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16. Abstract

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 indicates 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.

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CHARACTERIZATION OF HIGHWAY RUNOFF IN WASHINGTON STATE[a]

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ABSTRACT

During the first year of full-time operation of ten highway runoff monitoring sites in the State of Washington, a total of 241 storms were sampled with a composite sampling system developed by Clark (4). Analysis of the data indicated that a major fraction of solids loadings in runoff can be traced to sand used during winter ice conditions. Ratios of pollutants to solids were observed to be constant except during winter sanding periods where lower ratios were observed. A predictive model for cumulative pollutant loadings was derived as a function of cumulative traffic during storms. Traffic during the dry periods appeared to remove pollutants from the highways and are not significant in predicting pollutant loadings in the State of Washington.

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Abstract

During the first year of full-time operation of ten highway runoff monitoring sites in the State of Washington, a total of 241 storms were sampled with a composite sampling system developed by Clark (4). Analysis of the data indicated that a major fraction of solids loadings in runoff can be traced to sand used during winter ice conditions. Ratios of pollutants to solids were observed to be constant except during winter sanding periods where lower ratios were observed. A predictive model for cumulative pollutant loadings was derived as a function of cumulative traffic during storms. Traffic during the dry periods appeared to remove pollutants from the highways and are not significant in predicting pollutant loadings in the State of Washington.

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INTRODUCTION

This report covers the characterization of the pollutants found in highway stormwater runoff based on the first year (1979-80) of continuous statewide monitoring at nine sites in the state of Washington (38). The major topics to be explored include:

1. Comparison of the data collected from this project with previously published data.
2. Determination of trends in the data which may support the development of a model.
3. Determining the major sources of stormwater runoff pollutants and parameters which may influence their deposition and removal from the highway.
4. Improvements and recommendations indicated for the second year of monitoring, based on the initial year's results.

LITERATURE REVIEW

The types, amounts, and removal rates of pollutants found on the highway at a given time are a function of interrelated variables. Motor vehicle wear and emissions, local land use conditions, and highway maintenance practices are largely responsible for the pollutant mass residing on the roadway (9,11,13,20,23,24). Most of the specific highway runoff pollutants important to water quality are vehicle dependent (5,12,15, 28). The metals (lead, zinc, copper, chromium, and iron), the nutrients (nitrogen and phosphorus) and the hydrocarbons are all largely contributed by motor vehicle traffic (9,24,26). Shaheen (24) has shown that while a majority of the solids are related to traffic volumes, less than five percent originate from the vehicles themselves. This indicates vehicles must function both as a source and transport mechanism for pollutants.

The sources of pollutants deposited by vehicles consist of two types: direct and indirect or "acquired" pollutants. The distinction is important as direct sources of pollutants originate from the normal operation and frictional parts wear of the vehicle. Indirect or acquired sources of pollutants are solids plus direct pollutants that are "acquired" and carried by the vehicle for later deposition, (usually during storms).

Direct pollutants are considered to be a major source of many of the specific pollutants found in highway runoff. Much of the COD, grease and oils, nitrates, sulfate, and phosphorus deposited on the highway are attributed to oil leakage or gasoline and its combustion products. Tirewear contributes approximately 0.008 lbs/1,000 vehicle-miles of which 98% are oxidizable rubber compounds and 0.73% are of zinc oxides (5). Exhaust emissions average 0.235 lbs/1,000 vehicle-miles of which 45% is particulate lead and the remaining 54% is comprised of other metalic or organic hydrocarbon compounds (1,14). (This value is for leaded gasoline only.) These emission rates are fairly constant but will vary with the age, size, and condition of the vehicle, highway driving speeds and vehicle acceleration correspondingly increases. Changes in fleet fuel consumption to diesel fuels will significantly increase particulate emissions while alcohols will generally decrease emissions.

Indirect sources of pollutants include adjacent land uses, wind blown solids, litter and debris, and pavement wear. The specific source and type of acquired pollutant depends on where the vehicle has been and where the pollutant was picked-up. Probable common sources include: parking lots, urban and industrial areas, construction sites, dirt roads and farming areas.

Lastly, spills of recreational vehicle wastes, agricultural or chemical products, or oil and gas losses from accidents are an infrequent but possible source of highway pollutants, which are related to vehicular traffic volumes. These spills and losses, many times may go unnoticed if they are small but could be a large contributing factor to local runoff pollutant loads.

Sanding and deicing operations can be a major source and a significant fraction of the total solids and salt mass observed in highway runoff. Sanding deposition rates in the State of Washington are approximately 600 lbs per lane mile per storm of which 80% is sand and 20% is salt. These operations are the largest single source of solids at many of the sites during the winter period. The frequency of the sanding and deicing operations are variable, depending on the prevailing weather conditions, the road conditions and district's operation policy.

The major sources of pollutants from dustfall are from urban areas and lands adjacent to the highway. In urban-industrial areas deposition rates range from 1.0 to 3.0 lbs per acre-day and from 0.5 to 1.0 lbs per acre-day in rural areas (37). The surrounding land conditions next to the highway can significantly influence dustfall deposition rates.

Highway maintenance practices can greatly influence the pollutant mass. Street sweeping operations can remove anywhere between twenty-five to seventy-eight percent of the pollutant mass on the highway. Particle removal efficiencies by sweeping is size dependent, with the larger particles having a greater probability of being removed (1,9, 32). Most pollutants are characteristically associated with the dirt and dust found on the highway (1,7,9,10,12,13,34,29). Metal concentrations in highway runoff have been found to follow the total solids concentrations (4,15,26) and studies examining the soluble and particulate fractions indicate between ninety-three to ninety-nine percent is particulate (14,15,17,29). Many highway runoff models (9,12,18) assume a constant mass ratio of pollutant-to-solids in the estimation of a particular pollutant mass. Yet, in a recent study by Pitt (1979) (1), examination of street sweepings has shown that the types of pollutants associated with solids of different particle size ranges is quite variable. Chemical analysis indicates most pollutants have a higher mass ratio with the smaller diameter particles, except for copper and chromium which have a lower mass ratio with the smaller particles. The change in the lead mass ratio is from 0.008 to 0.00025 or a ninety-seven percent decrease over the range of particle sizes observed.

Pavement deterioration contributes only a small fraction to the pollutant mass on the highway (24). The impact of studded tire use is noticeable, but not quantified. The type of pollutant contributed may depend on the composition of the concrete and asphalt mix with asphalt exhibiting a greater influence on the COD, TOC and grease and oil than concrete (1).

In summary the major sources of TSS found in highway runoff are contributed by:

1. sanding and deicing operations--only during the winter period and frequency is site specific,

2. atmospheric dustfall-entirely site specific, influenced by the surrounding land uses and traffic volumes.

3. vehicular traffic--mostly from acquired sources, and

4. pavement destruction--only a minor source.

In Table 1 estimations of the TSS deposition rates from these sources for the Western Washington runoff sites are listed.

Table 1. Estimated TSS Deposition Rates for Western Washington

SOURCE	DEPOSITION RATE	ONE WEEK* CONTRIBUTION TO 1 ACRE/ 4 LANE SECTION
Sanding	500 lbs/lane mile	200 lbs
Dustfall		
rural	0.8 lbs/Acre-day	6 lb
urban	2.0 lbs/Acre-day	14 lb
Vehicles		
primary	0.3 lbs/1,000 vehicle-miles	105 lbs
Acquired		
rural	0.4 lbs/1,000 vehicle-miles	140 lbs
urban	0.1 lbs/1,000 vehicle-miles	35 lbs
Other	0.2 lbs/Acre-day	2 lbs
	*50,000 vehicles/day	rural: 453 lbs urban: 356 lbs

The mechanisms available for removal are determined by the highway conditions, especially whether the highway is wet or dry. The removal mechanisms for each situation and the possible parameters influencing the removal process are depicted in Figure I.

Removal of pollutants via natural surface winds or from traffic created winds and mechanical scrubbing are probably the major removal mechanisms in low precipitation areas. (2) The mechanical scrubbing action of the tires along with natural or vehicle created winds, helps to scour the road and to transport the pollutants away from the vehicle lanes and the highway. This process was shown by highway flushing studies performed on I-50 at Sacramento by Envirex (32,33), in which approximately 87% of the total pollutant mass from the highway on the median and distress lanes. Laxen and Little (15,17) has determined that a majority of the pollutants on the highway are located within three feet of the curb supporting this process. Most of the pollutants deposited on the driving lanes are rapidly blown on to the distress-median strips or completely off the highway.

Pollutant removal from the highways during wet weather periods is accomplished through scrubbing of the pavement either by the intensity of the rainfall or by mechanical energy from vehicles during the storm with subsequent removal via the stormwater runoff. Removal of the pollutants deposited on the highway based on rainfall intensity is well documented. Envirex estimates that a rainfall event of 1.0 inch or greater with a peak intensity equal to 0.5"/hr for at least one hour is required before 90% of the pollutants are removed.

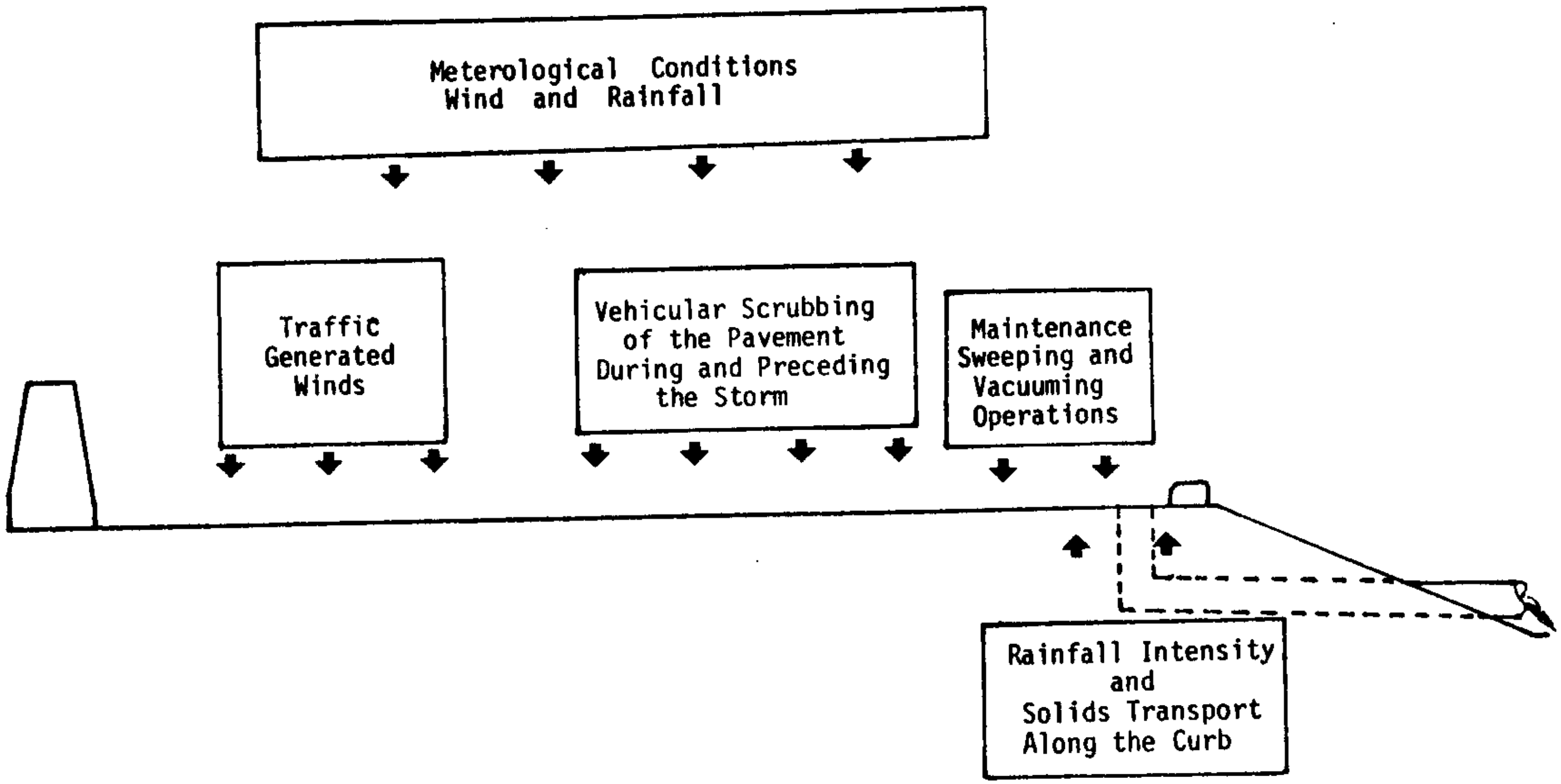


Figure 1. Total Suspended Solids and Pollutant Removal Mechanisms

Scrubbing of the pavement maybe also be accomplished by the tires from vehicles traveling on the highway during the storm period. Estimation of the energy transferred by a vehicle to the highway during a rainstorm, indicate approximately 5,000 to 7,000 vehicles per hour are required to equal the equivalent amount of energy imparted during a 0.5"/hr rainstorm (38). On high traffic volume sections of highways, this is probably the primary removal mechanism during wet weather periods.

