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Highway Runoff

Water Quality

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Highway Runoff in Washington State:

Model Validation and Statistical Analysis

A report prepared for the
Washington State Department
of Transportation Highway
Runoff Water Quality
Research Project

by

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ABSTRACT

Statewide sampling of highway runoff continued through 1980 - 81, and the resulting data has been aggregated with that from previous years to further investigate pollutant loadings. Results have validated the solids loading model previously proposed by Asplund (1980) for Western Washington highways and tentatively extended the model to Eastern Washington. Loadings of other pollutants can be predicted from total suspended solids loading using ratios derived from the data. These ratios may be taken as constants at any Washington State location for some pollutants or as linear functions of traffic for other contaminants. Comparison of runoff from a sulfur-extended asphalt pavement with runoff elsewhere indicates higher sulfate loads in the former case. A limited sampling program along an uncurbed highway section observed higher pollutant concentrations from these sections relative to curbed areas. Sampling of solids adhering to the undercarriage of automobiles produced widely varying results but suggested that vehicles traveling on rural or unpaved roads accumulate significant amounts of solids that can be released on highways. The final year of field sampling will concentrate on improving the loading models, especially for Eastern Washington application, and continuing the sulfur-extended asphalt study with a functional control site experiencing the same conditions.

TABLE OF CONTENTS

Page

INTRODUCTION

A five-year program is being sponsored by the Washington State Department of Transportation to determine the water quality impact of highway runoff. As a part of this program, previous researchers have provided an extensive literature review (Horner _et al._, 1977; Tseng, 1979; Aye, 1979; Clark, 1980; Eagen, 1980; and Asplund, 1980), characterized an urban runoff site (Tseng, 1979), developed a continuous composite sampler (Clark, 1980), established criteria and requirements for statewide runoff monitoring sites (Aye, 1980), and identified trends for pollutants found at ten selected sampling sites (Asplund, 1980; Chui, 1981).

The major topics covered in this report are:

1. Validating a predictive model proposed by Asplund (1980) with data collected between 1979 and 1981.
2. Establishing a relationship between total suspended solids and other pollutants.
3. Comparing runoff samples from sulfur asphalt pavement with conventional highway pavements.

Highway runoff is not recognized in most literature as a separate constitutent in nonpoint source pollution (Browne and Grizzard, 1979; Browne, 1981). Its threat to water resources has traditionally been aggregated with general urban runoff, the problems of which were compared with those caused by sewage effluent. This comparison has been expressed in terms of both concentration and mass/unit time loading (Pitt, 1978).

There is a growing awareness of the impacts, both short- and long-term, of highway runoff on receiving water bodies (Howell _et al._, 1979). Short-term impacts such as toxicity have been observed in algae growth (Portele, 1981; Winter _et al._, 1980), but long-term impacts on benthic macroinvertebrates are not conclusive (Howell et al., 1979). Impacts on juvenile trout are associated with particles transported by runoff, resulting either from the physical effect of gill clogging or irritation created by toxicants sorbed on the particles (Portele, 1981).

The literature suggests the following factors influence the water quality of highway runoff: precipitation patterns, volume and intensity; traffic volume; local land use; geological characteristics; highway maintenance practices and highway drainage design (Asplund, 1980; Kobriger et al., 1981; Meinholz et al., 1978; Tseng, 1979; Horner et al., 1977). Precipitation determines the length of time contaminants accumulate on the highway, the energy with which they are removed and the volume in which they are diluted. Traffic volume determines the amount of and the types of pollutants associated with normal vehicle operation, as well as the accompanying residues of road wear. Local activities such as construction and agriculture can contribute substantial amounts of sediment to highway surfaces. Vehicles connected with these activities or those traveling on unpaved roads "acquire" dirt for later deposition (Asplund, 1980). Highways in semi-arid regions can receive significantly greater quantities of material transported by winds compared to highways in more highly vegetated areas. Sweeping or sanding operations can remove or add pollutants on highway surfaces. The length of the flow paths (curbing versus no curbing) seems to be a major factor that determines the removal efficiency of pollutants via stormwater runoff (Asplund, 1980). Finally, accidental spillage or recreational vehicle wastes, agricultural or chemical products, and oil and gasoline losses from accidents are infrequent but often significant contributors of pollutants (Eagen, 1980).

