 5 percent level of significance were found with any of the independent variables examined for the

following constituent loads: boron, cadmium, nitrate-nitrogen, ammonia-nitrogen, total phosphorus, dissolved orthophosphate, oil and grease.

The following constituents exhibited a first flush pattern with relatively insignificant loads and concentrations: sulfate, iron, chromium, copper, manganese, nickel, bicarbonate ion, carbonate ion, calcium, magnesium, chloride, mercury, molybdenum, potassium, silica, and sodium.

RECOMMENDATIONS

The following recommendations are made:

1. Determination of constituent loads for COD, FR, total Pb, TKN, and total Zn from pavement highway surfaces should be made for proposed highway projects where the ADT is at least 30,000 vehicles and a nearby sensitive environmental receptor, such as a stream, river, or lake, exists. These determinations can be made by using Equations 3-10.

2. The regression equations developed in this research can be used for calculating constituent loads from the paved traveled way and shoulder area. To assess the effects of the constituent load on nearby receiving waters, the load must be routed through the drainage system and, ultimately, to the receiving water.

3. The constituent regression coefficients of the equations should be reevaluated in the future as alternative fuel sources and transportation designs, modes, and operations change. Besides quantifying constituent loads, a future monitoring study of transportation runoff waters should include monitoring of vegetation and aquatic life so that mitigation measures can be designed that are compatible with transportation facilities. Also, future studies should assess prior research efforts in this area and be aware of the pragmatic limitations of the research.

ACKNOWLEDGMENTS

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