One other possible removal mechanism during wet highway conditions is resuspension of pollutants on to vehicles from road spray. Visual observations during low intensity storms (Pacific Northwest drizzle) indicate that a net increase in the mass of solids on vehicles may occur during these periods. This mechanism may explain the process by which vehicles acquire solids for later deposition.

While scrubbing may remove the pollutants from the road surface or increase the vehicle source deposition rate, the transport of the pollutant off the highway is determined by the site and storm parameters. Curbing or the lack of it, is probably the single most influential factor in determining the amount of pollutants removed via the runoff. Curbing or guard rails may retain more air blown material than noncurbed sections.

The major effect of longer runoff paths due to curbing or drains is the decrease in the runoff velocity, causing the settling out of the solids along the curb and the culvert. The removal of the particulate pollutants and solids is determined by the runoff-volume-intensity-duration, the existing amounts of the solids along the curb, and the curb and culvert characteristics that define flow.

In summary two pathways, depending on whether the highway is wet or dry, control the removal mechanisms for the pollutants deposited on the highway. During dry periods, traffic created or naturally occuring winds coupled with mechanical scrubbing of the highway by tires from the vehicular traffic are the principal removal mechanisms. The significant fraction of the pollutants transported via this process are probably removed completely. Transport via the stormwater runoff is the primary removal mechanism during the wet periods. The pollutant removal process is further complicated when the stormwater is channeled, as the runoff velocity decreases causing a settling out of the particulate pollutants, for removal by subsequent storm runoff.

The parameters affecting the solids movement along the channel are similiar to sediment transport factors and may influence the amount of pollutants observed in a given runoff event. The first flush phenomena is related to the distance the runoff travels. Highways that are not curbed will have a smaller first flush contribution than those that are curbed and sewered.

SITE SELECTION

Aye (2) established criteria for the selection of highway stormwater runoff sampling sites for the state of Washington. Traffic and weather characteristics, pavement type and condition, surrounding land uses, highway maintenance practices and highway geometrics were all considered by Aye, as factors which could affect the quality and quantity of highway runoff.

Aye recommended six sites to represent the varied climatic and traffic conditions observed throughout the state. Besides the six sites recommended by Aye, three other runoff sites were chosen for their specific site characteristics. An elevated bridge section on SR-520 at Montlake in Seattle was included since it had been studied by Sylvester (25) in his highway runoff studies. Two sections of SR-270 near Pullman were also selected, since this highway is part of a sulfur extended asphalt project and its impact on pollutant loads in the stormwater runoff could be examined. A site description summary containing detailed information pertaining to each site is presented in Table 2 and site locations shown in Figure 2.

Each site was equipped with a flowsplitter-composite sampler rather that the conventional discrete automatic sampler. The equipment consists of: a flowsplitter sampling flume, an appropriately sized sample tank, a recording or bucket-type rain gauge, and sampling equipment that includes a paddle for mixing the sample, collection bottle, and disposable sample tank liners. Design and sizing of the site specific flowsplitter sampling flumes and corresponding sample tanks were based on the recommendation of Clark as fully discussed in his thesis (4) and shown in Figure 3. After the flumes were constructed, calibration tests were performed to determine their actual performance.

The mechanics of sampling are simple and are performed after the passing of every major storm system or when runoff has ceased and the

Table 2. Physical Characteristics of the Highway Runoff Sampling Sites

Site Location	Climate	Average Yearly Rainfall	Site Description	Physical Characteristics Area	Physical Characteristics Length	Highway Description # Width, Pavement Type, Barrier	Traffic Volumes (ADT)	Surrounding Land Use	Sampler	Flowsplitter # Faction Split
1. I-5 I-5 & 158th NE Northbound lanes Seattle, WA	Puget Sound Lowlands-Marine	32-45	A wide radius curve with a 1.1% grade on a limited access highway, Sample intake: from drop-box	53,140 ft^2 1.2 Ac	780' 0.15 mi	4-12' concrete lanes 10'-DL-asphalt-curb 10'-ML-asphalt-NJ	53,000	Urban Residental	U of W Seattle	0.0125
2. SR-520 SR-520 at Montlake Westbound lanes NOAA Parking Lot Seattle, WA	Puget Sound Lowlands-Marine	32-45	Elevated bridge section with 2% grade site includes runoff from on ramps, Sample intake: from NW corner drain after on-ramp	4,310 ft^2 0.099 Ac	150' 0.029 mi	2-12' concrete lanes 2'-DL-concrete-NJ 1'-ML-concrete-NJ	42,000	Urban	U of W Seattle	0.210
3. Vancouver I-205 & St.Johns St. Southbound lanes Vancouver, WA	Cascade Foothills-Marine	40-90	A wide radius horizontal curve on a limited access highway Sample intake: off existing drop-box S. of St. Johns St.	11,970 ft^2 0.28 Ac	220' 0.042 mi	3-12' concrete lanes 10'-DL-asphalt-curb 8'-ML-asphalt	8,600	Low Density Residential	WSDOT#4 Dist.Engr. Office Vancouver	0.044
4. Snoqualmie Pass I-90 at Mile post 41.5 Eastbound lanes North Bend, WA	West Slope Cascade Mountains	60-100	A wide radius curve with 1.2% grade on a limited access highway Sample intake: off curb	7,780 ft^2 0.18 Ac	140' 0.027 mi	3-12' concrete lanes 12'-DL-asphalt-curb 6'-ML-asphalt	7,700	Western Coastal Forest Undeveloped	WSDOT#1 Field Engr. Office North Bend	0.055
5. Montesano SR-12 0.5 miles West of SR-12 and Montesano, WA	Western Olympics-Coastal	70-100+	Curved approach to bridge section and a portion of the on-ramp, Sample intake: off curb	12,210 ft^2 0.28 Ac	310' 0.059 mi	2-12' asphalt lanes 8'-DL-asphalt-curb 6'-ML-asphalt	7,300	Agricultural Pasture Land	WSDOT#3 Field Main. Office Aberdeen	0.058, From 3-23-80 on 0.019
6. Pasco Interchange of SR-12 & SR-195 Eastbound lanes SR-12 Pasco, WA	Central Basin East Cascade Foothills	7-15	Wide radius horizonal curve in transition to a -0.9% horizontal grade, Sample intake: off existing culvert--site below grade	54,320 ft^2 1.25 Ac	1090' 0.21 mi	2-12' concrete lanes 10'-DL-asphalt-curb 4'-ML-asphalt 12'-asphalt gutter along DL	2,000	Semi-arid desert Undeveloped w/irrigation Agriculture	WSDOT#5 Field Engr. Office Pasco	0.009
7. Spokane I-90 at Latah Cr. Bridge Eastbound lanes eastern pier section Spokane, WA	Northeastern	17-28	Horizontal bridge section on a limited access highway, Sample intake: from 5 bridge drains at base of middle pier.	9,590 ft^2 0.22 Ac	180' 0.035 mi	3-12' concrete lanes 3'-DL-concrete-NJ 2'-ML-concrete-NJ	17,500	Urban	WSDOT#6 Dist. Main. Office Spokane	0.051
8. Pullman-8 SR-270 2.5 mi West of city, Eastbound lanes, Pullman, WA	Palouse - Blue Mountains	10-19	-1.0% horizontal grade on 30%-70% by weight sulfur-asphalt section of sulfur extended project, Sample intake: off curb	9,750 ft^2 0.22 Ac	500' 0.095 mi	1-12' asphalt lanes 7.5'-DL-asphalt-curb asphalt: 70% reg.mix 30% sulphur mix	2,500	Agriculture	WSU Pullman	0.071
9. Pullman-9 SR-270 2.5 mi West of city, Westbound lanes, Pullman, WA	Palouse - Blue Mountains	10-19	+1.0% horizontal grade on 30%-70% by weight sulfur-asphalt section of sulfur extended project, Sample intact: off curb	10,670 ft^2 0.25 Ac	500' 0.095 mi	1-12' asphalt lane 7.5'-DL-asphalt-curb asphalt: 70% reg. mix 30% sulphur mix	2,500	Agriculture	WSU Pullman	0.071
10. Pullman-Control SR-270 2.5 mi West of city, Eastbound lanes, Pullman WA	Palouse-Blue Mountains	10-19	-1.0% horizontal grade on asphalt control section of sulfur extended project, Sample intake: off curb	13,210 ft^2 0.30	500' 0.095 mi	1-12' asphalt lane 7.5'-DL-asphalt-curb asphalt: 100% reg. mix	2,500	Agriculture	WSU Pullman	0.071