A number of extensive models of nonpoint source water quantity and quality have been developed for the purposes of pollution control planning and design evaluation. The Stormwater Management Model (SWMM); Storage, Treatment, Overflow and Runoff Model (STORM); Nonpoint Source Pollutant Loading Model (NPS) and Storm and Agricultural Runoff Management Model (ARM) are typical models available to describe runoff from various watershed types.

Two basic models have been proposed for highway runoff accumulation water quality: (1) a deposition/washoff model applied to accumulation before and removal by individual storms; (2) a model of mass loading over time proposed for Washington State highways (Asplund, 1980; Asplund _et_ _al_., 1980, 1981). Models of the former type have been developed by Sartor and Boyd (1972); Sylvester and Dewalle (1972) and Envirex, Inc. (Kobriger _et_ _al_., 1981; Meinholz _et_ _al_., 1978).

The Envirex Model is based on data from five freeway sites representing some variation in highway design, traffic and climate. It predicts the total solids (TS) load in runoff from individual storms and has two major components: accumulation of pollutant and pollutant wash-off. Accumulation is modeled according to a linear function depending on accumulation period and traffic volume. Wash-off is expressed as an exponential function according to the runoff rate. The model also computes runoff volume from different highway types. Pollutants other than TS are predicted by linear regression from TS. The Envirex Model is summarized in Table 1.

Based on data collected during 1979 and 1980 from a series of Washington State highway sampling stations, the following model was proposed:

$$\mathrm{TSSL} = (K$$

$$\mathrm{SPL} = (K_p$$

Table 1: Summary of Envirex Model.

Type	Description	K_2	Runoff Volume	Flow Duration
I	Urban, elevated bridge deck 100% paved w/impact barriers containing each set of lanes, Milwaukee I-794	5.0	$Q = 0.969R - 0.018T$	$FD = 1.12RD + 0.69$
II	Mountable curbs w/paved and non-paved drainaged area, Milwaukee Hwy 45, Nashville I-40, Denver I-25	6.5	$Q = 0.470R^{1.369}\ DD^{-0.0858}$	$FD = 1.06\ RD + 1.179$ $(DD \geq 10)$ $FD = 1.27\ RD + 2.15$ $(DD < 10)$
III	Rural sites w/flush shoulder paved and non-paved runoff through ditches; Harrisburg I-81	12.0	$Q = 0.845R^{1.892}\ DD^{-0.654}$	$FD = 1.92\ RD + 4.18$ $(DD \geq 10)$ $FD = 1.48\ RD + 8.29$ $(DD < 10)$

POLLUTANT ACCUMULATION $P = Po + K_1 * HL * T$ where $K_1 = 0.007\ ADT^{0.89}$

POLLUTANT WASH-OFF $P_D = P(1 - e^{-K_2 * r})$ where $r = Q/FD$

VARIABLE DEFINITION

K_1 = pollutant accumulation rate (lb/mi-day)
K_2 = pollutant wash-off rate (hr/in)
Po = initial surface pollutant load (lb)
P = pollutant level after buildup (lb)
P_D = pollutant discharged (lb)
HL = highway length (mi)
T = time of accumulation (day)
r = average runoff rate (in/hr)
Q = runoff volume (in)
FD = flow duration (hr)
RD = rain duration (hr)
DD = number dry days prior to the event
ADT = average daily traffic
R = rainfall (in)

where: TSSL = total suspended solids (TSS) load (lb/curb-mi)

VDS = vehicles during storm (1000 vehicles), where the storm is considered to be the total period during which the roadway is wet

RC = average runoff coefficient, the flow volume:runoff volume ratio (dimensionless)

SPL = specific pollutant load of pollutants other than TSS (lb/curb-mi)

K = TSS runoff rate (6.4 lb TSS/curb-mi/1000 VDS)
K was empirically developed for fall-spring loads observed among the sampling sites west of the Cascade Mountains.

