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ASSESSMENT OF POLLUTANT LOADINGS AND CONCENTRATIONS IN HIGHWAY STORMWATER RUNOFF

A Report Prepared for the
Washington State Department of
Transportation Highway Runoff Water
Quality Research Project

by

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ABSTRACT

This report presents the final form of the Washington State highway runoff pollutant loading model, incorporating data from the five years of study. It also features a probabilistic analysis of concentration and loading data designed to express the chance of exceeding specific values in a given case. Other topics include further assessment of the toxicity of highway runoff and its causes and mitigation.

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INTRODUCTION

While several previous researchers have analyzed and modeled highway runoff quality (Sartor and Boyd, 1972; Sylvester and DeWalle, 1972; Shaheen, 1975; Kobriger et al., 1981), there was reason to believe that the results did not adequately represent Pacific Northwest conditions for impact assessment purposes. Accordingly, the Washington State Department of Transportation funded a comprehensive research effort to improve the understanding of the important controlling factors and model highway runoff pollutant generation and transport for use in impact analysis. Previous work under the program has focused on different facets of highway runoff. Clark (1980) developed a composite sampler allowing continuous storm sampling. Criteria and requirements for statewide runoff monitoring sites were established by Aye (1979). Asplund (1980) identified trends for various pollutants and formulated a predictive model for pollutant loadings. Chui (1981) calibrated this model and determined specific pollutant ratios. Biological effects of highway runoff were examined by Portele (1981). Reduced biological growth and toxicity were related to traffic volumes and seemed to be a function of heavy metal content in the runoff. Wang (1981) conducted mass balances on soils near highways and discovered that metals deposited on well-vegetated surfaces have low mobility. Grassy drainage channels were shown to effectively remove and retain metals.

During the fifth and final year of highway runoff monitoring, the main emphasis was directed towards the three Eastern Washington sites to increase the data base for this region. The Interstate-5 and Vancouver sites also were monitored to obtain samples for several special studies.

Major topics explored during this final year include:

1) Final calibration of the Washington State highway runoff model.
2) Final determination of the relationship between specific pollutants and total suspended solids (pollutant ratios).
3) Error analysis of the model and consideration of factors influencing error magnitude.
4) Frequency and probability distributions of pollutant concentrations and loadings.
5) Nutrient removal capacity of vegetated channels.
6) Comparison of sulphur concentrations in runoff samples from sulphur-extended asphalt pavement with those from other sites.
7) Verification of bioassay results showing potential toxicity of specific pollutants.
8) Precipitation study to determine possible sources for zinc at the Interstate-5 site.

GENERAL EXPERIMENTAL PROCEDURES

Sampling and Laboratory Analyses

Sampling was performed using the composite sampling system and procedures developed by Clark (1980) and described by Clark and Mar (1980) and Clark et al. (1981). The system consisted of a calibrated flow-splitter and collection tank. The flow-splitters were designed for each sampling location to capture a set proportion of the design storm flow, typically 1-2 percent.

Samples were analyzed for total and volatile suspended solids, chemical oxygen demand, total organic carbon, total phosphorus, nitrate+nitrite-nitrogen, and total Kjeldahl nitrogen by the methods documented by Asplund (1980) and Asplund et al. (1981, 1982). Metals (lead, zinc, and copper) were analyzed by inductively coupled plasma instrumentation as described by Wang (1981) and Wang et al. (1982).

A small number of samples from the Interstate 5 site were analyzed for grease and oil using the gravimetric separatory funnel method (number 413.1) of the U.S. Environmental Protection Agency (1979). These analyses were performed at the Municipality of Metropolitan Seattle laboratory.

Samples from a sulfur-extended asphalt pavement at Pullman, as well as samples from a nearby control site, were analyzed for total sulfur using the methylene blue method (Marczenko, 1976).

Data Preparation and Management

All procedures were conducted using the entire project data set. Some adjustments and corrections were made to the data set prior to analysis, as described below.

Certain storms were deleted from the data set for several reasons. Incorrect sampling procedures occasionally allowed storage tanks to overflow and act as sedimentation basins, resulting in artificially elevated total suspended solids loadings. During the winter, road sanding operations introduced extra solids. Mount St. Helens erupted during some sampling periods, and the storm runoff which contained ash was deleted for analysis purposes. A summary of all deleted storms and reasons for deletions are presented in Table 1.

In previous analyses, the Montesano site traffic volumes were estimated approximately. The traffic counter originally used to estimate traffic volumes for this site was located in Olympia, approximately 30 miles away. Asplund (1980) believed that the Olympia counter underestimated traffic volumes at the sampling site and estimated the Montesano volumes as approximately twice those at Olympia. In November 1980 a temporary traffic counter was installed for a week at the Montesano site. Based on a comparison of the Olympia traffic and the Montesano traffic for this period, Chui (1981) multiplied all Olympia traffic volumes by 1.5 to obtain corresponding Montesano traffic volumes. A temporary traffic counter was again installed at the Montesano site in September 1981 to verify these results. Comparison of these traffic volumes with the Olympia traffic volumes for the same time period gave a multiplication factor closer to 1.3. By running a simple linear regression, the following result was obtained:

$$\text{Montesano traffic} = (1.3)(\text{Olympia traffic}) + 166$$

All traffic volumes for the Montesano site were corrected using this equation.

Table 7: Summary of Deleted Storms

Site	Sanding	Volcanic Ash	Overflow	Missing Data
I-5 w/grit	114-120	---	---	1-49, 88, 89
I-5	97-99 114-120	---	---	1-35, 88, 89
I-5*	---	---	---	---
SR 520	15-23	---	---	---
Vancouver	31-33, 39-41, 47, 48, 51-53	58-62	---	93, 96-99
Snoqualmie Pass	5, 7, 8, 23, 24, 26, 29-31, 36	---	41, 43	---
Montesano	6, 8-14, 16-25, 45, 46, 53, 54	26-28, 30, 32, 39	42, 43, 50, 51, 55, 56, 61, 62, 64, 66, 68, 69	70, 71
Pasco	5-12, 28, 30, 31	17, 18		37-41
Spokane	---	---	---	14-17
Pullman-9	20, 21, 27	11-13		1, 4-6, 10, 28, 30
Pullman-C			40, 43, 44	1-6, 8, 10-37

CALIBRATION AND ANALYSIS OF THE WASHINGTON STATE HIGHWAY RUNOFF LOADING MODEL

The Washington State Highway Runoff Model (Asplund, 1980; Asplund et al., 1981, 1982) predicts total suspended solids loading in proportion to the product of runoff coefficient and vehicles traveling during storm, and as follows:

$$TSSL = (K)(VDS)(RC)$$

Where TSSL = total suspended solids loading (lb/curb mile)

VDS = vehicles traveling during storms (1000 vehicles)

RC = runoff coefficient

K = TSS runoff rate (lb TSS/curb mile-1000 VDS)

Other pollutant loadings are predicted with the use of pollutant ratios (the ratio of pollutant to total suspended solids):

$$SPL = (K_p)(TSSL)$$

where SPL = specific pollutant loadings (lb/curb mile)

K_p = specific pollutant ratio

This section will discuss final calibration of the model using the full project data set and an analysis of its prediction error.

TSS Loading Model

The TSS runoff rate K was determined for each sampling site by linear regression. Cumulative loading of total suspended solids per unit area or curb mile length was regressed against cumulative vehicles during storms to determine the slope K and y-intercept. On the basis of previous experience, the sites were divided into Eastern and Western Washington groups. The TSS runoff rate was calculated for each group as follows:

$$K = \sum_{i=1}^{n} \frac{K_i/RC}{n}$$

where i = site number of sites in each group

n = number of sites in each group

RC = runoff coefficient

The standard deviation and standard error for K also were computed.

TSS in highway runoff was hypothesized to originate from vehicles travling during storms and from build-up during dry periods (Asplund, 1980; Asplund et al., 1980, 1982). The contribution of passing vehicles alone was estimated using the I-5 data. This quantity was designated K_{car}. Storms from the I-5 site were grouped together according to the following framework:

1) A one-inch storm was assumed to clean the highway of fallout and accumulated pollutants.
2) A 48-hour maximum total grouped storm duration was selected to minimize the pollutant contributions from atmospheric fallout and transport from adjacent lands.
3) Predicted values from the Washington State Highway Runoff Model were compared to the observed loadings of the grouped storms. Storm groups with a 50 percent error or greater showed predictions that were too high, presumably due to the contributions of the passing vehicles.

All events in the interval between storms of one inch of rainfall or greater were combined, while the one inch or greater storms were considered separately. The storms used for the K_{car} calculation had a total duration of less than 48 hours and a 50 percent or greater error. The K_{car} factor for each selected storm group was calculated as:

$$K_{car} = \frac{TSS}{(VDS)(RC)(LENGTH)}$$

where TSS = total suspended solids observed (pounds)

LENGTH = curb length of drainage (mile)

Based on a simple arithmetic average, K_{car} for Western Washington approached 3 lb TSS/curb mile-1000 VDS. The Eastern Washington data were insufficient for a similar analysis.

The TSS runoff factor, K, was calculated by linear regression in units of lb TSS/curb mile-1000 vehicles and lb TSS/acre-1000 vehicles. All coefficients of determination, R^2, were quite high, showing a good linear relationship between cumulative vehicles during the storm and cumulative total suspended solids.

The TSS runoff rates and runoff coefficients for Eastern Washington and Western Washington each were grouped within small ranges of values, with Eastern Washington TSS runoff rates being substantially higher than those for Western Washington. Simple arithmetic averages were used to calculate the overall TSS runoff rates. Tables 2 and 3 list the final K values, the standard deviations, and the standard errors for Western and Eastern Washington, respectively. The TSS runoff rate $\pm$ one standard error for Western Washington was 6.4 $\pm$ .85 lbs TSS/curb mile-1000 VDS or 1.1 $\pm$ .24 lbs TSS/acre-1000 VDS. For Eastern Washington the factor was calculated as 26.3 $\pm$ 2.02 lbs TSS/curb mile-1000 VDS or 6.4 $\pm$ 1.75 lbs TSS/acre-1000 VDS. These values are in close agreement with previous researchers (Asplund, 1980; Chui, 1981).