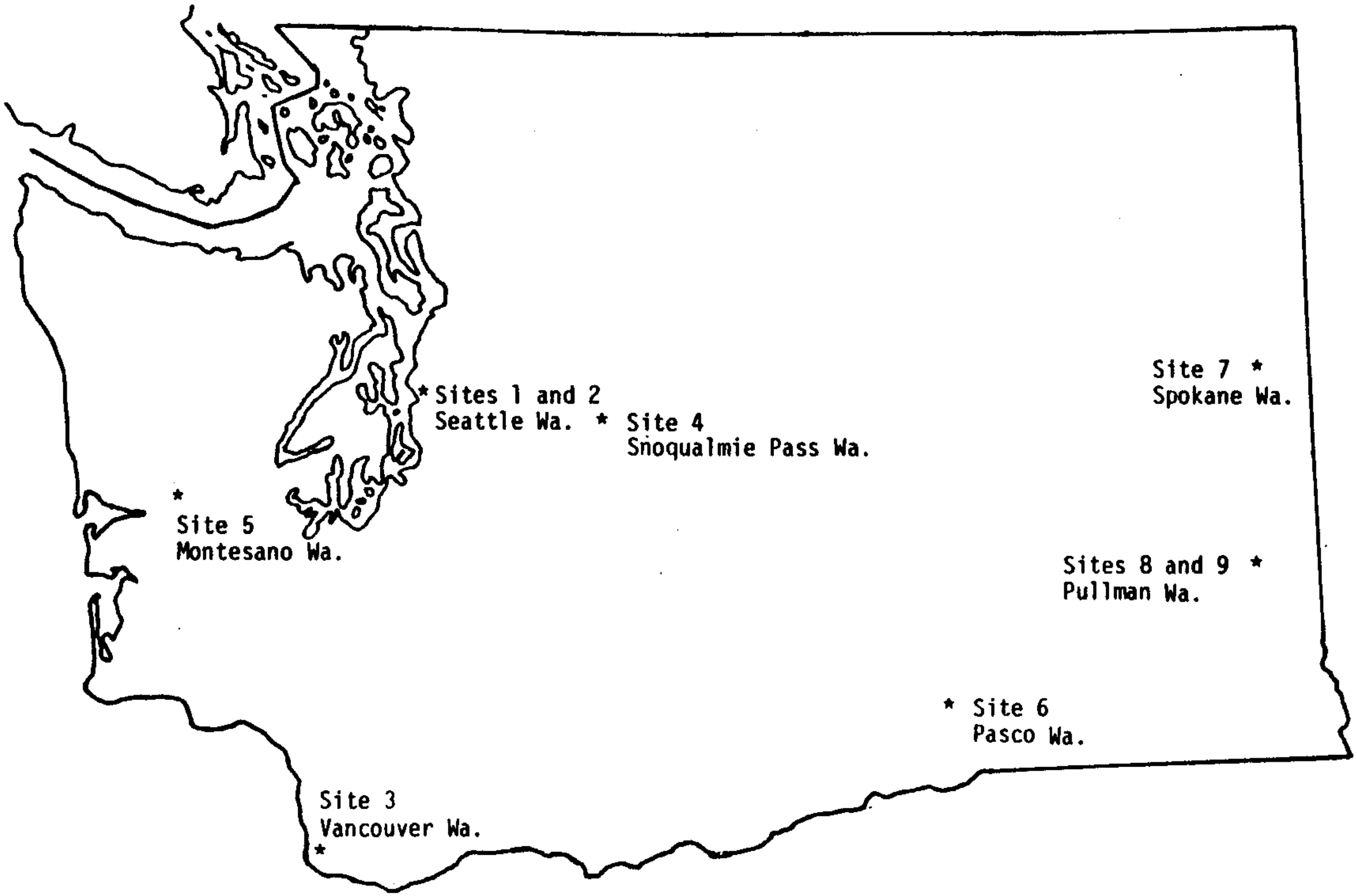


Figure 2. Sampling Site Locations in Washington State

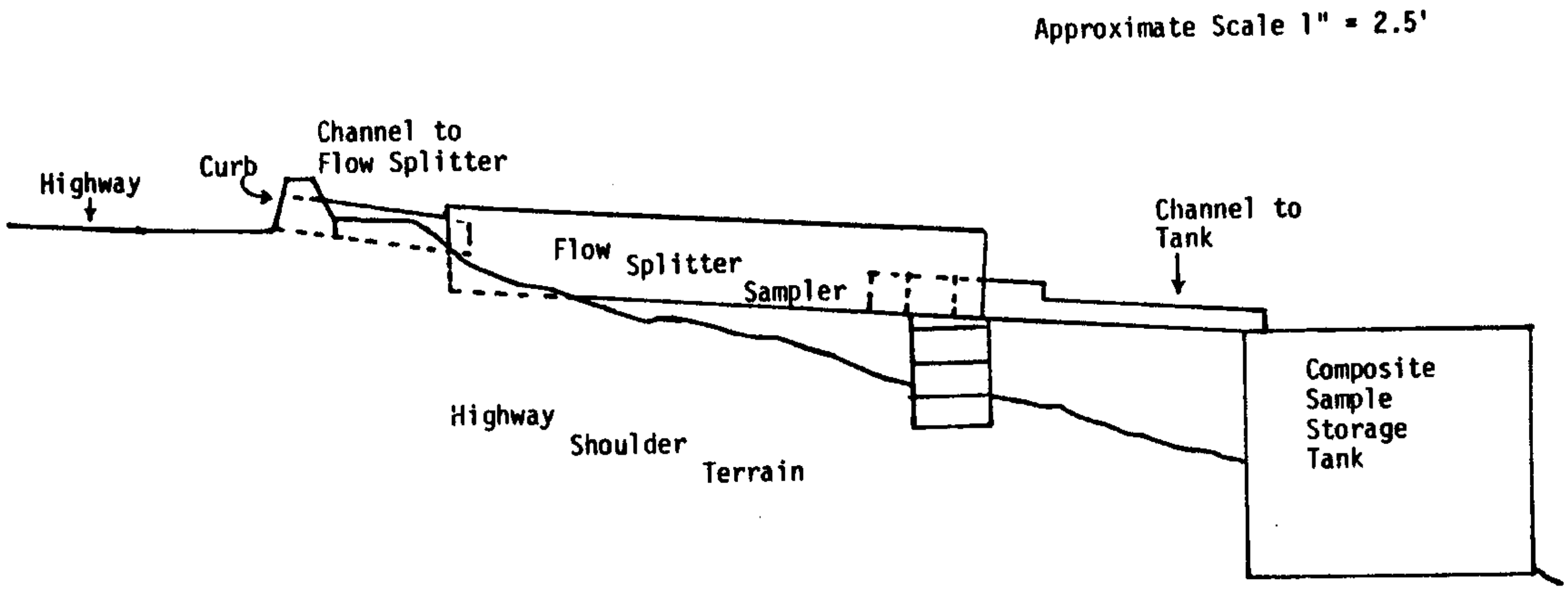


Figure 3. Layout of the Composite Sampling System on a Curbed Highway

pavement is dry. To sample, the depth of the runoff in the composite tank is first measured and is used to calculate the total runoff volume from the storm event. A paddle is then used to mix the sample until complete resuspension of the particles has been achieved, (approximately 5 minutes) at which time a sub-sample is removed for laboratory analysis. The remaining runoff in the sample tank is then drained and the plastic liners are replaced with a new set. During this time the flowsplitter is checked for clogging in the splitter section, that it is level perpendicular to the runoff flow and the rainfall volume is measured. These measurements and observations are then recorded on the field data sheet and are sent along with the runoff sample to the University of Washington for processing and analysis.

All the sites received routine maintenance in the summer including: refiberglassing the tank and flowsplitter, repairing any winter site damage, and modifying inlet channel and runoff duration recorders.

The accuracy and sensitivity of the instruments used to measure the precipitation and runoff volumes, could be a major contributor to the wide variation seen in TSS and pollutant runoff loads. Under ideal conditions, the uncertainty associated with the volume measurements from the flowsplitter is approximately 15 percent (4).

A tabular summary of the problems and solutions encountered at the runoff sites which could be possible sources of error are presented in Table 3.

Table 3. Summary of Site Problems and Sources of Errors (Solutions to Problems Encountered at the Runoff Sites)

Location	Specific Site Problems	Runoff Flow Problems: Measurement	Runoff Flow Problems: Storm Related	Traffic Measurement	Sample Collection	Laboratory
I-5	Loss of solids in H-flume (Collection and addition to composited sample) Recording rain gauge over estimated volumes	ISCO flow measurement over estimated flow (Installation of flow tranquilizer) Only minor clogging (Installation of netting)	Few	Excellent daily and VDS counts	No problems	No problems (Separate grit analysis for solids
SR-520	Leakage of site thru expansion joints (Site abandoned 6/80)	No problems Infrequent clogging	Few Tank overflowed 10 times	Excellent daily and VDS counts	No problems	Usual problems encountered with high solids levels (All samples measured with grad cyl or sludge pipets)
Vancouver	Possible flow barrier between concrete-asphalt lanes (Installation of patch on lane)	No problems Infrequent clogging	Few	Excellent daily counts, Est. of storm duration for VDS counts (Installation of recording rain gauge)	No problems Excellent collection and shipping ~2 days	No problems, Low values associated with site increased relative error
Snoqualmie Pass	No problems Winter freeze-up Jan-Mar 15, 1980	No problems Infrequent clogging	Foundation washed out (Replaced by next storm) Tank overflowed 12 times	Excellent daily counts VDS est. as for Van. (Possible install. of recording rain gauge)	Multiple compositing of storms due to infrequent sampling (New sampler will sample on demand	No problems
Montesano	Questionable drainage area-contribution of flow from bridge section (proposed dye tests)	No problems Infrequent clogging	Long duration storms caused frequent overflow 15 times (Installation of flowsplitter)	Poor daily counts, counter 35 mi to E, VDS est. accord to Van. (Installation of counter and recording rain gauges)	Infrequent sampling during winter period (Will now sample twice a week or more of necessary)	Problems due to high solids as above
Pasco	Site below grade, Sand in sampling equip., Possible inaccurate drainage area (Proposed flushing tests)	Frequent clogging (Installation of netting on collection grate)	Tank floated twice, low winter runoff volumes due to snowfall (Install. of drywell and concrete tank)	Poor daily counts, VDS est. as above (Installation of counter and runoff duration recorder)	No problems Approximately shipping time - 2 days	Problems due to high solids as above
Spokane	Initial vandalism (Installation of cage around site) Winter freeze-up	No problems Infrequent clogging	Multiple composite winter storms due to freeze-thawing of run-off	Poor daily counts, VDS est. as above (Install. of counter in 5/80 and runoff duration recorder)	No problems, Site is sampled on demand, approximate shipping - 4 days	Problems due to high solids as above
Pullman-8	Repeated vandalism Animals reported in flowsplitter (site moved 5/80)	Frequent clogging (Installation of netting)	Grab samples only due to winter freeze-up of site	No daily counts	No problems	Problems with total sulfur test replaced with SO^4 test
Pullman-9	Same as site 8 (Cage built around site)	Same as site 8	Same as site 8	No daily counts	No problems	Same for site 8

RESULTS

Composite sampling throughout the state using a flowsplitter composite sampling system is predicated on several major assumptions. These conditions include:

1. The flowsplitter will accurately sample, with minimal error, a constant fraction of a wide variety of runoff flows which can be seen at a site.
2. The flowsplitter will split without any bias, a constant fraction of the particulate and dissolved pollutants in the runoff.
3. A representative sample can be extracted from the runoff collection tank.
4. The runoff samples may be collected periodically and shipped unrefrigerated with no significant degradation of the sample.

Clark (4) in his thesis concluded that the flowsplitter could accurately sample a wide range of runoff flows. In laboratory calibration tests, he determined the flowsplitter was capable (within a 15 percent uncertainty) of accurately removing a fixed fraction of the total flow in the channel proportional to the flow rate. In addition he showed that the flowsplitter composite sampling system could provide a representative stormwater runoff sample similiar to one composited from an automatic discrete sampling system.

Specific laboratory tests and procedures established in the initial year of analysis at the I-5 and SR-520 sites were continued in this project (4,26,11). The methods and the associated errors for these procedures are summarized in Table 4.

Table 4. Methods Used in the Analysis of Highway Stormwater Runoff.

Pollutant Test	Procedure				Analysis		Averaged Estimated Laboratory Error %
	Standard Methods	EPA Methods of Chem. Analysis	Atomic Absorption Method	IR Carbon Analysis	Initial within 48 hours	Later Frozen or Preserved	
TSS	X				X		15
VSS	X				X		15
COD	X				X		10-15
TOC	X			X		X	12-38
Grease & Oil		Freon-extraction & distillation, then run as TOC		X		X	18-53
Lead			X			X	12
Zinc			X			X	9
Copper			X			X	7
NO_3-NO_2-N		X				X	16
TKN		Micro X				X	18-100
Total Phos.	X					X	14
Chloride	Specific Electrode X					X	8
Specific Conductance	X				X		Serious Solids Inhibition Problems w/test.

Initial analysis, usually completed within 60 hours after receipt of the sample included: total suspended solids (TSS, TSS=total nonfilterable residue (31)), volatile suspended solids (VSS, VSS=volatile nonfilterable residue (31)), chemical oxygen demand (COD), conductivity and pH. During this time a representative aliquot of the sample would be taken and the initial processing for analysis of: the metals (lead, zinc, copper), the nutrients (total phosphorus, Kjeldahl nitrogen, nitrate-nitrite nitrogen), the organics (total organic carbon, grease and oils as carbon) and chloride concentrations would begin.