K_p = specific pollutant:TSS ratio, similar to the potency factor employed in NPS, SWMM and STORM

The model was validated and is intended to apply over the long-term (monthly or annually), rather than on an individual storm basis.

In the Washington State model, traffic volume, observed when the highway pavement is still wet, is a major factor in determining the quantity of pollutants expected in the stormwater runoff. This feature contradicts the Envirex Model, where the average runoff rate determines the amount of pollutant found in runoff, and follows from fundamental differences in the precipitation patterns at the sites providing the data bases. The Envirex sites generally experience relatively intense but brief storms, whereas Western Washington State has extended rains of low intensity. Asplund (1980) suggested that vehicles traveling on a dry road retain some material on the undercarriage and generate winds which remove other particles from the highway. While the roadway is wet, splash removes the retained material, which may either be sprayed from the highway or join the runoff. In the Pacific Northwest, transport of highway contaminants appears to be more a function of kinetic energy provided by moving vehicles than by rainfall.

EXPERIMENTAL EQUIPMENT AND PROCEDURES

Highway Runoff Sampling

Ten sampling sites representing varying climatic conditions, traffic and surrounding land uses were selected across the State of Washington. Their specific locations and characteristics were described by Asplund *et al*. (1980, 1981). During more than two years of operation, approximately 500 storms were monitored at these sites. Asplund *et al*. (1980, 1981) documented the results through Spring 1980, and the work reported here expands that data base by 260 storms monitored in 1980 - 81, employing the total data set in the analysis (Chui, 1981).

Sampling at each site is accomplished with the use of the composite sampling system developed and tested by Clark (1980) and described by Clark and Mar (1980) and Clark *et al*. (1981). The system consists of a flow splitter discharging to a composite sample tank. Vertical dividers placed parallel to the flow enable the flow splitter to divert a set fraction of the runoff to the tank. Water depth in the tank is gauged to estimate total runoff volume, and the contents are thoroughly mixed prior to sampling. A plastic bag liner prevents cross-contamination of samples. It was demonstrated that loadings obtained with the compositing system are almost identical to those estimated from the results of an automated discrete sampling sequence, when laboratory and flow measurement errors are resolved (Clark and Mar, 1980; Clark *et al*., 1981).

Total precipitation for each storm was measured either by automated, continuously recording rain gauges or manually gauged rainfall collection buckets. Storm duration was determined from the record at automated stations or from the nearest weather station with hourly precipitation records at other sites. The Washington State Department of Transportation (WSDOT) performed traffic counts with automated equipment at or near each sampling location.

1980 Site Maintenance

All sampling sites received routine maintenance during the summer of 1980. A new coat of fiberglass was painted on the inside wall of each flow splitter and composite tank. After the coating dried, the channel surface of the flow splitter was polished uniformly with fine grade sandpaper.

The SR-520 site was terminated after June, 1980 for the following reasons:

1. Results from SR-520 were very similar to results from the I-5 site.
2. There was considerable leakage of stormwater through expansion joints of the SR-520 bridge.
3. The size of the collecting tank was insufficient to capture water from large storms.

A new sampling site, designated I-5* and located adjacent to the initial I-5 site, was installed in July, 1980. The purposes of installing this site were:

1. To verify the pollutant trends observed by Asplund (1980) at the I-5 site.
2. To investigate the effects on water quality of the elimination of the H-flume at the I-5 site.

Due to the configuration of the I-5 site, the H-flume empties into the flow splitter. Settling of solids occurred in the flume, and these solids had to be collected manually.

Specific Site Problems and Solutions

A. I-5 Site

The solids that settled in the H-flume were collected and weighed, and a sample was taken for laboratory analysis. These solids often accounted for more than half of the total suspended solids load. This material was then added back into the storm loads for the events when they were collected. Results for these events are reported as "I-5 w/grit" and are probably better representations of the actual stormwater runoff loads than those which neglected the grit in the H-flume.