Table 2: Final TSS Runoff Rate K (lb/curb mile-1000 VDS)

lb/curb mi basis

Region	Sites Included	Ave. K (lbs/curb mi-1000 VDS)	Standard Deviation	Standard Error
Western Washington	I-5 with grit I-5 no grit I-5* SR 520 Vancouver Snoqualmie Pass	6.4	2.08	.85
Eastern Washington	Pasco Spokane Pullman-9	26.3	3.49	2.02

Table 3: Final TSS Runoff Rate K (lb/acre-1000 VDS)

<u>lb/acre basis</u>

Region	Sites Included	Ave. K. (lbs/acre-1000 VDS)	Standard Deviation	Standard Error
Western Washington	I-5 with grit I-5 no grit I-5* SR 520 Vancouver Snoqualmie Pass	1.1	.59	.24
Eastern Washington	Pasco Spokane Pullman-9	6.4	4.30	1.75

There have been questions concerning the units for the TSS runoff rate K. The most common units for pollutant loading rates used in the literature are mass per unit area-time or mass per unit length-time. In the case of highways, units incorporating traffic volume frequently are used, such as mass per unit area-vehicle or mass per unit length-vehicle. Units of K were reconsidered to evaluate whether those best representing the data were selected.

For this analysis the TSS runoff rate was calculated twice, once using lb per curb mile-1000 vehicles and again using lb per acre-1000 vehicles. Figures 1 and 2 illustrate the relationship between TSS runoff rate expressed in each unit and number of traffic lanes for Western Washington sites. Similar graphs were plotted for Eastern Washington stations. As the number of traffic lanes increased, the TSS runoff rate, expressed on an area basis, decreased. In other words, for a given area and traffic volume, the TSS runoff rate decreased as the number of lanes increased. TSS runoff rate expressed on a curb mile basis was relatively constant and seemed independent of the number of traffic lanes. The Washington Highway Runoff Model operates on the assumption that, for a given traffic volume, there is a specific TSS runoff rate that should not vary as the number of traffic lanes varies. These results suggest that the pollutant removal efficiency of the third or fourth lane from the curb is minimal. Pollutants that fall from vehicles or are delivered via atmospheric fallout to the lanes furthest from the curb are splashed or blown off the highway or back onto the vehicles; they are not removed from the highway by stormwater runoff. Therefore, the TSS runoff rate for use in the Washington State Highway Runoff Model has the units of lbs TSS/curb mile-1000 VDS. These units are more sensitive to the actual deposition and removal processes that determine stormwater runoff loads.

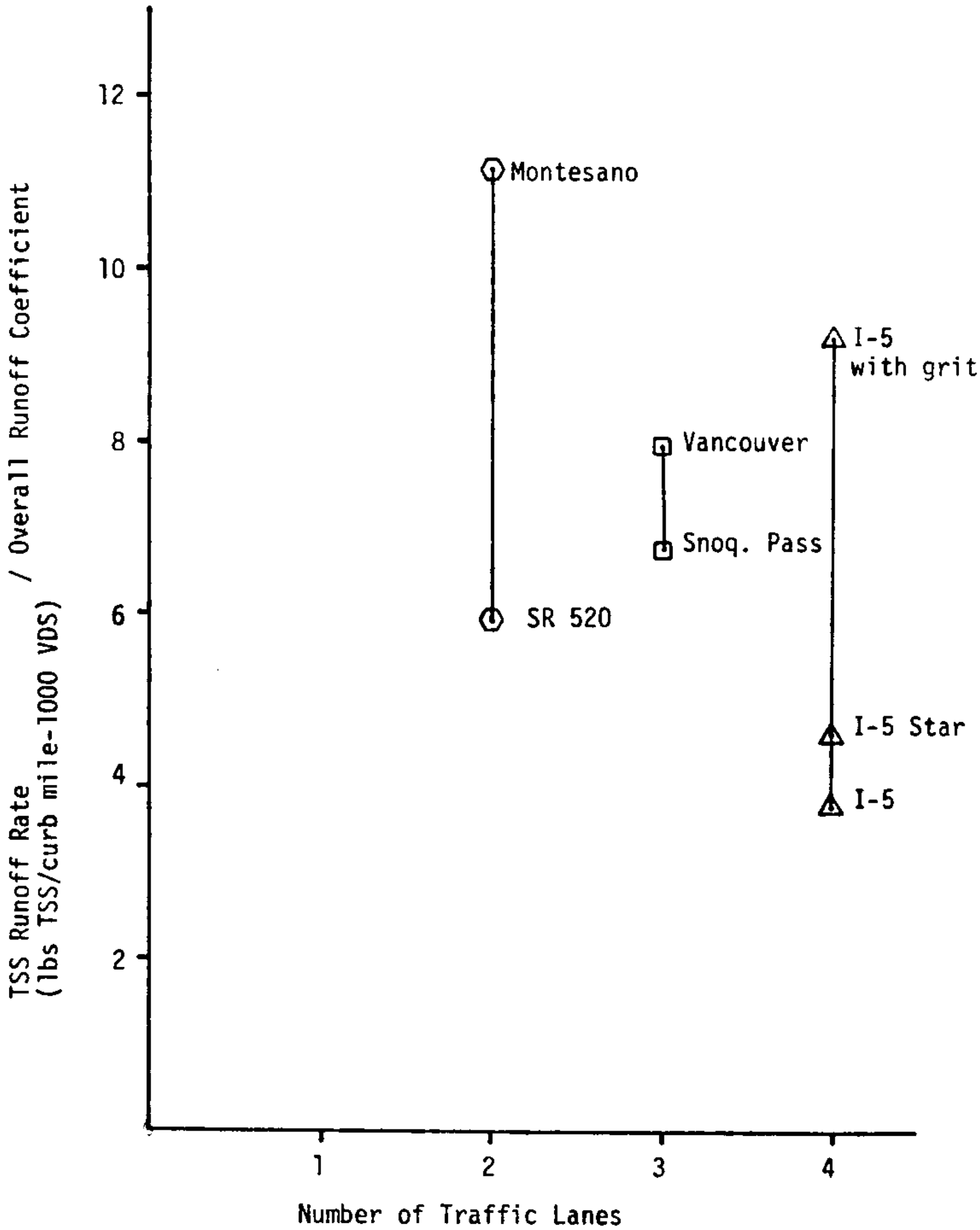

Figure 1: TSS Runoff Rate (lbs/curb mile-1000 VDS) Versus Number of Traffic Lanes for Western Washington Sites

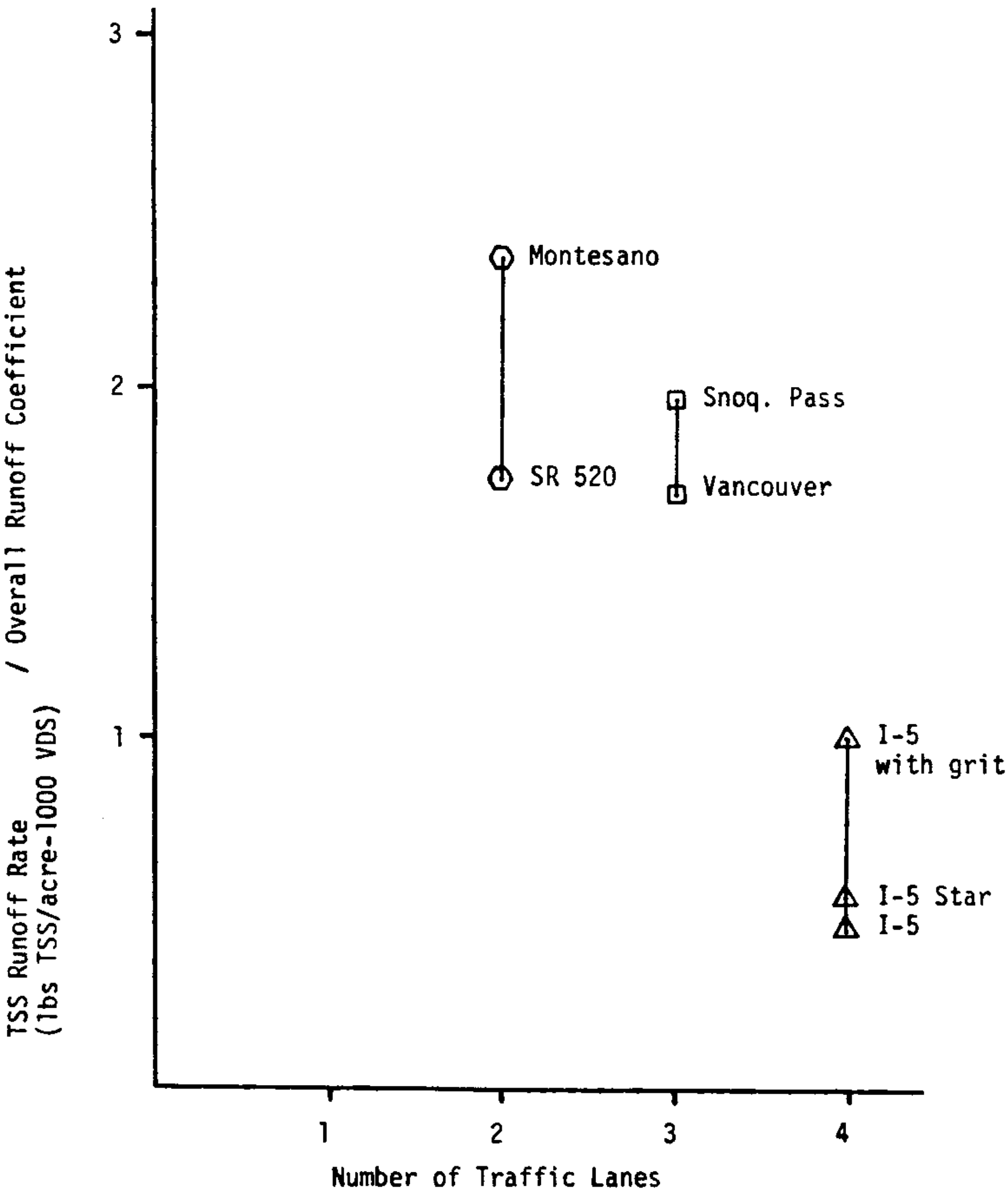

Figure 2: TSS Runoff Rate (lbs/acre-1000 VDS) Versus Number of Traffic Lanes for Western Washington Sites

The overall Eastern Washington TSS runoff rate was much larger than that for Western Washington. Since the Eastern Washington sites experienced a much lower traffic volume, the larger TSS runoff rate is due to other contributions, such as atmospheric fallout and loading from adjacent lands. Much of the land in Eastern Washington is used for agricultural purposes, which can increase TSS contributions from adjacent lands. Data were obtained for total suspended particulates in the atmosphere at the air pollution monitoring station closest to each highway runoff sampling station (Washington State Department of Ecology, 1981; Puget Sound Air Pollution Control Agency, 1980). The Eastern Washington sites consistently showed higher suspended particulate measurements than Western Washington sites (1980 geometric means ranging 79-114 $\mu g/m^3$ at three Eastern Washington locations versus 12-54 at five Western Washington stations). These figures suggest a higher TSS deposition potential from the atmosphere for Eastern Washington sites and the likely explanation for the high TSS runoff rate for the region.