To minimize operator bias and to maintain an internal standard of accuracy each specific pollutant parameter test was performed by the same individuals during the 1979-80 sampling period. While the quality checks all reported an acceptable variation, samples from highway runoff showed a much greater deviation between replicates in the reported COD, TSS, and VSS values. Much of this deviation can be attributed to the particulates, for the greater the total suspended solids concentration, the larger the variability reported between replicate samples. Clark (4) and Horner (11) both reported similiar observations.

A field test to determine the efficacy of the sampling procedure for the runoff sample collection tank was performed after storm 120 at the I-5 site. Previous results indicated that the current procedure to "vigorously stir" the tank for three to five minutes with a canoe paddle and then to immediately sample would produce a representative sample. To confirm the results the test involved sampling after 0.0, 0.5, 1.0, 3.0, and 5.0 minutes of stirring. A ten minute interval between each period allowed for partial settling of the particles after mixing from the previous test. No noticeable difference was observed.

To test the feasibility of shipping unrefrigerated highway runoff water samples taken from the various sites, a sample degradation study was undertaken. The major concern in degradation of the sample was the oxidation and loss of the organic compounds in COD, TOC, VSS, and grease and oils parameter tests. The results indicated no degradation of the samples during the maximum expected transit period of six days.

The distribution of the monitored events at the nine sites from September 1979 to June 1980 are presented in Table 5.

Table 5. Monitored Storm Events at the Runoff Sites

Site	no. of events	Monitoring Period
I-5*	54	9-79 to 6-80
SR-520*	43	9-79 to 6-80
Vancouver	61	8-79 to 6-80
Snoqualmie Pass	12	9-79 to 1-80, 4-80 to 6-80
Montesano	27	10-79 to 6-80
Pasco	17	9-79 to 3-80, 5/80 to 6-80
Spokane	6	9-79 to 6-80
Pullman - 8	9	9-79 to 6-80
Pullman - 9	6	9-79 to 3-80
Pullman - control	6	4-80 to 6-80

*This report is based on data only gathered during the 1979-1980 sampling season at these sites. Previously collected data from these sites are included in the Water Quality Data Set[34]--from the Highway Runoff Project and reports by Tseng[26] and Clark.[4]

Seasonal summaries from the various sites for each specific pollutant are presented. The fall-spring seasonal period corresponds to the period from September 1 to October 31, 1979, and April 1 to June 1,

1980. The winter period corresponds to the period from November 1, 1979 through March 31, 1980. Sites in which sampling was not complete for a specific period are noted on the summary tables. Specific traffic, precipitation and runoff volumes for the seasonal periods at each site are presented in Table 6.

The basic unit used in the presentation of the seasonal data is weight per unit area (lb /Ac). This unit was initially chosen since it could be equally applied to all the sites and could act as a common denominator for the comparison of the pollutant runoff loads. The pollutant mass for a storm event is calculated as follows:

$$PM = \frac{K\ C\ RV}{A}$$

where PM = pollutant mass (lbs/Ac)
C = concentration (mg/l)
A = drainage area (Ac)
K = conversion coefficient
$6.245 \times 10^{-5}\ \frac{lb - l}{mg\ ft^3}$

And the runoff volume is determined by:

$$RV = \frac{\text{total volume in composite tank } (ft^3)}{\text{flowsplitter splitting fraction}}$$

for the SR-520 site the major leakage in the expansion joints resulted in lower coefficients and required an expression;

$$RV = 269.5 \times \text{rainfall (in)}$$

The total error propagated in the calculation of the seasonal pollutant runoff loads as displayed in the seasonal summaries exhibits an average coefficient of variation of 25 percent. This assumes that the measurements of the drainage area, runoff volume and concentration values are independent, and are based on average variations in the concen-

Table 6. Seasonal Rainfall, Runoff and Traffic Data

Site	Fall - Spring Period				Winter Period			
	Rainfall (in)	Runoff (ft^3	Total Traffic	Traffic During	Rainfall (in)	Runoff (ft^3)	Total Traffic	Traffic During
I-5	9.60	33,600	6,000,000	444,000	26.3	74,400	8,460,000	1,960,000
I-5 w/grit	4.70	26,100	2,990,000	233,000	7.27	16,400	2,030,000	547,000
SR-520	9.66	2,530	4,420,000	374,000	24.2	7,210	4,570,000	872,000
Vancouver	16.0	5,310	1,370,000	106,000	29.2	5,980	1,210,000	107,000
Snoqualmie Pass	11.5	4,430	985,000	154,000	30.4	15,200	417,000	202,000
Montesano	17.4	18,600	881,000	168,000	49.7	35,900	970,000	447,000
Pasco	2.56	7,040	150,000	2,900	2.17	10,600	375,000	5,600
Spokane	3.02	1,250	2,080,000	144,000	5.86	4,500	2,790,000	331,000
Pullman-9	3.88	2,120	--	--	--	--	--	

tration values and runoff volumes of 15 percent, and drainage area of 10 percent.

Conversion of pollutant runoff loads or rates presented in this report from English to corresponding metric units are facilitated by:

$$kg/Ha = lb/Ac \cdot 1.12$$

$$kg/Ha\text{-centimeter rain} = lb/Ac\text{-in rain} \cdot 0.441$$

or

$$kg/curb\ km = lb/curb\text{-}mi \cdot 0.282$$

$$kg/curb\ km\text{-centimeter rain} = lb/curb\ mi\text{-in rain} \cdot 0.111$$

where curb mile equals the length of highway in only one direction (1/2 half the total width) and lane mile is equal to curb mile multiplied by the number of lanes in that direction.

Seasonal summaries of total suspended solids data are presented in Table 7.

Comparison of TSS, COD and lead seasonal pollutant runoff rates from this project with other studies by Metro (12), Sylvester and DeWalle (25) and Envirex (9) are displayed in Table 8. As can be seen from this table, seasonal loading rates from this project are similar to previously reported northwest studies.

During the period of this report two major eruptions occurred from the Mount St. Helens volcano which resulted in the deposition of ash at five of the highway runoff sites. Table 9 lists the sites involved, along with the deposition amounts and subsequent storm TSS characteristics.

Table 7. Seasonal Summaries for Total Suspended Solids

Site	Fall - Spring Period				Winter Period			
	Concentration (mg/l)		Pollutant Loading	Monitoring Period	Concentration (mg/l)		Pollutant Loading	Monitoring Period
	Average	Range	(lbs/acre)	(days)	Average	Range	(lbs/acre)	(days)
I-5	115	32-452	198	120	220	47-848	839	150
I-5 w/grit	203	50-741	272	60	443	54-1370	372	30
SR-520	272	76-894	434	120	402	97-854	1830	135
Vancouver	48	13-140	58	150	119	16-168	162	150
Montesano	155	95-335	379	90	248	51-1260	2780	150
Pasco	199	38-587	85	75	168	19-512	56	135
Spokane	1278	67-2490	238	120	331	85-968	742	150
Pullman-9	64	14-522	28	90	-	-	-	-
Snoqualmie Pass	49	23-117	76	120	400	30-586	2120	60

Table 8. Comparison of the Seasonal Runoff Rates from Washington State and Envirex Runoff Sites

		I-5	SR-520	Vancouver	Montesano	Snoqualmie Pass	Pasco	Spokane	Pullman-9	Sylvester & DeWolfe	Metro Bellevue	Metro Preston	Envirex[1] All Site	Envirex I-794	Range
Fall-Spring Runoff Rates															
TSS	lb/curb mi-day	36.8	12.4	2.56	20.0	4.13	11.5	12.6	0.80	10.8	34.7	13.3	13.2	27.5	0.8-36.8
	lb/curb mi-1000 vehicles	0.74	0.34	0.28	2.05	0.54	3.44	0.72	-	0.25	1.74	0.66	0.22	0.53	0.22-1.74
COD	lb/curb mi-day	9.22[2]	6.39	3.25	9.27	9.59	5.12	10.6	1.67	5.80	23.4	9.60	7.80	20.9	1.67-23.4
	lb/curb mi-1000 vehicles	0.18[2]	0.17	0.36	0.95	1.24	1.54	0.61	-	0.14	1.17	0.48	0.13	0.41	0.13-1.54
Pb	lb/curb mi-day	0.12	0.60	BDL	0.03	BDL	BDL	0.02	BDL	1.64	0.13	0.10	0.06	0.30	BDL-1.64
	lb/curb mi-1000 vehicles	0.002	0.002	BDL	0.003	BDL	BDL	0.001	-	0.04	0.0065	0.0049	0.0011	0.01	BDL-0.04
Winter Runoff Rates															
TSS	lb/curb mi-day	101.	46.3	7.1	88.0	234.	2.53	31.1	-	N/A	N/A	N/A	N/A	108.	2.53-108.0
	lb/curb mi-1000 vehicles	1.50	1.37	0.87	13.6	33.7	0.91	1.67	-	N/A	N/A	N/A	N/A	1.83	0.87-33.7
COD	lb/curb mi-day	22.7[2]	25.9	4.02	28.1	53.5	2.71	20.2	-	N/A	N/A	N/A	N/A	69.3	2.71-69.2
	lb/curb mi-1000 vehicles	0.40[2]	0.77	0.50	4.34	7.70	0.98	1.07	-	N/A	N/A	N/A	N/A	1.32	0.40-7.70
Pb	lb/curb mi-day	0.43	0.17	BDL	0.12	0.11	0.003	0.06	-	N/A	N/A	N/A	N/A	0.82	BDL-0.82
	lb/curb mi-1000 vehicles	0.006	0.005	BDL	0.02	0.02	0.001	0.003	-	N/A	N/A	N/A	N/A	0.02	BDL-0.02

1 Yearly TSS Runoff Rate
2 Does Not Include Grit Fraction

Table 9. Volcanic Ash Deposition on the Runoff Sites

Site	Date of Erruption	Deposition (in.)	Event no.	Rainfall (in.)	Subsequent Date	Storm Event TSS Runoff Load lb/Ac	Storm Event TSS Runoff Rate (lb/cb-mi-1000 vps VDS)
Pasco	5-18-80	Trace	17	1.0	5-27-80	50	320
Pullman	5-18-80	0.5	NS	0.37	NS	NS	NS
Spokane	5-18-80	0.8	7	0.31	6-10-80	580	700
Montesano	5-25-80	0.2	27	1.05	6-2-80	550	440
Vancouver	5-25-80	<0.1	59	0.66	5-28-80	30	70

NS = no sample

As expected the subsequent storm events exhibited increases in the TSS runoff rates between 7 to 20 times the average all-spring values, with the largest increases observed at the greater ash deposition sites.

No increases were observed in the pollutant runoff rates at any of the sites as analysis of the ash samples from Montesano and Spokane indicated low pollutant levels associated with the solids as displayed in Table 10. (These values are consistent with the Battelle study on volcanic ash in reference 36.)

Table 10. Composition of Lead, Zinc, and Copper in Volcanic Ash

Site	Location of Collected Ash Sample	Collection Date	Average Metal Concentration (ppm-Ash) Pb	Zn	Cu
Montesano	highway shoulder adjacent to site	6-1-80	7	14	13
Spokane	from rain gauge	6-10-80	10	24	27

Removal of the ash deposited on the highway in the Spokane and Pullman areas was accomplished primarily from plowing and flushing the roadway by WSDOT maintenance personel. Ash was reported on the highways in these areas for approximately 10-15 days after deposition, due to the large amounts of ash being redeposited daily by winds and resuspended by vehicular traffic. Approximately twenty-four hours after the second major eruption, a majority of the ash had been removed from the driving lanes at the Montesano and Vancouver sites. Ash was still observed on the distress and median lanes during this period and subsequent rainfall (>1.0") at both locations on May 26-27 and again on May 30 removed the ash off the highway.