B. I-5* Site

The volume of runoff collected was considerably less than expected based on the estimated drainage area. Numerous attempts have failed to explain the low runoff coefficient, but it is suspected that the site is too flat and some of the runoff is lost to an adjacent drainage area. The area used in data analysis was revised based on runoff coefficients of large rainstorms from the adjacent I-5 site.

C. Vancouver Site

Low runoff coefficients were also experienced at this site. The problem was solved in March, 1981, when leakage in the culvert which led to the composite sampling system was located and eliminated.

D. Pasco Site

This site experiences problems of poor drainage and drifting sand. Sand is often found in the flow splitter and in the composite tank. Drifted sand was removed in the Fall of 1981. A continuous recording rain gauge on loan from FHWA was installed in March, 1981 for better estimation of rainfall duration.

E. Pullman-Control Site

Volcanic ashfall plugged the pipe between the splitter and the collector. Repair of the system was inadequate, and the samples were rejected because much of the solids escaped collection. A new pipe has been installed, and it is expected that the site will function normally during the final year of the project.

Laboratory Analyses

Samples were collected from the composite tanks as soon after the storms ended as possible. Those from sites in the Seattle area were transported directly to the laboratory and refrigerated. Those from sites elsewhere in the state were shipped to the laboratory via parcel mail. A previous study (Asplund _et_ _al_., 1980) demonstrated no measurable degradation of the constituents of interest during the mailing period.

Usually completed within 60 hours after receipt of the sample were analyses for total and volatile suspended solids (TSS and VSS) and chemical oxygen demand (COD), all according to the provisions of the American Public Health Association (1975). During this period representative aliquots of the sample were taken and the initial processing done for analyses of total organic carbon (TOC), metals (Pb, Zn, Cu), total phosphorus (TP), nitrate + nitrite - nitrogen (NO_3 + NO_2 - N) and total Kjeldahl nitrogen (TKN). TOC was measured on a Beckman model 865 infrared analyzer. During the early part of the project, metals were analyzed with an Instrumentation Laboratory IL-353 atomic absorption spectrophotometer. Later, most metals analyses were performed with a Jarrel-Ash inductively coupled plasma (ICP) spectrophotometer. TP was determined by the Ascorbic Acid method following persulfate digestion (American Public Health Association, 1975), NO_3+ NO_2 - N on a Technicon Auto Analyzer II using a cadmium reduction procedure and TKN by a micro-Kjeldahl technique.

SUMMARY OF MONITORING RESULTS

Pollutant Concentrations

Table 2 summarizes pollutant concentrations measured in 1980 - 81, including solids added by winter sanding and the Mount St. Helens ashfall. Compared to the pollutant concentrations previously reported by Asplund (1980), TSS concentrations at Western Washington sites not affected by volcanic ashfall were generally lower due to lack of sanding during the mild winter of 1980 - 81. The TSS contribution of volcanic ash is quite evident at sites which received ashfall (Vancouver, Montesano, Pasco and Pullman-9). Spokane also received ashfall, but much was washed from the bridge section at that site by WSDOT clean-up operations and did not enter the runoff sampled.

There were pronounced fluctuations in Pb concentrations, with mean values varying with traffic volume. Spokane had zinc concentrations notably higher than any other site, apparently because of a local smelter.

Pollutant Loading Rates

A wide diversity of units have been used in the literature to express stormwater runoff (Horner et al., 1977). Most common in the case of highway runoff are mass/unit area/unit time, mass/unit highway length/unit time and mass/unit highway length/unit traffic.

Table 3 presents the loading rates in Kg/ha/yr representing all data collected between 1979 and 1981. Table 4 lists loadings in lb/curb-mi/day and lb/curb-mi/1000 vehicles for three major pollutants. In this tabulation the latter unit reflects total vehicles, not just those traveling during storm events. All of these loading expressions were explored in connection with meteorological and traffic variables in statistical analyses. No consistently valid relationships, that might be used in predicting loads, were discovered, however.