Specific Pollutant Ratios

The specific pollutant ratios K_p were determined by plotting the specific pollutant load against the total suspended solids load. Linear regression with the y-intercept forced to zero was used to establish the regression line for the plot. This method removes the y-intercept from the analysis and allows a direct comparison of the slopes, K_p, for all sites. Scatter plots of the various pollutants versus the TSS loading demonstrated that, as TSS was reduced, the pollutant loading also was decreased. Since a majority of the specific pollutants were associated with the particulate fraction, total removal of TSS would lead to very low specific pollutant loads. Most coefficients of determination for the regressions were greater than 0.9, showing that the variability of the data can be described by the regression line forced through the origin (Dunn and Clark, 1974).

By visual inspection of the specific pollutant ratios and average daily traffic data, it was seen that volatile suspended solids, chemical oxygen demand, nitrate + nitrite-nitrogen and total phosphorus ratios were relatively constant. These pollutant ratios were site- and traffic-independent. The heavy metal ratios showed a positive relationship with average daily traffic (ADT). Regression of these ratios against ADT produced coefficients of determination exceeding 0.85 in all but one case, indicating a strong linear relationship between the heavy metal ratio and average daily traffic. The total Kjeldahl nitrogen ratio seemed to be constant for Western Washington sites and lower but constant for Eastern Washington sites. The overall specific pollutant ratios are summarized in Table 4.

Model Validation

An analysis of the Washington State Highway Runoff Loading Model was conducted to determine trends and patterns of predicted versus actual solids loadings for individual and grouped storm events and to establish factors that reduce the discrepancies. Because the same data used in model development also were employed in this analysis, it does not provide a true representation of model error but rather fit with observed values at one site. The I-5 without grit data set was used because it was the most complete available offered continuous storm data. The predicted total suspended solids was obtained from the model as:

$$PTSSL = (K)(VDS)(RC)(LENGTH)$$

Table 4: Summary of Overall Specific Pollutant Ratios

Pollutant	Expression	Specifications	R^2
Volatile Suspended Solids	$K_{VSS} = .17$	For all sites.	
Chemical Oxygen Demand	$K_{COD} = .43$	For all sites.	
Lead	$K_{Pb} = 1.45*10^{-4} + 8.65*10^{-8}*ADT$	For Western sites.	.978
	$K_{Pb} = 5.32*10^{-4} + 2.75 \times 10^{-8}*ADT$	For Eastern sites.	.996
Zinc	$K_{Zn} = 1.45*10^{-4} + 3.01*10^{-8}*ADT$	For Western sites.	.864
	$K_{Zn} = 1.97*10^{-4} + 3.21*10^{-7}*ADT$	For Eastern sites.	.932
Copper	$K_{Cu} = 7.93*10^{-5} + 2.70*10^{-9}*ADT$	For all sites.	.739
Total Kjeldahl Nitrogen	$K_{TKN} = 2.68 \times 10^{-3}$	For Western sites except Vancouver.	
	$K_{TKN} = 1.21 \times 10^{-3}$	For Eastern sites.	
Nitrate-Nitrite	$K_{NO_3-NO_2} = 2.01 \times 10^{-3}$	For all sites.	
Total Phosphorus	$K_{TP} = 2.10 \times 10^{-3}$	For all sites.	

where: PTSSL = predicted total suspended solids load (lbs)

K = 6 lbs TSS/curb mile-1000 VDS

The analysis was performed on the I-5 site individual, grouped, and cumulative storm data. Storms were grouped as described earlier. Chui (1981) discovered that deviations of predicted loadings versus actual measurements fluctuated between positive and negative and suggested that the discrepancies could be reduced by considering storms grouped by frontal system. The fit was defined as the predicted load minus the observed load, and the percent deviation was defined as the fit divided by the observed load. The fit, percent deviation, cumulative fit and cumulative percent deviation were plotted against time, number of vehicles passing during storms, and total traffic passing during the sampling period to determine trends in the model error. The University of Washington SIMPLOT plotting routine available at the Academic Computer Center was used to obtain the plots.

The full set of plots is available in Little (1982). Figure 3 illustrates one result using individual storm data. Such plots indicated that the model generally overestimates individual storm TSS loadings. The pattern of fit did not differ significantly whether plotted against total traffic, traffic during storms, or time.

For grouped storm data the model predictions were much closer to the observed TSS loads. The magnitude of the maximum deviation was greater than with the individual storm data, but the fit and percentage deviation fluctuated more closely around zero.

Study of the graphs for the cumulative data set indicated no difference in the cumulative fit or cumulative percent deviation pattern whether plotted against cumulative vehicles during storms or time. As the number of vehicles or time increased, the fit between predicted and observed loadings steadily

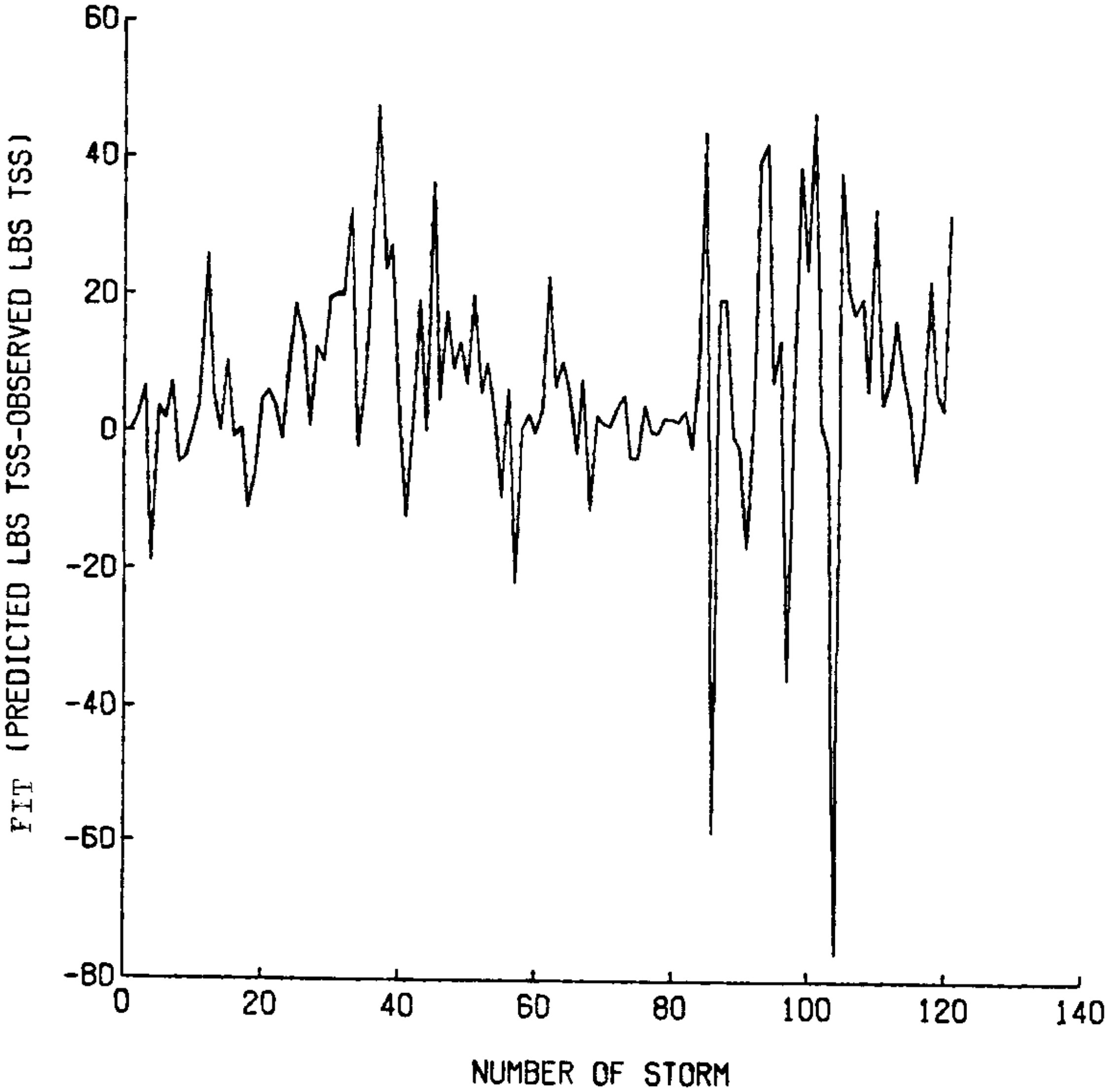

Figure 3: Fit **Versus Time for TSS Loads for the I-5 Individual Storm Data**

decreased. It decreased in a more linear, constant fashion when plotted against vehicles during storms. A better fit resulted when the cumulative percent deviation was plotted against increasing cumulative vehicles during storms or time. The average cumulative percent deviation seemed to approach a value of approximately 70-80 percent for the I-5 site.

Many factors influenced the fit of the data. Storms with large discrepancies usually were associated with precipitation of low intensity, short duration, or occurring after sanding operations. The deviation decreased when storms were grouped by storm front. Grouping storms reduces the error introduced by varying storm intensities and durations within frontal systems.

Measurements of the parameters used in the model, such as VDS and runoff coefficient, also can increase the overall deviation. The runoff coefficient is variable and is affected by wind, traffic, and the geometry of the drainage area. Accurate determination of an overall runoff coefficient for use in the model is important in evaluation of fit. The overall runoff coefficient at the I-5 site ranged from 0.11 to greater than 1.0, with a mean of 0.72. Use of a coefficient of 0.62, i.e., assuming RC was overestimated by 0.10, decreases the average percent deviation by 25 percent. Therefore, for a small range in runoff coefficient values, the model gives results with a large range in fit.

There also are systematic and random errors associated with the VDS values. Equipment malfunction may produce inaccurate counts. Some vehicles may be able to leave or enter the highway before being counted due to the location of the traffic counters. Hourly tabulations of traffic volumes were the finest time increment available at many sites, which makes traffic volume estimation on a smaller time scale impossible. The VDS factor includes traffic that passed during small amounts of rainfall, which may not wet the pavement enough to enhance pollutant transfer to or from the vehicles. In this case the predicted loadings would be higher than the observed loads.