Analysis of the previously presented data indicates that the individual traffic and storm parameters such as: traffic volumes during or preceding the storm, the length of the dry period, or the rainfall intensity/duration/volume characteristics seem to exhibit little influence on the TSS runoff loads at the I-5 and SR-520 sites. In Table 11, the simple correlation coefficients ("r values") from the analysis of these parameters with TSS runoff loads for the I-5 and SR-520 sites are listed. As can be seen from Table 11 little correlation exists on an individual storm basis.

Tseng's (26) work with the SR-520 data during the 1978-79 sampling period indicated that a possible relationship may exist between cumulative rainfall or runoff volume and the cumulative pollutant mass. These plots impose an interstorm relationship which helps to reduce discrepancies associated with the individual storm and pollutant data,

Table 11. Simple Correlation Coefficients (r values) for Site and Storm Characteristics and TSS at the SR-520 and I-5 Sites

	Vehicles During Storm	Vehicles Preceding Storm	Dry Days Before Storm	Precipitation	Average Intensity	Peak Intensity
TSS SR-520	0.46	0.14	0.23	0.45	0.28	0.50
TSS I-5 w/grit	0.62	0.28	0.31	0.71	0.17	0.62

and may improve the relationship between pollutant runoff loads (lb/curb mile) and the storm and traffic parameters.

From this analysis, only cumulative vehicles during the storm or cumulative rainfall duration exhibit a linear relationship with cumulative TSS (Figure 4a through e). These two parameters display similar relationships with TSS because traffic volumes at the SR-520 site are surprisingly uniform on a daily basis and correlate strongly with rainfall.

The relationship between cumulative (TSS (lb/curb mi.) and cumulative traffic volumes during the storm for the SR-520 site resembles a stair step pattern as displayed in Figure 4e. The fall and spring periods of this graph are characterized by a linear relationship, interrupted by two steps in the slope during the winter period.

A total of 241 storm events were sampled during 1979-80 for the ten sites monitored. For each storm the parameters listed in Table 4 were determined, providing data on solids, COD, TOC, metals, nutrients, and grease and oils. Data were analyzed on a storm by storm basis as well as cumulatively over the year. Correlations with dry days and traffic preceding a storm were not significant (38). Positive correlations were observed for cumulative pollutant loading versus cumulative traffic during storm events. A complete display of these data and correlations are presented by Asplund (38).