Table 2: Summary of Pollutants Concentrations$^{(1)}$ in Washington State Highway Runoff, 1980-81 (including road sand and volcanic ash).

Site	TSS	VSS	COD	Pb	Zn	Cu	TKN	NO_3+NO_2-N	TP
I-5	(97) **106** 552-14 (54)	(51) **37** 428-4 (54)	(181) **150** 1291-34 (54)	(.269) **.466** 1.166-.08 (43)	(.672) **.638** 3.093-.112 (45)	(.041) **.043** .283-.013 (43)	(.671) **1.175** 2.968-.409 (18)	(.784) **1.281** 3.032-.118	(.024) **.226** .671-0 (38)
I-5*	(100) **131** 452-30 (25)	(26) **39** 126-13 (25)	(101) **135** 549-47 (25)	(.766) **.760** 3.775-.304 (19)	(1.084) **.968** 4.769-.201 (19)	(.021) **.043** .112-.021 (19)	(1.152) **1.519** 3.408-0 (6)	(.911) **1.179** 2.863-.234 (6)	(.161) **.224** .726-.090 (23)
Vancouver	(179) **106** 833-21 (35)	(9) **13** 35-0 (35)	(28) **45** 122-4 (37)	(.048) **.073** .165-.002 (21)	(.059) **.056** .186-.003 (11)	(.025) **.025** .093-.01 (21)	(118) **55.0** 339-.387 (14)	(1.910) **1.636** 5.811-.552 (7)	(.078) **.113** .323-.007 (27)
Snoqualmie Pass	(57) **63** 270-13 (31)	(9) **12** 39-1 (31)	(26) **44** 136-14 (32)	(.088) **.086** .408-.010 (19)	(.143) **.101** .559-.002 (15)	(.011) **.022** .053-.006 (19)	(.326) **.335** 1.054-0 (9)	(.584) **.693** 2.430-.129 (13)	(.116) **.150** .479-.047 (22)
Montesano	(2390) **798** 15010-22 (42)	(62) **45** 304-4 (42)	(140) **109** 685-7 (42)	(.926) **.556** 4.184-.032 (26)	(.826) **.380** 4.008-.004 (23)	(.142) **.089** .648-.00 (25)	(1.813) **1.586** 5.832-0 (17)	(1.682) **1.067** 7.321-.094 (19)	(.596) **.441** 2.328-.033 (35)
Pasco	(1165) **570** 5050-31 (20)	(130) **79** 585-9 (20)	(308) **265** 1106-40 (21)	(.188) **.196** .691-.055 (12)	(1.950) **.352** 7.190-.219 (12)	(.029) **1.039** .099-.011 (12)	(7.768) **8.628** 19.43-2.296 (4)	(.503) **.793** 2.070-.287 (10)	(.603) **.666** 2.010-.019 (11)
Spokane	(400) **370** 1037-48 (5)	(66) **65** 174-15 (5)	(148) **219** 437-106 (5)	(.146) **.167** .326-.04 (3)	(2.904) **.929** 10.774-4.96 (5)	(.027) **7.033** .068-.004 (4)	(1.194) **7.156** 6.312-.800 (2)	(.762) **1.208** 1.713-.332 (3)	(.497) **.998** 1.454-.340 (4)
Pullman-9	(1146) **622** 4545-59 (18)	(31) **37** 117-7 (18)	(116) **110** 523-27 (20)	(.388) **.227** 1.303-.028 (11)	(.161) **.199** .527-.029 (10)	(.033) **.044** .116-.015 (10)	(.495) **1.146** 1.713-.313 (9)	(.700) **.791** 2.489-.258 (11)	(1.049) **.810** 3.732-.155 (12)

KEY:

Site	Pollutant
Site ID	(St.Dev.) **MEAN** Max-Min (# Cases)

Notes: (1) All concentrations are given in mg/l.
(2) TOC analyses for 1980-81 are not yet complete.