Predicted TSS loadings were computed for the I-5 storm set using actual runoff coefficients observed in each event. Figure 4 shows a plot of cumulative percentage deviations for these predictions. This graph indicates that deviations were relatively high for few events but decreased over a longer time span. The prediction for the full period was low by 11.4 percent.

The relatively small discrepancies resulting when storms were grouped by fronts and, even moreso, accumulated over a number of storms, demonstrates that the greatest utility of the model is in forecasting total loadings over an extended period. This outcome was expected, since cumulative data were used in model development. The sensitivity of the model to runoff coefficient suggests that predictions could be improved by correcting K for a specific site using a factor appropriate to the site if available.

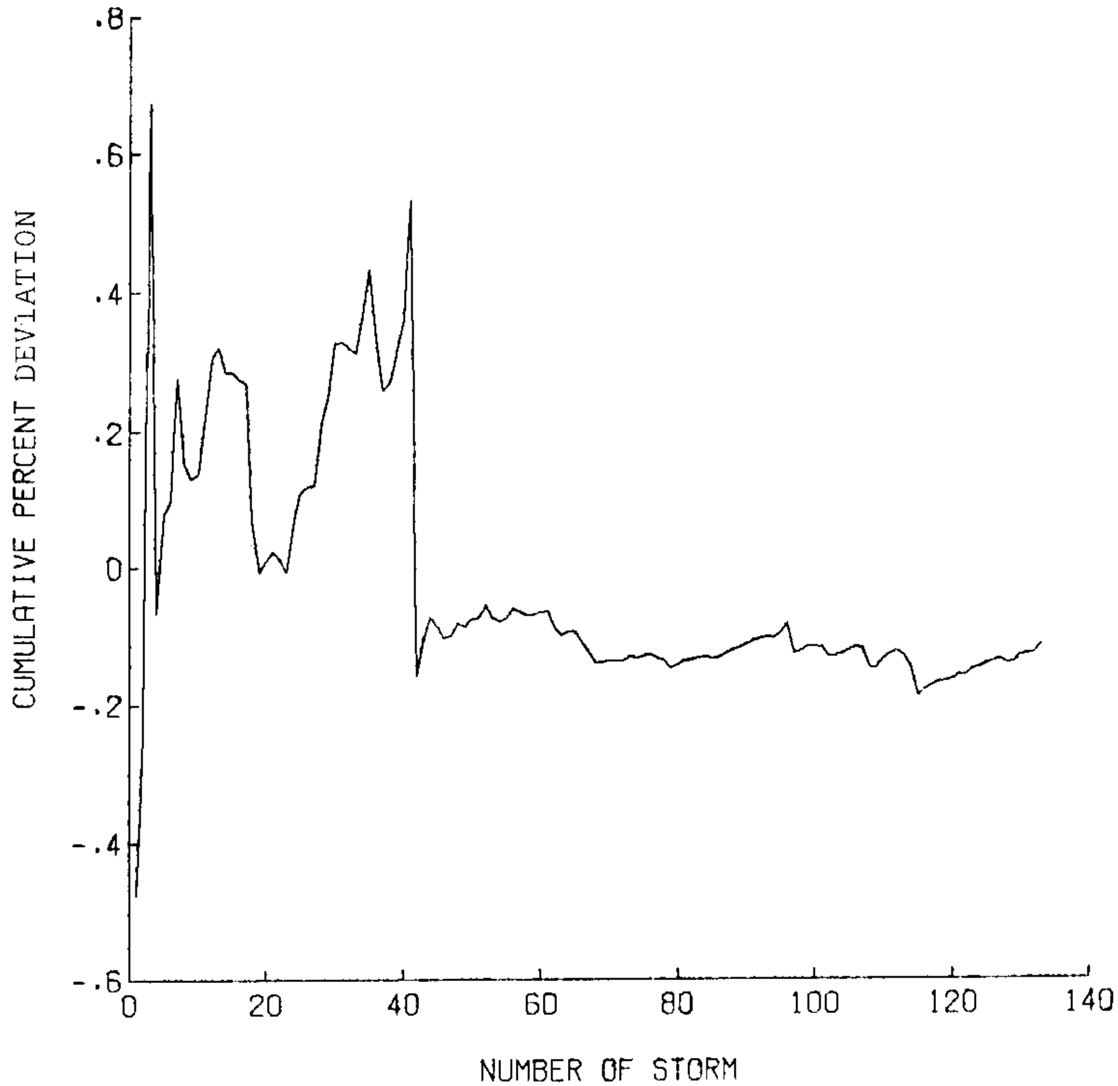

Figure 4: Cumulative Percent Deviation Versus Time for TSS Loads at I-5 Site, Using Actual Runoff Coefficients

FREQUENCY AND PROBABILITY DISTRIBUTIONS

In addition to long-term pollutant loadings, it is desirable to have some knowledge of individual event concentrations, which can cause acute impacts on aquatic biota. With highly variable data, the best strategy to gain this understanding is to establish the underlying probability distributions. The Nationwide Urban Runoff Program (NURP) (U.S. Environmental Protection Agency, 1982) established that a log-normal distribution described stormwater pollutant concentration and loading data from 38 sites representing 12 geographical areas nationwide. The data base represents 824 separate storm events. Each observation was based on a flow-weighted average concentration of a pollutant in a particular storm event.

The log-normal distribution, in simple terms, is the distribution of a variate whose logarithm obeys the normal law of probability. If the data follow the log-normal distribution, then determinations made using a Gaussian assumption are invalid. For the log-normal distribution the geometric mean is preferred to the arithmetic mean as a measure of central location (Aitchison and Brown, 1969). Although log-normal distributions have not been applied widely to water quality constituents, there are many examples of such distributions in nature.

Procedure

A log-normal distribution was investigated for the highway runoff pollutant concentrations. First, cumulative frequency tables and plots were made for each site. Data were then grouped by geographical area, magnitude of rainfall, land use and traffic volume. The sites were divided into Eastern and Western Washington and high- and low-traffic cases.

The probability graphs were plotted on log-probability paper. The actual percentage of values greater than a given concentration was plotted versus the concentration. Percent greater than "x" was calculated from the grouped cumulative frequency data as:

$$\%\ \text{greater than x} = \frac{\text{cumulative frequency greater than "x"}}{N}$$

where: x = any given concentration

N = total number of storms for the group

The graphical representation was used as a qualitative indication of log-normality. Log-normal data describe a straight line on such a plot. A similar analysis was performed on the TSS loading data.

Results of the Analysis

Cumulative frequency tables and histograms were prepared from the data for each site used in the analysis. These tables were used for visual confirmation of possible patterns and distributions. Figure 5 illustrates the cumulative frequency for TSS at the Interstate-5 site. The shape of the histogram and the pattern of the TSS concentrations shown are typical of all sites.

An example of a log concentration-probability graph is shown in Figure 6. Figure 7 displays the TSS mass loading probability distribution for Western Washington. Probability graphs for all cases are contained in Little (1982).

The TSS concentration, TSS mass loading and volatile suspended solids probability plots represent extensive data and closely approximate straight lines, showing a strong log-normal population distribution. For these plots, the high, low and combined traffic probability distributions are essentially parallel.