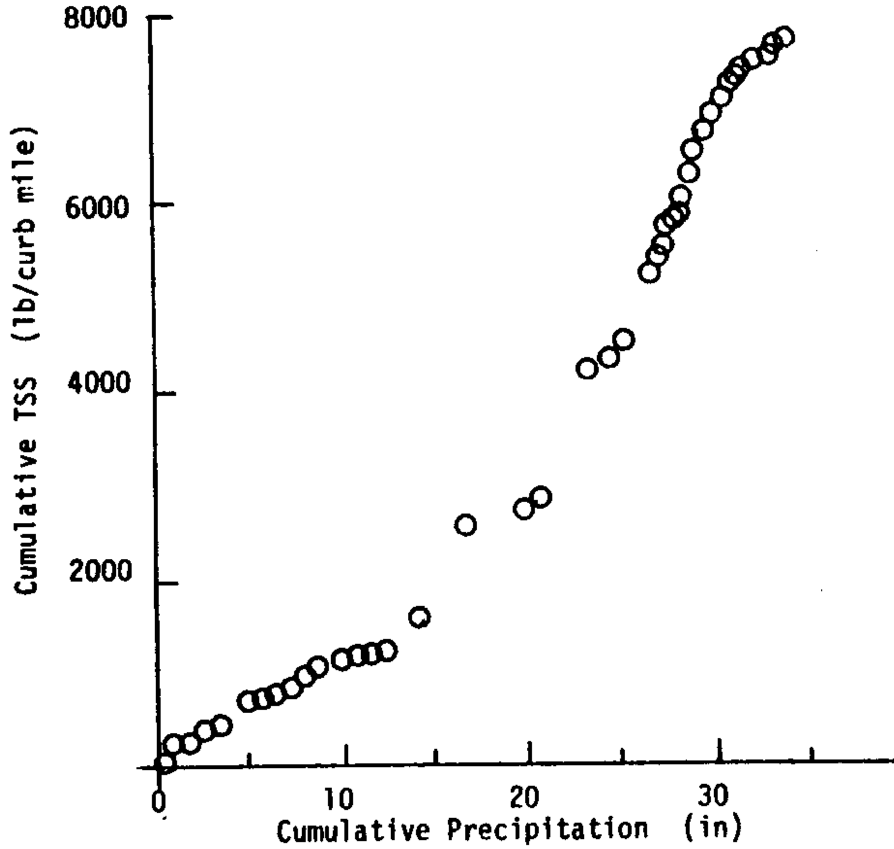


Figure 4a. Cumulative TSS Versus Cumulative Precipitation at the SR-520 Site

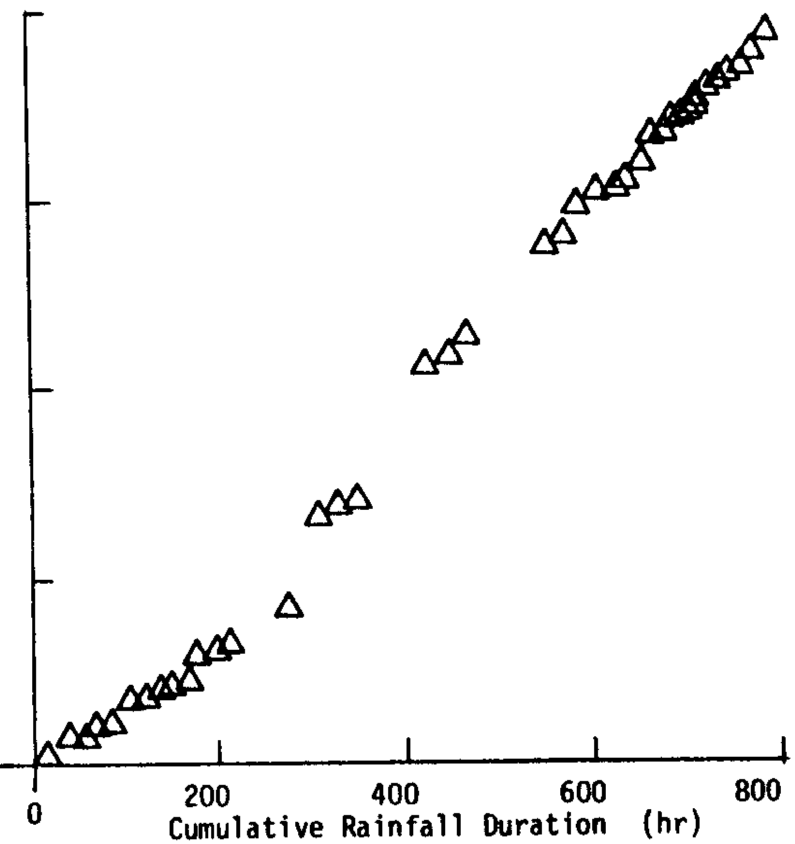


Figure 4b. Cumulative TSS Versus Cumulative Rainfall Duration at the SR-520 Site

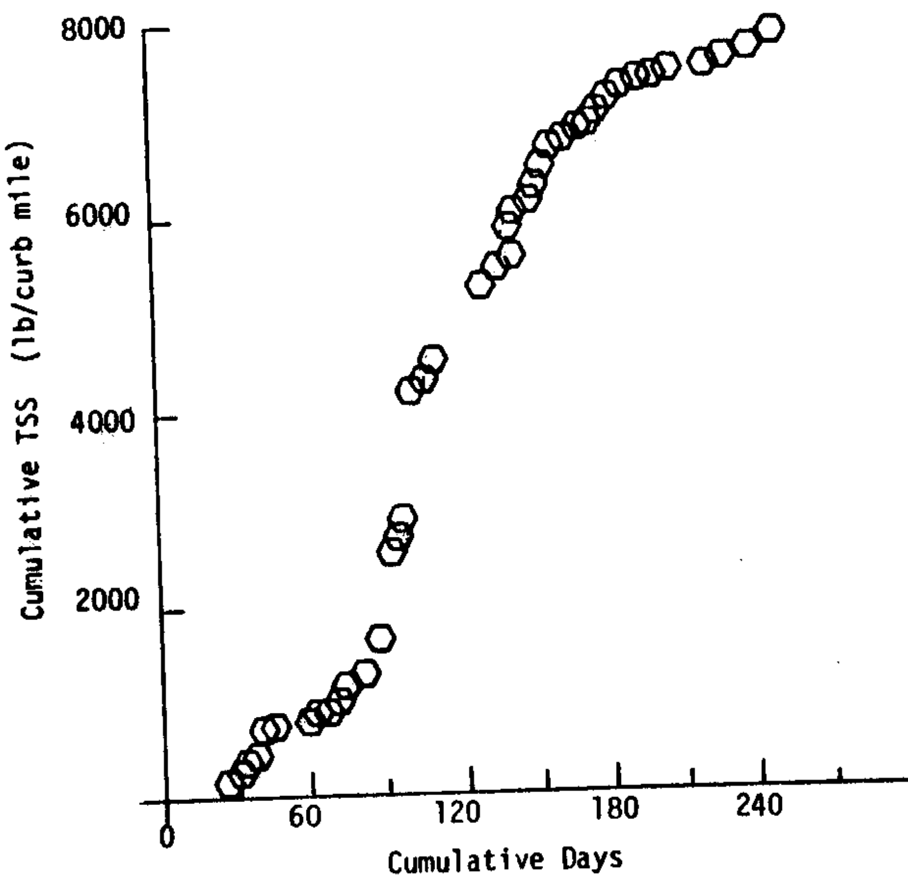


Figure 4 c. Cumulative TSS Versus Cumulative Sampling Period for the SR-520 Site

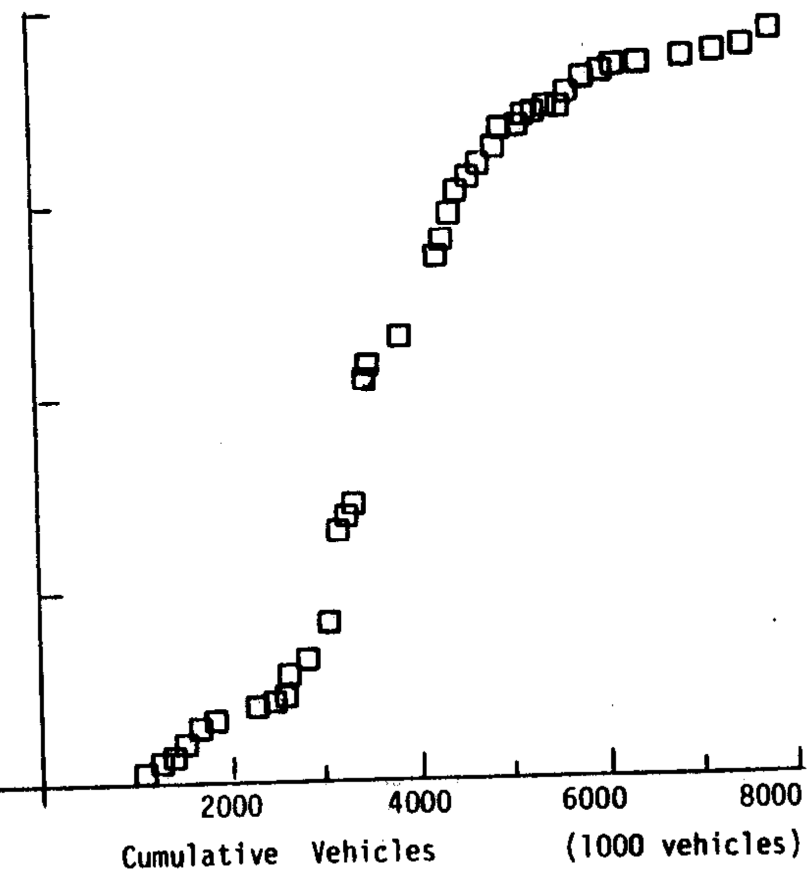


Figure 4 d. Cumulative TSS Versus Cumulative Traffic Volumes for the SR-520 Site

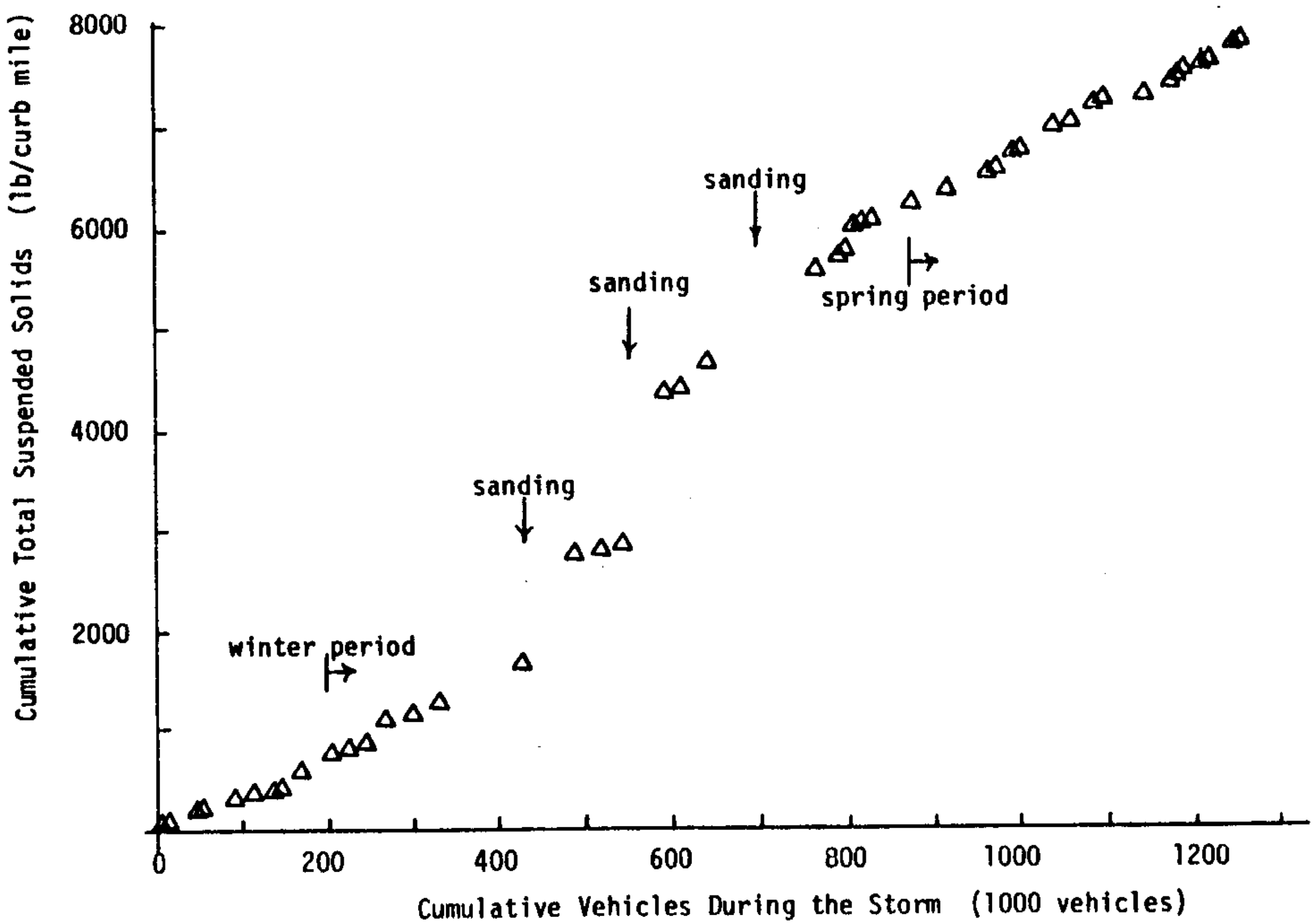


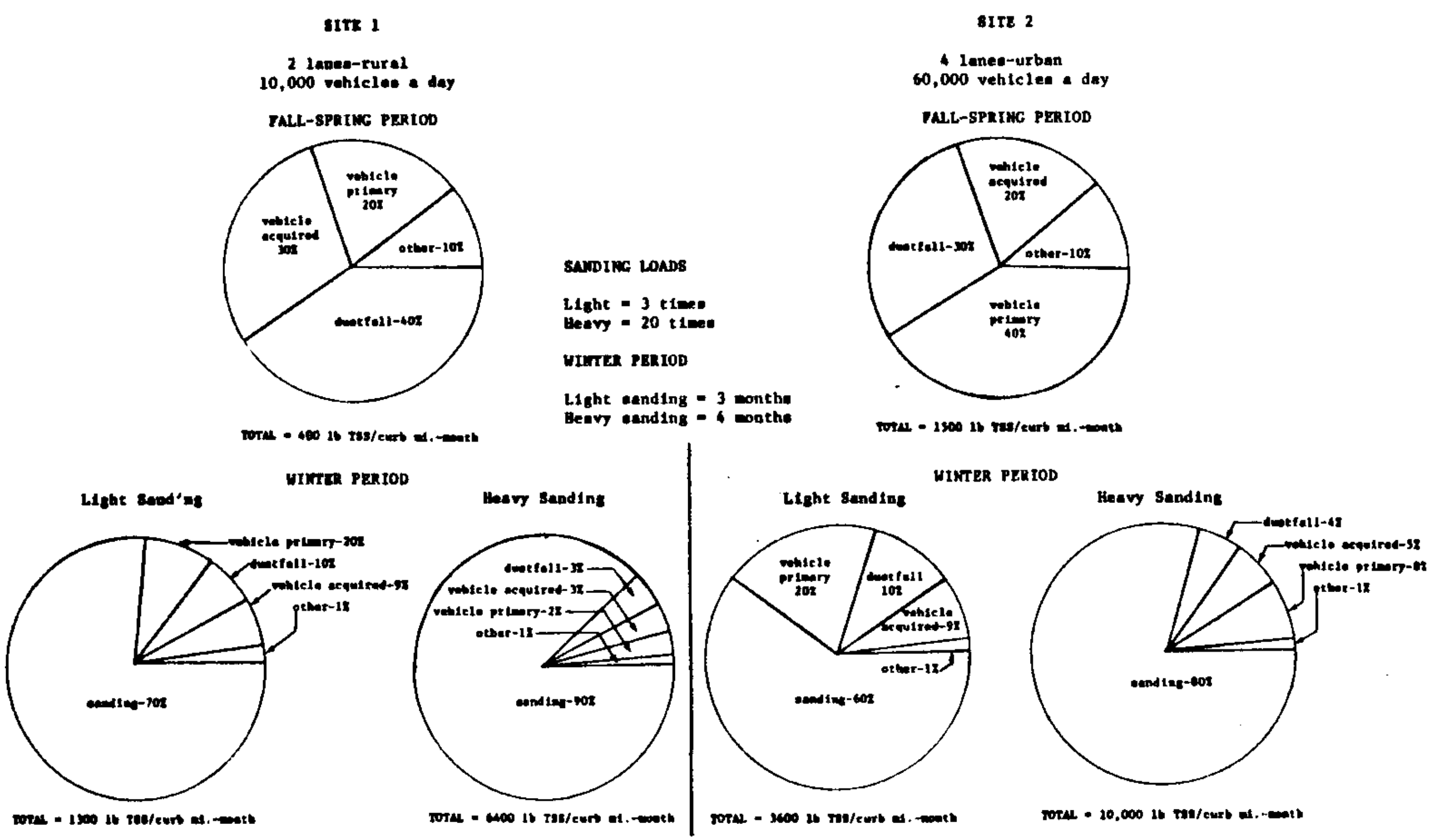
Figure 4 e. Cumulative Total Suspended Solids Versus Cumulative Traffic Volumes During the Storm for the SR-520 Site

DISCUSSION OF RESULTS

The possible sources of highway pollutants, their deposition and removal mechanisms, and parameters influencing the pollutant mass in highway stormwater runoff as reflected by these field data suggest:

1. A stair-step function exists between the relactionship of cumulative TSS and cumulative VDS. During the fall-spring period the majority of the TSS in the runoff is related to traffic volumes during the storm. During large winter storms the steps are observed and are related to the increased contribution from non-vehicle related solids, such as sanding operations, and non-highway runoff solids. Volcanic ash would also introduce steps in these correlations.
2. For most sites, the relationship between pollutant and TSS appears to be linear until excess amounts of TSS are encountered. When there is insufficient pollutant amounts present to saturate the TSS, the ratio will fall.
3. Development of a pollutant runoff model is possible given the vehicles during the storm, runoff coefficient, and winter sanding loads.

As illustrated in Figure 5, vehicular traffic, sanding and deicing operations, pavement deterioration, and atmospheric dustfall are all probable major contributing sources of highway pollutants. The type of pollutant deposited and the rate of deposition from each of these sources depends on the influence of the source and site specific parameters. Pavement wear and surrounding land use seem to be only minor contributors of pollutants in highway runoff.



* Note: These values are for TSS deposition loads and are not stormwater runoff loads.

2 Lanes = 4.6 acres = 1 curb mi.
4 Lanes = 7.3 acres = 1 curb mi.

Figure 5. Estimated Monthly Contributions from the Major Sources of TSS for Two Typical Western Washington Highways*.

A composite graph exhibiting the seasonal TSS runoff rates, derived from the observed linear relationships between cumulative TSS and cumulated VDS for the various sites is presented in Figure 6. Generally the lower TSS runoff rates (lb/curb mile-1,000VDS) are observed during the fall-spring season where vehicular traffic and dustfall are probably the principal contributors, where as during the winter period sanding operations may account for the major fraction of the TSS deposited on the highway.

The high TSS runoff rates observed during the fall-spring period at the Pasco site and during the winter periods for the other runoff sites are caused by large increases in the contributions of non-vehicle related solids from other sources. At the Pasco site, the high fall-spring period TSS seasonal runoff rate is attributed to the large estimated dustfall deposition rate, and the corresponding low dry period removal rate, due to the low traffic volumes at the site.