Table 3: Annual Loading Rate in Kg/ha/yr (including sanding applications and volcanic ashfall).

Site	TSS	VSS	COD	TOC[1]	Pb	Zn	Cu	TKN	NO_3+NO_2-N	TP
I-5	980	231	787	40.4	4.42	2.32	.223	4.96	5.70	2.40
I-5 w/Grit[2]	1561	-	-	-	-	-	-	-	-	-
I-5*	923	254	740	-	4.62	2.84	.355	1.66	1.24	1.96
SR-520	3766	851	2101	342.1	15.92	4.21	.732	15.65	6.75	6.75
Vancouver	314	55	195	46.3	.13	.22	.034	31.95	2.17	.60
Snoqualmie Pass	2770	361	1026	218.3	1.67	2.01	.361	6.99	6.56	6.23
Montesano	6175	961	3868	63.6	5.48	2.56	.565	13.72	8.00	8.23
Pasco	320	45	181	31.3	.08	.47	.030	2.22	.80	.73
Spokane	1498	241	1187	44.9	.69	10.40	.118	17.27	3.52	3.06
Pullman-9	1355	68	206	-	.32	.39	.065	2.78	2.42	1.00

Notes: (1) TOC loadings reported exclude 1980-81.
(2) Includes large particles which settled in flume upstream of flow splitter and were collected for analysis.

Table 4: Loading Rates in lb/curb-mi/day and lb/curb mi/1000 vehicles (including sanding and volcanic ashfall).

	TSS		COD		Pb	
	(1)	(2)	(1)	(2)	(1)	(2)
I-5	19.3	.33	15.6	.27	.0088	.00015
I-5 w/Grit(3)	31.0	.53	-	-	-	-
I-5*	18.3	.31	14.7	.25	.0917	.0015
SR-520	31.4	.87	17.5	.48	.133	.0036
Vancouver	5.0	.56	3.1	.35	.002	.0002
Snoqualmie Pass	44.8	6.15	16.6	2.28	.027	.0038
Montesano	71.7	9.07	44.9	5.71	.064	.0080
Pasco	4.6	1.44	2.6	.81	.001	.0003
Spokane	23.0	.96	18.3	.81	.011	.0005
Pullman-9	8.5	4.69	1.3	.71	.002	.0011

Notes: (1) lb/curb-mi/day
(2) lb/curb-mi/1000 vehicles
(3) Includes large particles which settled in flume upstream of flow splitter and were collected for analysis.

In Asplund's (1980) previous analysis, summarized by Asplund et al., (1980, 1981), cumulative TSS load in lb/curb-mi versus cumulative vehicles during storms (VDS) yielded the best linear correlation. The correlation with VDS rather than total traffic is a significant departure from published literature. Attempted correlations between TSS mass loadings and meteorological variables were not as satisfactory as the TSS-VDS association for the Washington State data.

The association between cumulative TSS load and cumulative VDS has been reevaluated using the 1980 - 81 data along with the earlier results. Figures 1 - 3 illustrate the relationship for three sampling sites. In these plots the normal approximately linear relationship is broken in a stair-step fashion coincident with large solids additions in excess of those occurring during ordinary highway operations.

A large loading increase at Montesano is evident following the late May 1980 eruption of the Mount St. Helens volcano, which distributed ash to that site. Visual observation suggested that ash can be removed nearly completely from the highway surface by vortex winds generated by fast moving vehicles in a matter of days, but strong prevailing winds redistribute nearby ash deposition back onto the highway surface. It is this cycle of removal and redistribution that causes the ash to be present in stormwater runoff over an extended period.