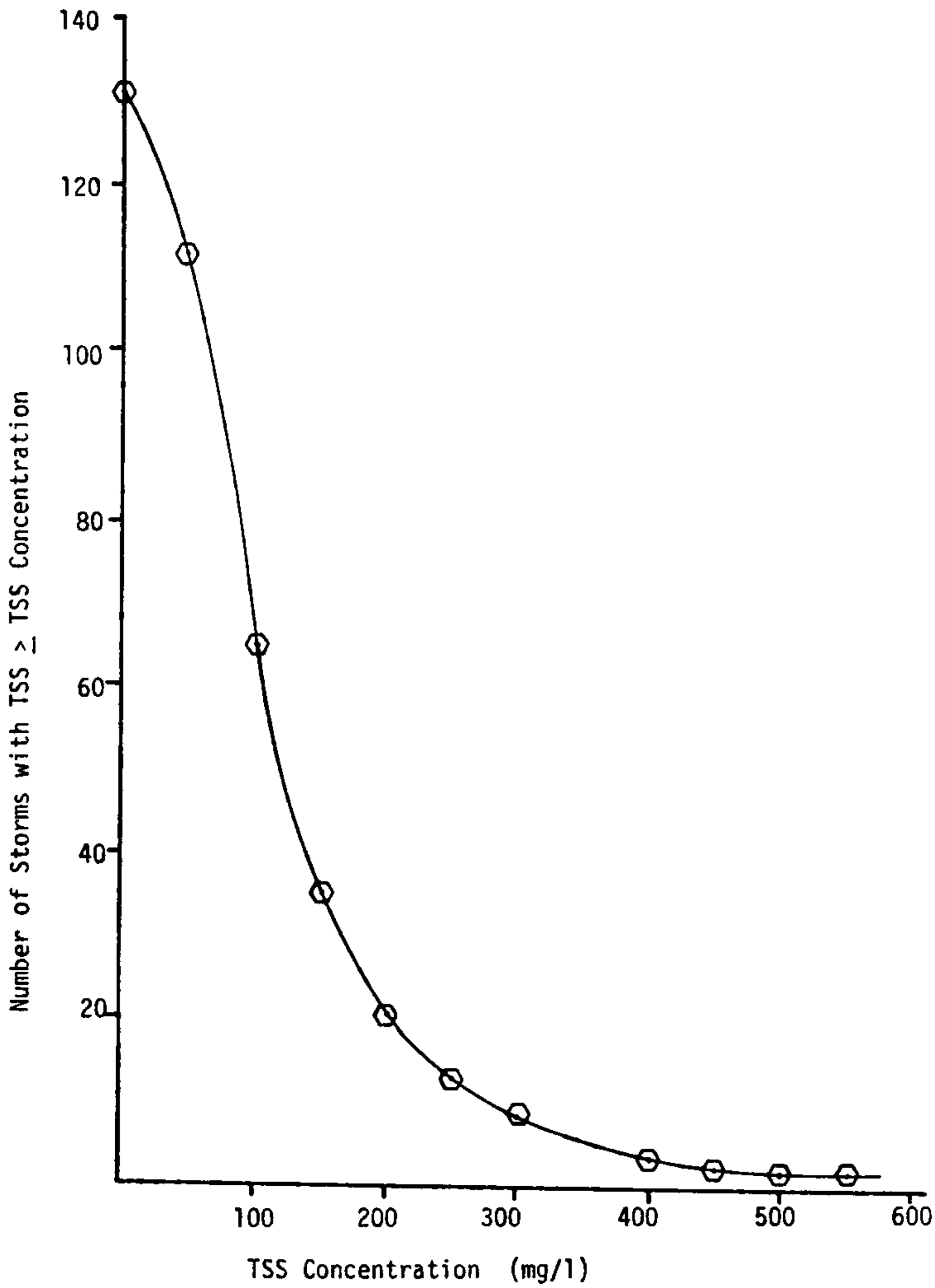

Figure 5: Cumulative Frequency of TSS Concentration for the I-5 Site

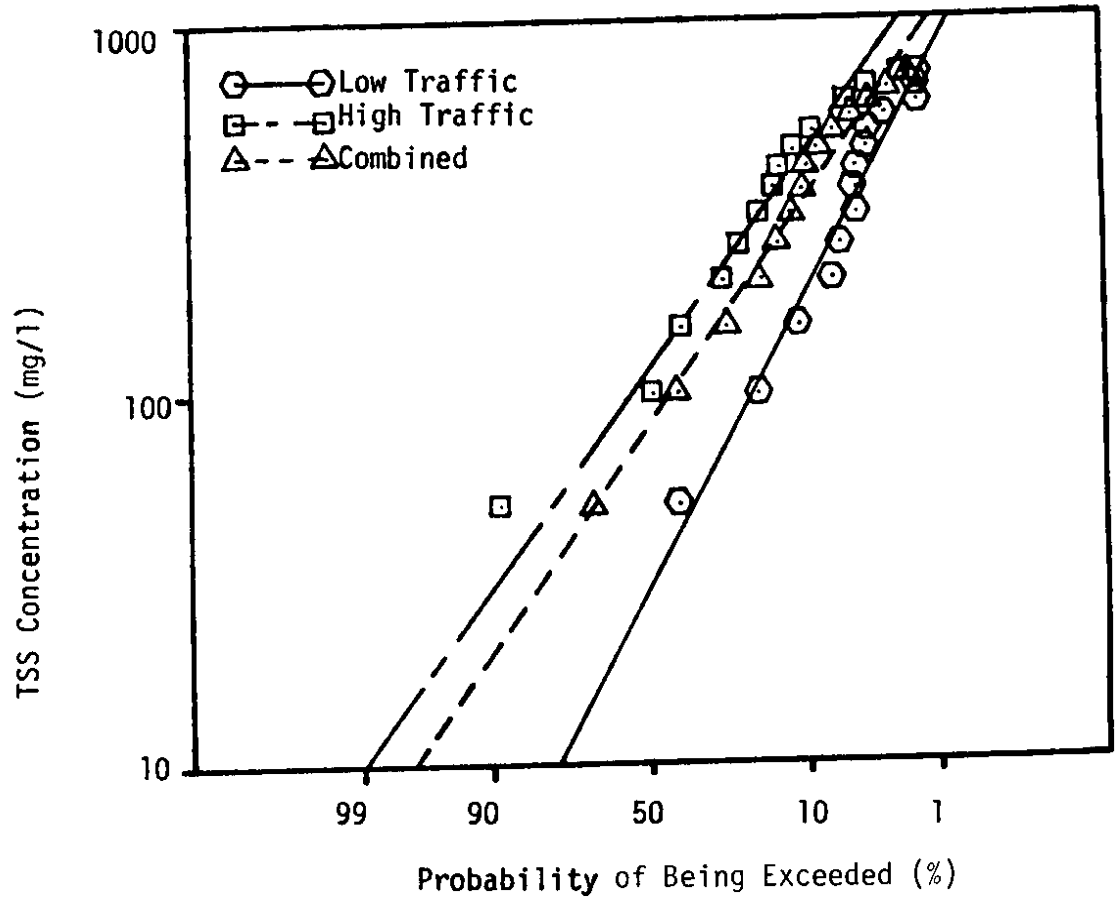

Figure 6: Probability Distribution of TSS Concentration for Western Washington Sites

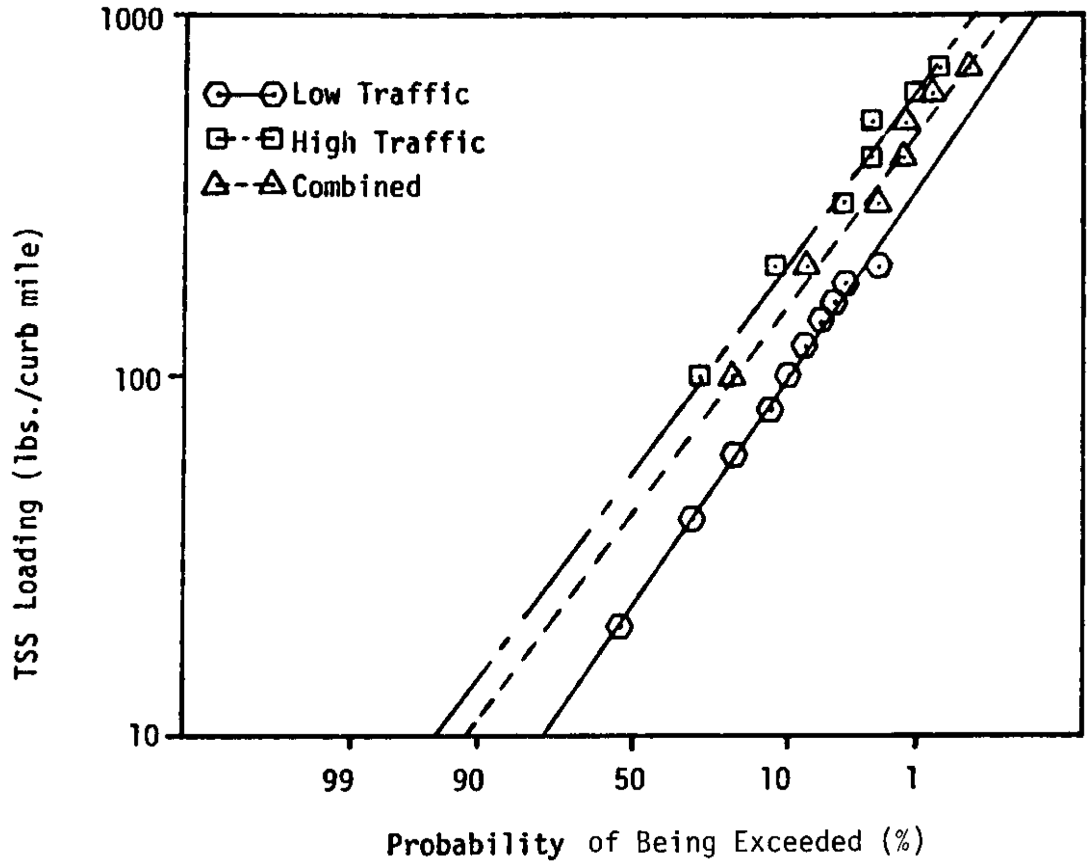

Figure 7: Probability Distribution of TSS Loading for Western Washington Sites

The probability plots for the nutrients, metals and chemical oxygen demand are not as close to linear as the TSS graphs. The data for these pollutants are not as continuous nor as extensive as those for TSS. For these pollutants, the Western Washington probability graphs are more uniform and approximate straight lines to a higher degree than the Eastern Washington cases.

As the final step in this analysis, the log concentration-probability distributions for each contaminant were plotted separately for Eastern and Western Washington high- and low-traffic cases. Parallel curves were added to these graphs representing pollutant reductions of various amounts. These reductions could be achieved by treatment, dilution by receiving waters, or a combination of the two. When available, water quality criteria were added to the graphs to serve as a basis for judgment of effect and impact assessment. Figure 8 provides an example of such a plot.

Horner and Mar (1982) used the Washington State Highway Runoff Loading Model and the individual event probability relationships and incorporated them into a guide for assessing impacts of highway runoff. These tools can be used to assess impact by determining loadings of the various pollutants on a long-term cumulative basis and concentrations and loadings on a probabilistic basis for individual storms. Highways that produce large quantities of pollutants may be pinpointed quickly and treatment of the runoff may be recommended. Changes in pollutant concentrations or loadings caused by highway expansions can be calculated readily. Biological and physical impacts of highway runoff on lakes and streams can be defined on both a long- and short-term basis, aided by criteria that have been established previously.

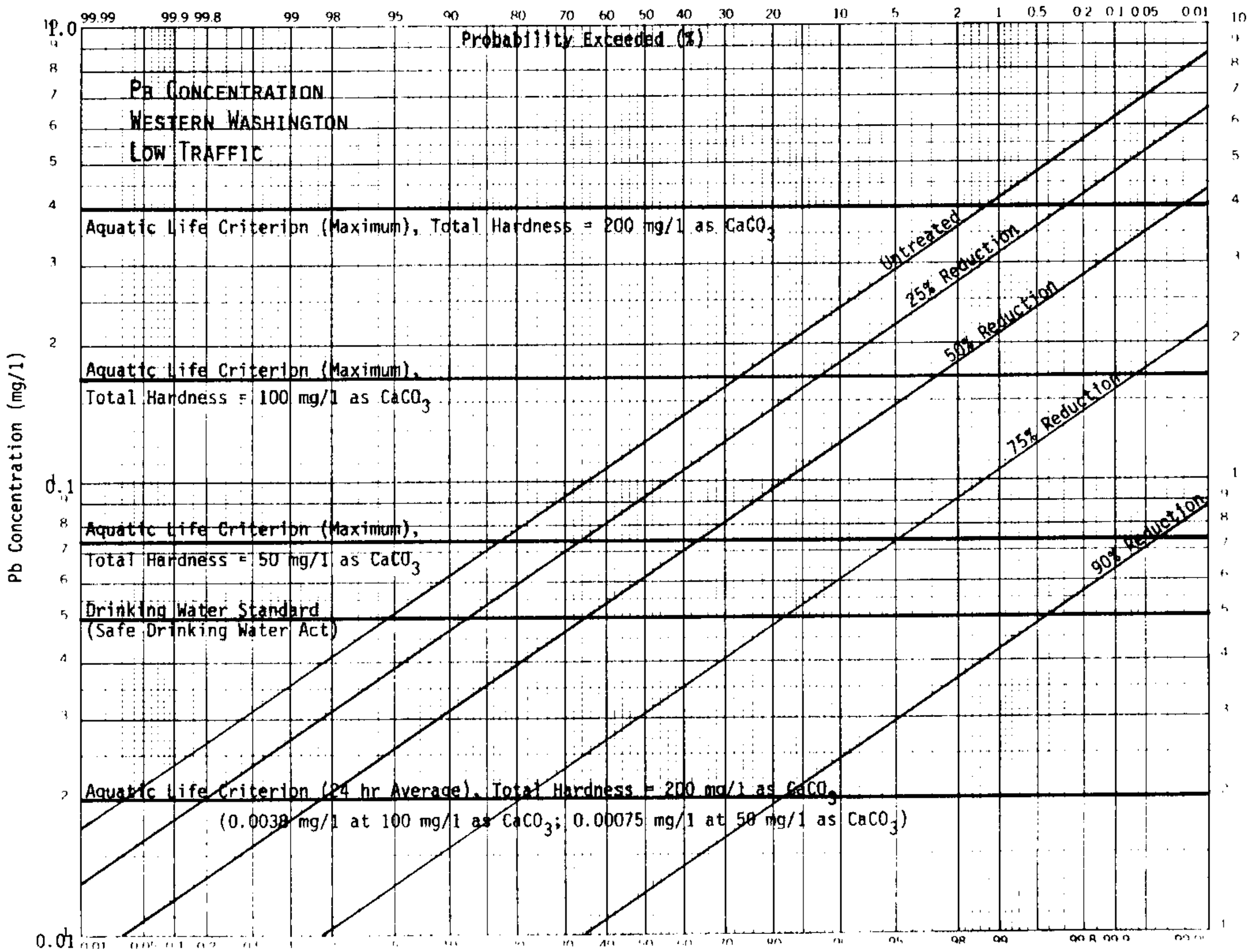

Figure 8: Lead Concentration - Probability Distribution for Western Washington Low Traffic Cases