In examining the influence of the runoff coefficent on the fall-spring TSS runoff rate at the western sites, the resulting linear equation as displayed in Figure 7 was observed. From this relationship the mean TSS runoff rate as determined by the western sites is 6.4 lb TSS/ 1,000VDS, (RC corrected). This value represents the pollution generation level on a highway. The high correlation between the fall-spring period TSS runoff rate and runoff coefficient at these sites (CC=0.97) indicate that the storm runoff coefficient and vehicles during the storm are probably the major influential parameters in determining the TSS runoff loads, during this period. Runoff coefficients are a function of leakage from the roadway, splash and wind blown mist, and the

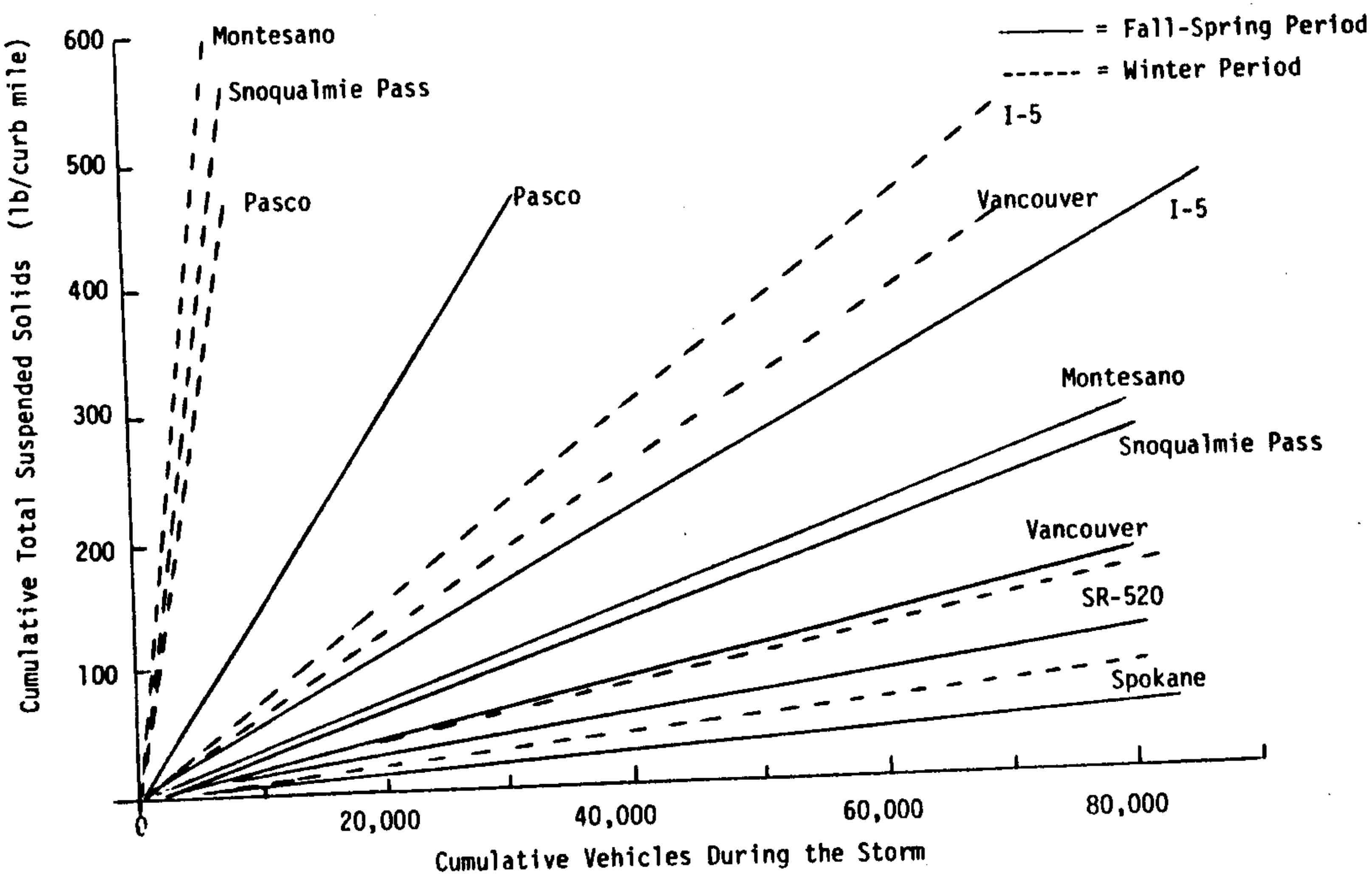


Figure 6. Estimated Seasonal TSS Runoff Rates for the Various Runoff Sites*

*Derived from the observed linear relationships between the cumulative TSS to cumulative VDS plots

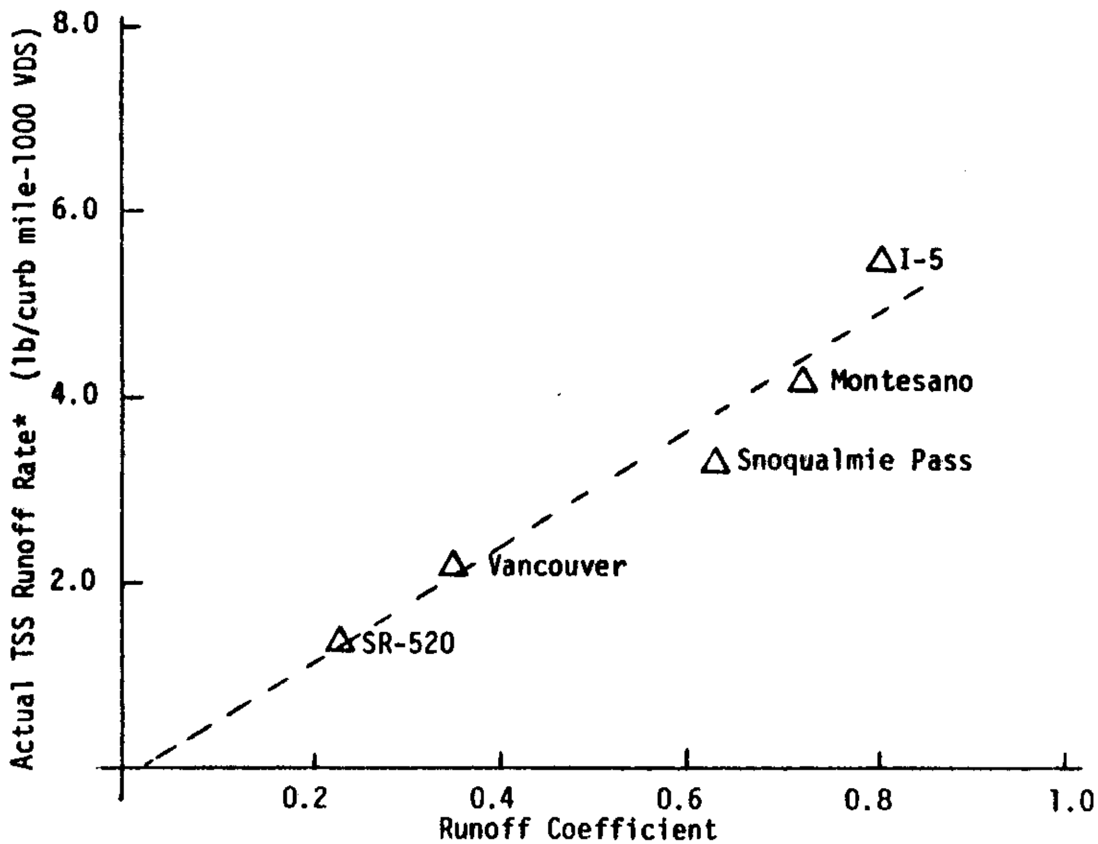


Figure 7. Total Suspended Solids Runoff Rate Versus Runoff Coefficient for the Fall- Spring Period at the Western Sites*.

* Derived from the cumulative TSS to cumulative VDS plots and based on actual runoff loads at the SR-520 site.

geometry on the test area. Runoff that does not enter the collection system should have the same pollution concentrations as the collected runoff.

Several possible interpretations regarding the pollutant deposition-removal process are possible based on the fall-spring linear relationship between cumulative TSS and cumulative VDS. Two interpretations which may explain these linear relationships are:

I.

A majority of the solids observed in highway stormwater runoff are contributed by the number of vehicles crossing the site during the storm. Any solids deposited during the dry periods, preceding the storm would only be a minor contributor to the TSS runoff load. This explanation considers the vehicles during the storm as the major contributor to the total solids stormwater mass. It also suggests effective dry period pollutant removal mechanisms or a minimal deposition of solids during the dry periods; yielding a low amount of solids storage on the road surface to account for the minor contribution to the TSS runoff load from the highway during the storm event.

or II.

A variable fraction of the solids which exist on the highway are washed off during the storm and the amount of the washoff fraction is determined by the traffic volumes during that storm event. This second contrasting interpretation considers the highway as a source of solids of which a major fraction has been deposited during the dry periods preceding the storm. The amount of solids that are scrubbed off the pavement is dependent on the number of vehicles during the storm. In this case the number of vehicles during the storm only contribute a minor fraction of the TSS load in the stormwater runoff and their function is to serve as a removal mechanism by scrubbing the highway surface, instead of a major contributor as in the first interpretation.

The mass of the pollutant-to-total suspended solids can be represented at all sites by a non-linear relationship as presented in Figure 8. The relationship has an initial linear region where the pollutant-to-solids ratio is constant. The slope of an initial linear region for each pollutant is site specific and is determined by the principal sources of the pollutant, the corresponding deposition rates and the mass of the solids deposited on the highway. Asplund (38) presents data for metals and nutrients as well as COD.

The non-linear region of the relationships is characterized by large increases in the TSS mass corresponding to smaller increases in the specific pollutant mass for an increasingly smaller ratio of pollutants-to-solids. The curve in this region could be said to be "pollutant limiting" and ideally the area under the curve should be approaching the total pollutant mass available for the particulate fraction in stormwater runoff.

Equations predicting the pollutant loads in the runoff need to be developed. Since the relationship of pollutants-to-solids are well defined and specific pollutant ratios can be determined by the TSS mass, or as in the case of lead, the TSS runoff rate, estimation of the TSS

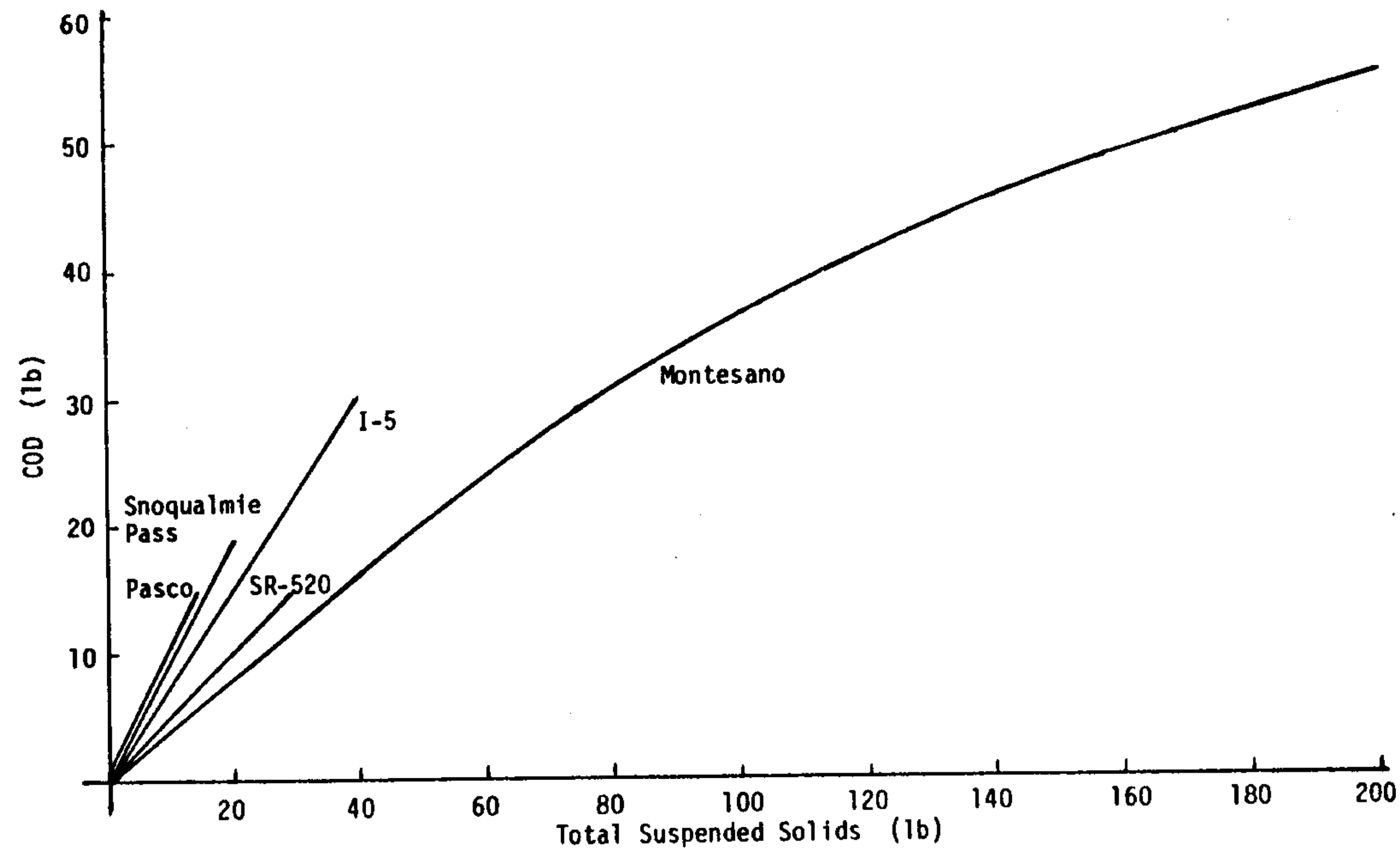


Figure 8. Composite COD to Total Suspended Solids Plot for the I-5, SR-520, Montesano, Snoqualmie Pass, and Pasco Sites

runoff load is crucial, for accurate modeling of the pollutant mass in the stormwater runoff.