SPECIAL STUDIES

Pollutant Reduction by Vegetated Channel Drainage

Wang (1981) and Wang et al. (1982) discovered that vegetated drainage channels effectively captured and retained solids and metals from highway runoff water. Removal efficiency increased as flow path length was increased. However, mud or paved channels showed insignificant ability to remove metals from the runoff.

Most municipal wastewaters contain large concentrations of nutrients, and nitrogen and phosphorus can cause eutrophication when discharged to surface waters. Grass filtration has been shown to be effective in removing nitrogen and phosphorus from wastewater. Khalid et al. (1981) demonstrated that grass filters were especially effective in removing nitrogen, but phosphorus removal efficiency varied over a wide range. Results indicated the presence of an aerobic-anaerobic zone in the soil that enhances nitrification-denitrification processes and leads to larger nitrogen losses to the atmosphere. The plant uptake of nitrogen accounted for 23 - 62 percent of the applied ammonium-nitrogen. Initial phosphorus removal and retention were high; but after long periods of flooding of the soil, the phosphorus sorption capacity markedly decreased. This decrease was accompanied by an increase in phosphorus mobility. The phosphorus removal efficiency was greatly enhanced by addition of lime to the soil.

A limited study was undertaken to investigate the nutrient and grease and oil removal capacity of vegetated channels. Highway runoff was diverted to a grassy channel adjacent to Interstate-5. Immediately after a storm, samples were carefully removed from the channel at a distance of 73 meters (240 feet) from the diversion. Samples also were taken from the composite storage tank upstream of the channel for comparison. Seven samples were collected from each point between September and November of 1981 for nutrient analyses, and three sample sets were tested for grease and oil (U.S. Environmental Protection Agency, 1979).

Prior to November, the nutrient concentrations in water taken from the vegetated channel were less than those in the samples from the storage tank. Total phosphorus, nitrate+nitrite-nitrogen and soluble reactive phosphorus all exhibited concentrations in the samples from the vegetated channel at least 20 percent lower than those upstream of the channel. Total and volatile suspended solids concentrations also showed decreases of at least 65% in the samples from the vegetated channels. The last two samples, taken on November 1 and 20, had higher soluble reactive phosphorus in the vegetated channel sample than in the sample from the storage tank. Total phosphorus, however, remained lower at the end of the channel.

Nutrients are removed in overland flow by reducing the solids in the stormwater and by plant uptake. Possible reasons for the decrease in nutrient removal efficiency exhibited by the last two samples include reduced vegetation growth in the fall and decomposition of dead plant material, releasing stored nutrients. Khalid et al. (1981) also observed that with prolonged flooding of the soil, such as would occur during the fall and winter rains, phosphorus removal and retention decreased.

The samples tested for grease and oil exhibited the following results:

	Oil and Grease (mg/l)	
Date of Storm	Composite Tank	Vegetated Channel
1/25/82	12.0	0.8
1/26/82	17.4	4.6
2/01/82	10.0	3.3

Oil and grease removal efficiencies thus ranged from 67 to 93 percent, although the tests were performed during the winter.

The nutrient and oil and grease studies represent too few data points on which to draw conclusions. The results, nevertheless, suggest that vegetated channels could serve to reduce pollutants in categories other than solids and metals, which were demonstrated in more extensive studies earlier.

Algal Bioassays

The effects of heavy metals on algae have been studied thoroughly. Lead and zinc, particularly, seem to be responsible for inhibition of algal growth. Winters and Gidley (1980) found that inhibition occurred in bioassays exposing algae to highway runoff when the total metal content, excluding iron, consisted of 80 - 95 percent lead and zinc.

Portele (1981) and Portele et al. (1982) showed reduction in algal biomass as the proportion of highway runoff in the sample increased. Bioassays run on highway runoff samples from Interstate-5 resulted in biomass yields significantly less than the controls. Algal bioassays also were performed on samples from the I-90 Snoqualmie Pass and SR-520 sites. A comparison of the results from these three sites indicated no apparent toxicity in either SR-520 or the I-90 samples. The absence of toxicity in the I-90 samples was expected on the basis of the lower traffic volume at the site. The traffic volume on SR-520, however, is comparable to I-5. Subsequent chemical analyses revealed higher zinc concentrations in the I-5 samples. Soluble copper was also significantly higher in the I-5 samples, suggesting a possible synergistic effect between copper and zinc. Other researchers have documented possible synergistic effects between metals. Braek (1976) found that the toxicity of copper and zinc together could not be accounted for by the toxicity of the two metals alone. There is also evidence of synergistic and antagonistic effects between other metal combinations (Christensen, 1979).

Additional algal bioassays were conducted on samples from I-5, Spokane and Pasco to confirm previous observations and to represent Eastern Washington conditions. Samples were transported by air in coolers packed with ice and vermiculite. Upon delivery they were filtered immediately and then frozen until analysis. Chemical analyses performed on samples included pH; nitrate+nitrite- and ammonia-nitrogen; dissolved lead, copper and zinc; and soluble reactive phosphorus (Strickland and Parsons, 1972). The algal bioassay procedure followed the method of Miller et al. (1978). Portele (1981) provided details of the technique.

Figures 9 illustrates algal bioassay results for one sampling site. Similar graphs for all sites were presented by Little (1982). All tests exhibited a pattern of reduced algal biomass as the fraction of highway runoff increased. The bioassay conducted with water from the I-5 vegetated channel resulted in significantly better growth at all dilutions than in the test performed with runoff directly from the highway. The direct runoff sample had a dissolved zinc concentration more than twice that in the grassy channel, and other metals also were substantially higher. Portele (1981) and Portele et al. (1982) reported on the comparative toxicity to rainbow trout fry of direct highway drainage versus vegetation-filtered runoff, observing considerably greater mortality in bioassays using direct runoff.

The Pasco and Spokane bioassays exhibited a long lag before heavy growth occurred but, ultimately, much higher biomass than I-5 samples. Nutrient concentrations were considerably higher in these Eastern Washington samples. The lag may have been due to adjustment by the algal cells to these high nutrient concentrations.

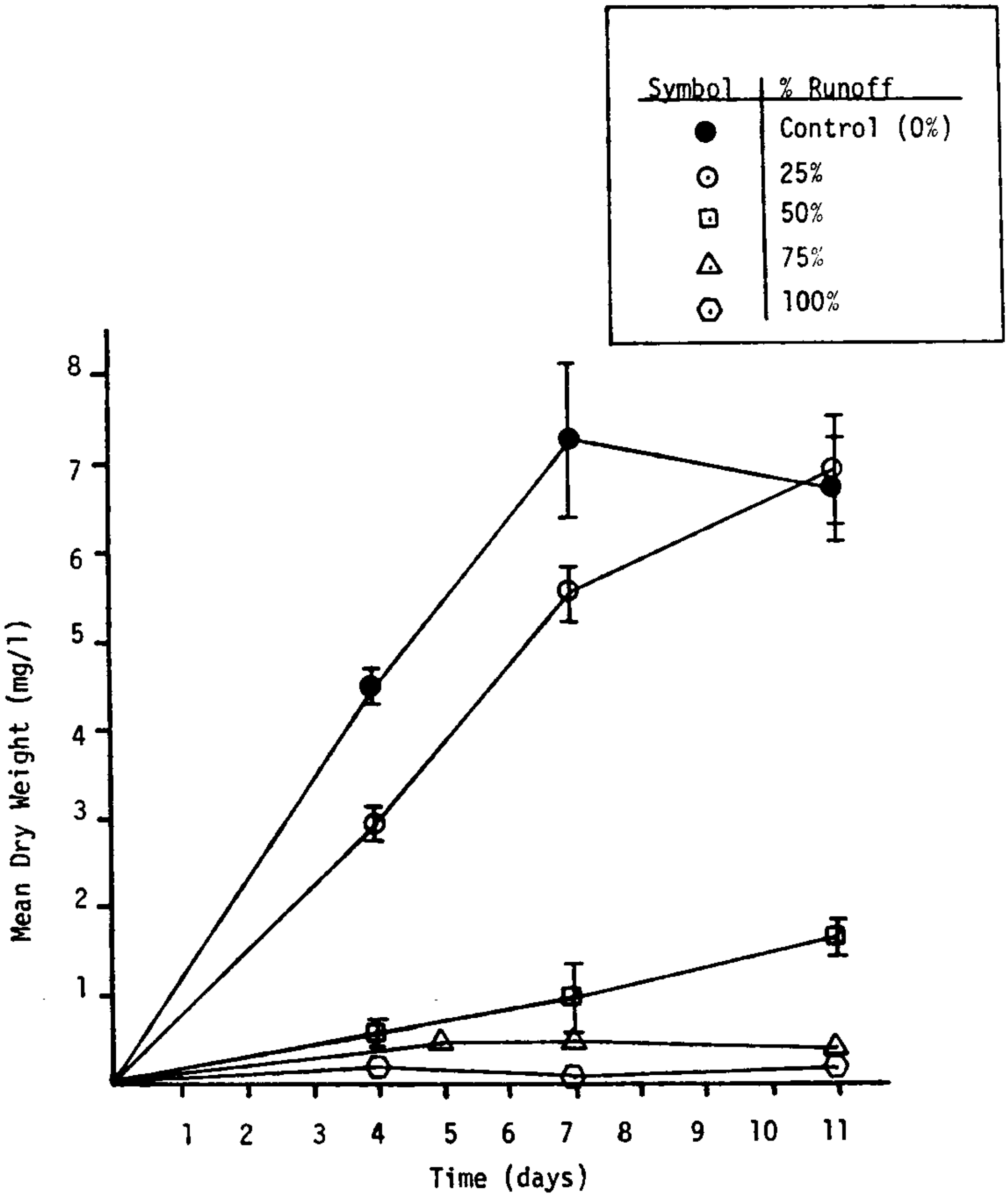

Figure 9: Mean Dry Weight of Selenastrum capricornutum Exposed to Storm Runoff From Interstate 5 (± one standard error)