Specifically the equations for these relationships are:

$$\text{TSS load (lbs/curb mile)} = (K)(VDS)(RC)$$

$$\text{Pollutant load (lbs/curb mile)} = (K_p)(\text{TSS Load})$$

where the factors are defined as:

K — The TSS runoff rate factor K, is an empirically derived seasonal constant obtained from Figure 7. The value of this factor represents the mass of the TSS in the runoff "associated" with the VDS. For the fall-spring periods at the western sites this value is 6.4 lbs/curb mile-1,000VDS. This factor may vary depending on the principal source of deposited solids as is observed between the fall-spring and winter period runoff rates.

VDS — This variable represents the number of vehicles on the highway section of interest during the storm event. The duration of the storm is considered to run from the beginning and through the rainfall period until the highway is dry.

RC — The runoff coefficient is the ratio of the actual to expected runoff based on the rainfall and the drainage area and its degree of imperviousness. Both the VDS and the runoff coefficient are influenced by the storm characteristics such as intensity, duration, and volume.

K_p — The factor K_p is the ratio of pollutant P to TSS. These values are determined from the specific pollutant-to-solids graphs presented in Figures 8, 9, and 10.

The use of the TSS runoff loading equation is only valid for locations where traffic volumes are the principal TSS source or primary removal mechanism.

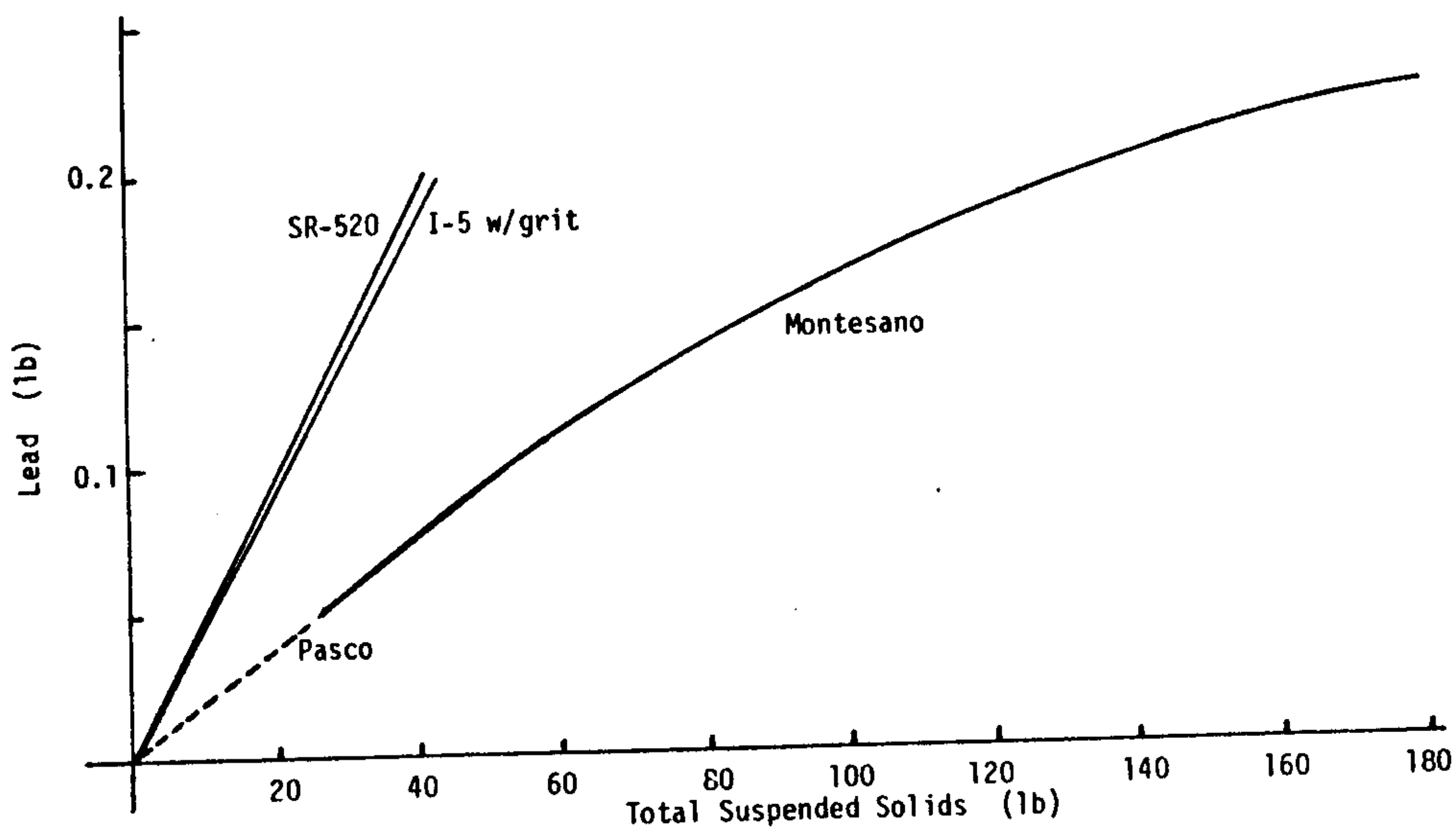


Figure 9. Composite Lead to Total Suspended Solids Plot for the I-5, SR-520, Montesano and Pasco Sites

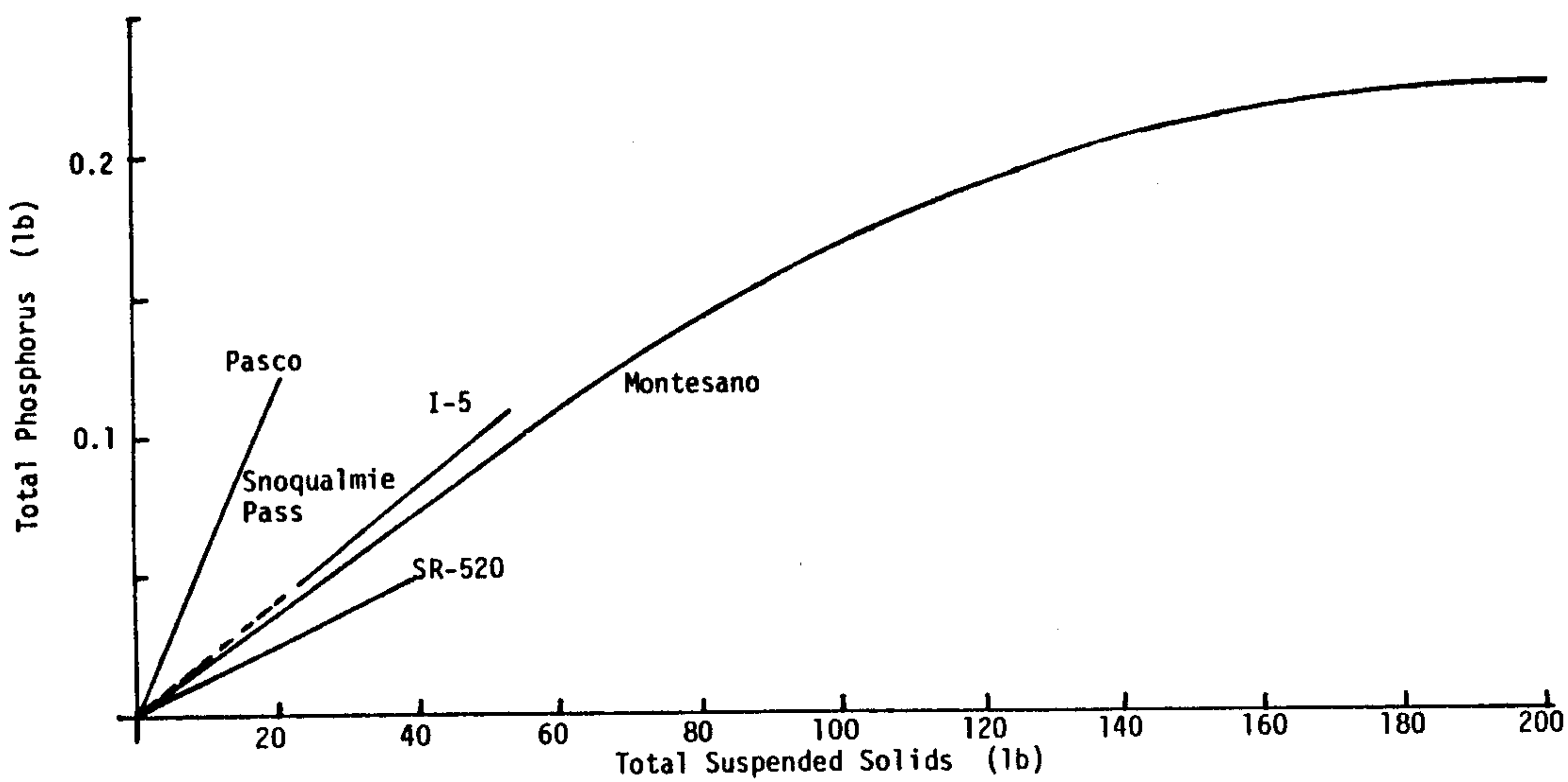


Figure 10. Composite Total Phosphorus to Total Suspended Solids Plot for the I-5, SR-520, Montesano, Snoqualmie Pass and Pasco Sites

More information is required on the amount of TSS contributions by the various sources for the eastern Washington sites and winter sanding loads for all the sites before equations can be developed which will accurately model these conditions.

RECOMMENDATIONS AND CONCLUSIONS

Recommendations:

1. Continued monitoring of all the runoff sites is required to expand the data set and to confirm the observations and trends presented in this report.

2. Information pertaining to WSDOT sanding and sweep/flushing activities including, sanding and sweeping frequency, their associated deposition and removal rates, need to be recorded since these activities can significantly influence the amount and percentage of the observed TSS and pollutant runoff loads.

3. Special studies should be performed to confirm the role sanding, maintenance and land use have in determining the solids and pollutant loads in the storm water runoff.

Conclusion:

1. The traffic volumes during the storm are either a major source or a removal mechanism. These volumes are a function of storm duration.
2. The amount of existing or deposited TSS on the highway determines the pollutant-to-TSS ratio and the amount of pollutants adsorbed (saturation of the solids).

3. Other sources such as dustfall, sanding, spills, accidents, and surrounding land uses contribute to the TSS and pollutant loads on the highway at a variable rate.
4. Comparison of the Envirex urban site (I-794) to the I-5 and SR-520 sites indicate that the pollutant runoff rates at the Seattle sites are 4 to 6 times larger than the Envirex site.

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