Analysis of Heavy Metals in Precipitation

Previous results showed higher metal concentrations, particularly zinc, in I-5 runoff than in samples from SR-520, which has a comparable traffic volume. I-5 runoff also was considerably more toxic to aquatic life than that from SR-520 (Portele, 1981; Portele et al., 1982). Precipitation samples were analyzed to determine whether the rain at the Interstate-5 site had higher metal concentrations than rain in the vicinity of SR-520. More Hall, on the University of Washington campus, served as a convenient collection point near the latter site. Precipitation at both sites was collected in standard eight inch precipitation gages. All samples were collected after at least 0.5 inches of rain had fallen and were transported to the laboratory for heavy metals analysis. A total of ten sets of samples were taken over a period of five months (September-February, 1980-81). Table 5 summarizes the results.

For eight of the ten samples, the rain collected at the I-5 site contained higher zinc concentrations than that sampled on the campus. During the sampling period, the average zinc concentration in the I-5 rain was .0714 mg/ℓ compared to .0558 mg/ℓ at More Hall. Zinc concentrations were more variable in the More Hall precipitation than at the highway runoff site. The two highest values at More Hall occurred during a northerly wind, from the direction of the I-5 site. Excluding these two values, the difference between zinc concentrations at the two sites was statistically significant ($P < 0.05$). Studies conducted by Knudson et al. (1976) support the claim that rain in northern Seattle generally contains higher zinc concentrations than surrounding areas. Factor analysis of the data showed an independent but unidentified source of zinc in that area.

Lead and copper concentrations also were higher in rainfall at the I-5 site than on campus. These data exhibited considerable variability, and differences were not statistically significant.

Table 5: Precipitation Analysis Summary

Metal (mg/ℓ)	I-5 Site Rain		More Hall Rain	
	Average	Standard Deviation	Average	Standard Deviation
Zn	.0714	.0490	.0668	.0616
Pb	.1287	.0737	.0283	.0296
Cu	.0196	.0087	.0156	.0046

Sulphur-Extended Asphalt Pavement

A sulphur-extended asphalt pavement was installed at the end of August 1979 on Washington State Highway 270, just west of Pullman. The Pullman 9 site was placed along the sulphur-extended asphalt pavement, while the Pullman Control site collected runoff from a section of the same highway with conventional pavement.

The Pullman sites were monitored for total sulphur and sulphate concentrations in the stormwater to determine whether the sulphur-extended asphalt pavement contributed excess sulphur to the runoff. All samples from the Pullman sites received during the 1981-82 sampling period were analyzed for total sulphur concentration (Marczenko, 1976). Several samples from the Pullman sites and elsewhere had been analyzed earlier for sulphate concentrations for comparison (Chui, 1981).

These earlier results demonstrated that initial sulphate concentrations and runoff rates were higher at Pullman than at other sites. Concentrations never approached the Public Health Service guideline for drinking water (250 mg/l), however. In 1981-82 the mean total sulfur concentration was lower in runoff from the sulfur-extended asphalt site (2.6 mg/l; S.D. = 1.3 mg/l) than from Pullman-Control (3.5 mg/l; S.D. = 1.0 mg/l). The experimental pavement tested in Pullaman does not appear to pose any danger to water quality from the standpoint of sulfur.

CONCLUSION

Work during the final year of the Highway Runoff Water Quality research project confirmed the applicability of a pollutant loading model proposed during preceding years. Calibration with the full data set established the TSS runoff rates for Western (6.4 lb/curb mile-1000 vehicles) and Eastern Washington (26 lb/curb mile-1000 vehicles) at values very close to those computed earlier. The final year's work also confirmed that other pollutant loadings can be estimated in proportion to TSS and provided proportionality constants to make those estimates. An exercise in model validation, comparing predicted to observed loadings at one site, demonstrated the model's utility in predicting cumulative loadings over a number of storm events. Substantial discrepancies resulted when the model was employed to estimate individual storm loadings, however.

A probability analysis was performed to provide an assessment tool for pollutant loadings and concentrations in runoff from individual events. The data were found to be log-normally distributed, and graphs were prepared to estimate the probability of exceeding any given concentration (or loading) in any storm under several geographic and traffic conditions.

Several special studies were conducted during the final year of the project. Investigation of nutrient and oil and grease removal resulting from drainage through a vegetated channel indicated substantial reductions, except in the late fall, when soluble phosphorus increased in the channel. Algal bioassays demonstrated reduced growth inhibition by toxicants in highway runoff when drained through vegetation. Simultaneous analysis of metals in precipitation at two different sites in Seattle suggested that the elevation in zinc concentration in highway runoff from I-5 north of Seattle compared to

SR-520, a highway with similar traffic volume, was due to high zinc in rainfall at the I-5 site. Comparison of total sulfur in runoff from a sulfur-extended asphalt pavement and a control site near Pullman demonstrated no water quality threat from the experimental pavement.

REFERENCES

Aitchison, J. and J.A.C. Brown, The Log-Normal Distribution, Cambridge University Press, Cambridge, England, 1969.

Asplund, R.L., "Characterization of Highway Stormwater Runoff in Washington State," M.S.E. Thesis, Department of Civil Engineering, University of Washington, 1980.

Asplund, R.L., J.F. Ferguson, and B.W. Mar, "Characterization of Highway Runoff in Washington State," FHWA WA-RD-39.6, Report to Washington State Department of Transportation by Department of Civil Engineering, University of Washington, 1980.

Asplund, R.L., J.F. Ferguson, and B.W. Mar, "Characterization of Highway Runoff in Washington State," J. Environ. Eng. Div. ASCE 108:391-404, 1982.

Aye, R.C., "Criteria and Requirements of Statewide Highway Runoff Monitoring Sites," FHWA WA-RD-30.5, Report to Washington State Department of Transportation by Department of Civil Engineering, University of Washington, 1979.

Braek, G.S., D. Malnes and A. Jensen, "Heavy Metal Tolerance of Marine Phytoplankton, IV, Combined Effect of Zinc and Cadmium on Growth and Uptake in Some Marine Diatoms," J. Exp. Mar. Biol. Ecol., 42(1):39-54.

Christensen, E.R., J. Schertig and P.S. Dixon, "Effects of Manganese, Copper and Lead on Selenastrum capricornutum and Chlorella stigmatophore," Water Res., 13:79-92.

Chui, T.W.D., "Highway Runoff in the State of Washington: Model Validation and Statistical Analysis," M.S.E. Thesis, Department of Civil Engineering, University of Washington, 1981.

Chui, T.W., B.W. Mar and R.R. Horner, "Highway Runoff in Washington State: Model Validation and Statistical Analysis," RHWA WA-RD-39.13, Report to Washington State Department of Transportation by Department of Civil Engineering, University of Washington, 1981.

Clark, D.L., "Composite Sampling of Highway Runoff," M.S.C.E. Thesis, Department of Civil Engineering, University of Washington, 1980.

Clark, D.L. and B.W. Mar, "Composite Sampling of Highway Runoff, Year 2, August 1978-August 1979," FHWA WA-RD-39.4 Report to Washington State Department of Transportation by Department of Civil Engineering, University of Washington, 1980.

Clark, D.L., R.L. Asplund, J.R. Ferguson, and B.W. Mar, "Composite Sampling of Highway Runoff," J. Environ. Eng. Div. ASCE 107:1067-1081, 1981.

Dunn, O.J. and Clark, V.A., Applied Statistics: Analysis of Variance and Regression, John Wiley and Sons, 1974.

Horner, R.R. and B.W. Mar, "Guide for Water Quality Impact Assessment of Highway Operations and Maintenance," FHWA WA-RD-39.14, Department of Civil Engineering, University of Washington, 1982.

Khalid, R.A., I.C.R. Holford, M.N. Mixon and W.H. Patrick, "Nitrogen and Phosphorus Reaction in Overland Flow of Wastewater," EPA-600/52-81-150, Summary U.S. Environmental Protection Agency, Washington, D.C., 1981.

Knudson, E.J., D.L. Duewer, G.D. Christian, and T.V. Larson, "Application of Factor Analysis to the Study of Rain Chemistry in the Puget Sound Region," In: Chemotronics: Theory and Application, ACS Symposium Series 52, p 80-116, 1976.

Kobriger, N.P., T.L. Meinholz, M.K. Gupta and R.W. Agnew, "Constituents of Highway Runoff, Vol. III: Predictive Procedure for Determining Pollutant Characteristics in Highway Runoff," FHWA/RD-81/044, Report to Federal Highway Administration by Envirex, Inc., Milwaukee, 1981.

Little, L.M., "Model Calibration and Probability Distributions for Washington State Highway Runoff Water Quality, M.S.C.E. Thesis, Department of Civil Engineering, University of Washington, 1982.

Marczenko, Z., Spectrophotometric Determination of the Elements, Halsted Press, Chichester, England, 1976, pp. 504-515, 1976.

Miller, W.E., J.C. Greene and T. Shiroyama, "The Selenastrum capricornutum Printz Algal Assay Bottle Test: Experimental Design, Application and Data Interpretation Protocol," EPA-600/9-78-018, U.S. Environmental Protection Agency, Corvallis, Oregon, 1978.

Portele, G.J., "The Effects of Highway Runoff on Aquatic Biota in the Metropolitan Seattle Area," M.S. Thesis, Department of Civil Engineering, University of Washington, 1981.

Portele, G.J., B.W. Mar, R.R. Horner and E.B. Welch, "Effects of Seattle Area Highway Stormwater Runoff on Aquatic Biota," FHWA WA-RD-39.11, Report to Washington State Department of Transportation by Department of Civil Engineering, University of Washington, 1982.

Puget Sound Air Pollution Control Agency, "1980 Air Quality Data Summary," Puget Sound Air Pollution Control Agency, Seattle, 1980.

Sartor, J.D. and G.B. Boyd, "Water Pollution Aspects of Street Surface Contaminants," EPA-R2-72-081, U.S. Environmental Protection Agency, Washington, D.C., 1982.

Shaheen, D.G., "Contributions of Urban Roadway Usage to Water Pollution," Report to U.S. Environmental Protection Agency, Contract No. 86-01-0197 by Biospherics, Inc., 1975.

Strickland, J.D.H. and T.R. Parsons, "A Practical Handbook of Seawater Analysis," Second Edition, Bulletin 167, Fisheries Research Board of Canada, Ottawa, 1972.

Sylvester, R.O. and F.B. DeWalle, "Characteristics and Significance of Highway Runoff Waters," Report to the Washington State Highway Commission by Department of Civil Engineering, University of Washington, 1972.

U.S. Environmental Protection Agency, "Methods for Chemical Analysis of Water and Wastes," EPA-600/4-79-020, Environmental Monitoring and Support Laboratory, Cincinnati, 1979.

U.S. Environmental Protection Agency, "Preliminary Results of the Nationwide Urban Runoff Program," Water Planning Division, Washington, D.C., 1982.

Wang, T.S., "Transport, Deposition and Control of Heavy Metals in Highway Runoff," M.S.E. Thesis, Department of Civil Engineering, University of Washington, 1981.

Wang, T.S., D.E. Spyridakis, B.W. Mar, and R.R. Horner, "Transport, Deposition and Control of Heavy Metals in Highway Runoff," FHWA WA-RD-39.10, Report to Washington State Department of Transportation by Department of Civil Engineering, University of Washington, 1982.

Washington Department of Ecology, "Washington State Air Monitoring Data for 1980," Washington State Department of Ecology, Olympia, WA, 1981.

Winters, G.L. and J.L. Gidley, "Effects of Roadway Runoff on Algae," FHWA/Ca/TL-80/24, California State Department of Transportation, 1980.

LIST OF REPORTS

WA-RD-39.1. Vause, K.H., J.F. Ferguson, and B.W. Mar, "Water Quality Impacts Associated with Leachates from Highway Woodwaste Embankments", September 1980.

Laboratory and field studies of a woodchip fill on SR-302 demonstrated that the ultimate amounts of COD, TOC, and BOD per ton of woodchips can be defined and that this material is leached exponentially by water. After a year the majority of the pollutant has been removed, suggesting that pre-treating of the woodchips prior to use in the fill can reduce the pollutant release from a fill. Thus, chips should be protected from rainfall and groundwater intrusion to avoid the release of leachate. Release of leachate onto tidal lands can cause beach discoloration, and an underground deep outfall may be required.

WA-RD-39.2. Horner, R.R. and E.B. Welch, "Effects of Velocity and Nutrient Alternations on Stream Primary Producers and Associated Organisms", November 1978.

Velocity and nutrient studies at 12 sites in Western Washington streams indicated that 50 cm/sec is the critical average current velocity where the productive base of the food web is impacted. Swiftly flowing stream rich in nutrients should not be slowed to this value, and slowly flowing streams should not be altered to have velocities greater than this value.

WA-RD-39.3. Horner, R.R., S.J. Burges, J.F. Ferguson, B.W. Mar, and E.B. Welch, "Highway Runoff Monitoring: The Initial Year", January 1979.

This report covers the initial 15 months of effort to review the literature, select a prototype site, compare the performance of several automatic sampling devices, and install a prototype sampling site on I-5 north of Seattle.

WA-RD-39.4. Clark, D.L. and B.W. Mar, "Composite Sampling of Highway Runoff: Year 2", January 1980.

A composite sampling device was developed that can be installed at less than ten percent of the cost of automatic sampling systems currently used in Federal highway runoff studies. This device was operated for one year, along-side an automatic sampler at the I-5 site, to demonstrate that the two systems provide statistically identical storm composites.

WA-RD-39.5. Aye, R.C., "Criteria and Requirements for Statewide Highway Runoff Monitoring Sites", July 1979.

Criteria for selecting statewide monitoring sites for highway runoff were established to provide representative combinations of climate, traffic, highway, land use, geographic, and topographic characteristics. Using these criteria, a minimum of six sites were recommended for use in this research.

WA-RD-39.6. Asplund, R., J.F. Ferguson, and B.W. Mar, "Characterization of Highway Runoff in Washington State", December 1980.

A total of 241 storm events were sampled at ten sites during the first full year of statewide monitoring of highway runoff. Analyses of these data indicate that more than half of the observed solids in this runoff is traced to sanding operations. The total solids loading at each site was correlated with traffic during the storm. The ratio of other pollutants to solids was linear when there was sufficient traffic-generated pollutants to saturate the available solids.

WA-RD-39.7. Mar, B.W., J.F. Ferguson, and E.B. Welch, "Year 3 - Runoff Water Quality, August 1979 - August 1980", January 1981.

This report summarizes findings detailed in WA-RD-39.4 and WA-RD-39.6 plus the work of Zawlocki on trace organics in highway runoff. Several hundred compounds tentatively identified by GC-MS (Gas Chromatography-Mass Spectrometer) were grouped into nine categories, which were not mutually exclusive. Major components of these categories were petroleum products used by vehicles and incompletely combusted hydrocarbons. The concentrations of these trace organics groups were low compared to criteria proposed for protection of aquatic life.

WA-RD-39.8. Eagen, P.D., "Views of Risk and Highway Transportation of Hazardous Materials - A Case Study in Gasoline", November 1980.

While gasoline represents one-third of all hazardous materials transported in the country by trucks, the risk associated with gas transportation, as viewed by the private sector, is small. Public perceptions of risk are much greater due to lack of knowledge on probabilities and consequences of spills. Methods to improve knowledge available to the public on gasoline spills and methods to improve estimates of environmental damages from gasoline spills is presented. Generalization of methodologies to hazardous materials in general are discussed.

WA-RD-39.9. Zawlocki, K.R., J.F. Ferguson, and B.W. Mar, "A Survey of Trace Organics in Highway Runoff in Seattle, Washington", November 1981.

Trace organics were surveyed using gas chromotography coupled to mass spectrometry for highway runoff samples from two Seattle sites. The characterization of the organics exhibited concentrations of aliphatic, aromatic, and complex oxygenated compounds. Vehicles, including exhaust emissions, were concluded to be the source of many of the organics.

WA-RD-39.10. Wang, T.S., D.E. Spyridakis, R.R. Horner, and B.W. Mar, "Transport, Deposition, and Control of Heavy Metals in Highway Runoff", January 1982.

Mass balances conducted on soils adjacent to highways indicated low mobility of metals deposited on well-vegetated surfaces. Grass drainage channels were shown to effectively capture and retain metals (e.g. a 60 m channel removed 80 percent of the original Pb concentration). Mud or paved channels, however, demonstrated little or no ability to remove metals from runoff. Metal release studies suggested that acid precipitation could release metals bound in the soil, especially where low buffering capacity exists.

WA-RD-39.11. Portele, G.J., B.W. Mar, R.R. Horner, and E.B. Welch, "Effects of Seattle Area Highway Stormwater Runoff on Aquatic Biota", January 1982.

The impacts of stormwater runoff from Washington State freeways on aquatic ecosystems were investigated through a series of bioassays utilizing algae, zooplankton, and fish. Algae and zooplankton were adversely affected by the soluble fraction of the runoff, while suspended solids caused high mortalities of rainbow trout fry. In addition, BOD_5 values similar to those reported in the stormwater literature were measured; however, there were indications that results were influenced by toxicity to microbial populations.

WA-RD-39.12. Chui, T.W., B.W. Mar, and R.R. Horner, "Highway Runoff in Washington State: Model Validation and Statistical Analysis", November 1981.

Results of the second year of full-time operation of nine monitoring sites in the State of Washington produced 260 observations of highway storm runoff. A predictive model was developed based on the data from two years of observation for total suspended solid loads. A high correlation was demonstrated between total suspended solids and COD, metals, and nutrients. The major factor controlling pollution loads from highways in Washington State is the number of vehicles passing during each storm, not those preceding storms.

WA-RD-39.13. Mar, B.W., J.F. Ferguson, D.E. Spyridakis, E.B. Welch, and R.R. Horner, "Year 4 - Runoff Water Quality, August 1980 - August 1981".

This report summarizes findings presented in WA-RD-39.10, 39.11, and 39.12. Included are the results of studies aimed at improving and extending Asplund's solids loading model, increasing data on the ratios of various pollutants to TSS in the runoff, investigating the fate of heavy metals in drainage systems, and conducting bioassays on sensitive organisms exposed to highway runoff.

WA-RD-39.14. Horner, R.R. and B.W. Mar, "Guide for Water Quality Impact Assessment of Highway Operations and Maintenance", August 1982.

Procedures particularly applicable to Washington State have been developed to assist the highway designer in evaluating and minimizing the impacts of highway runoff on receiving waters. The guide provides computation procedures to estimate pollutant concentrations and annual loadings for three levels of analysis which depend on the watershed, the discharge system, and traffic. It further provides means to judge the potential impacts of the runoff on receiving waters.

WA-RD-39.15. Horner, R.R. and E.B. Welch, "Impacts of Channel Reconstruction in the Pilchuck River", August 1982.

A five-year study was performed to compare conditions in the Pilchuck river before and after channel reconstruction associated with rerouting Highway SR-2. The study focused on sediment particle-size analyses, benthic macroinvertebrates, and fish. Substrates comparable to control areas developed in all portions of the new channel within one year after construction. The available data on invertebrates and fish gave no indication of deterioration in diversity, quantity or size in the reconstructed channel. The report provides recommendations for further improvements in the design of stream channel changes should there be no alternative to their construction.

WA-RD-39.16. Mar, B.W., R.R. Horner, J.F. Ferguson, D.E. Spyridakis, and E.B. Welch, "Summary -- Washington State Highway runoff Water Quality Study, 1977 - 1982", September 1982.

The final report on the research project summarizes the results presented in detail in the preceding reports and graduate student theses.

WA-RD-39.12.1 Little, L.M., R.R. Horner, and B.W. Mar, "Assessment of Pollutant Loadings and Concentrations in Highway Stormwater Runoff", April 1983.

This report presents the final form of the Washington State highway pollutant loading model, incorporating data from the five years of study. It also features a probabilistic analysis of concentration and loading data designed to express the chance of exceeding specific values in a given case. Other topics include further assessment of the toxicity of highway runoff and its causes.

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