Similar stair-step behavior in cumulative TSS load versus cumulative VDS plots can also be observed at most other sampling sites. These steps correspond to periods when there was snowfall or highway icing. Figure 1 suggests sanding occurred in late November 1979, January 1980, late November 1980 and mid-December 1980 at the Montesano site. A more dramatic

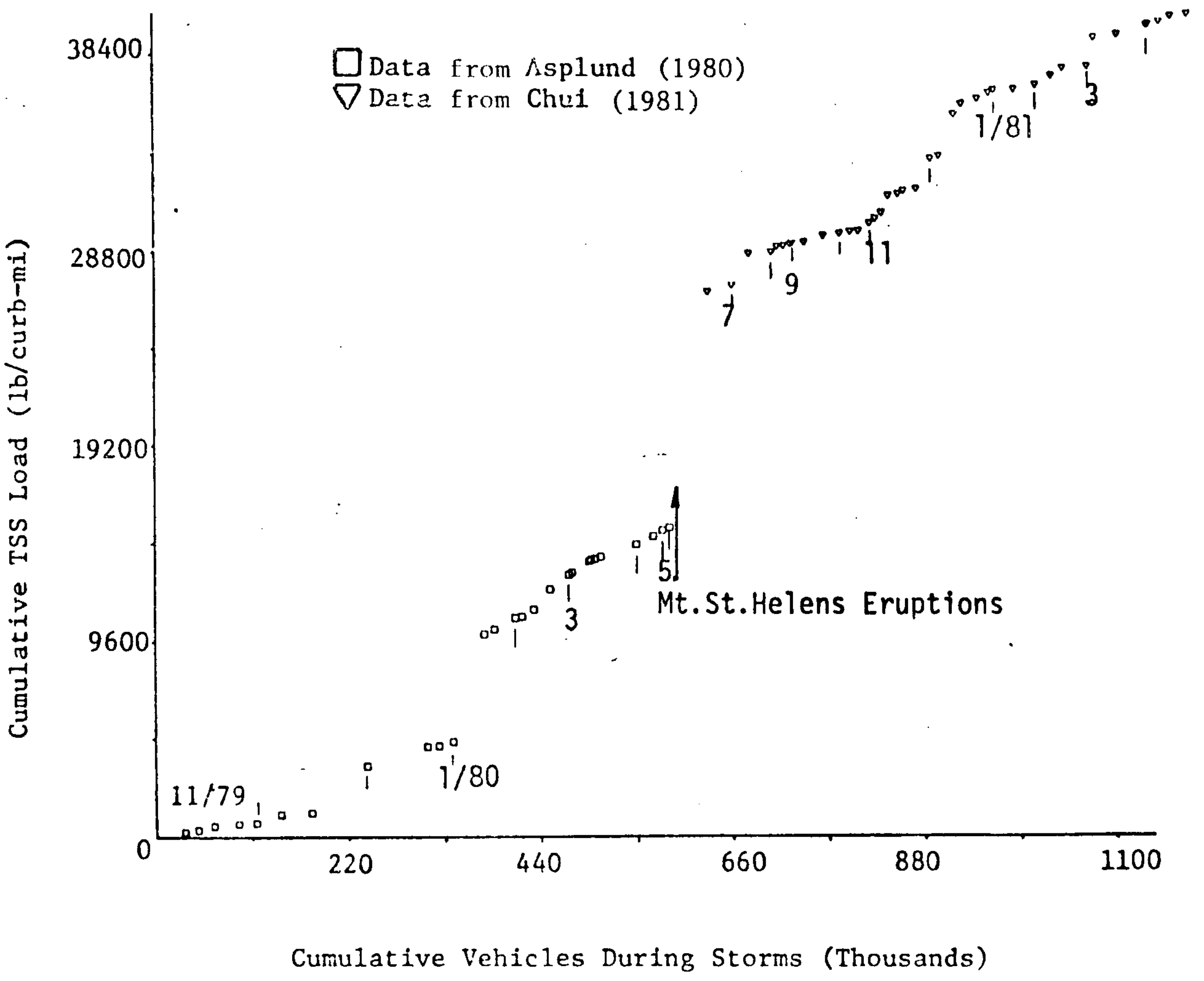


Figure 1: Cumulative TSS Load Versus Cumulative Vehicles During Storms for the Montesano Site (Including Sanding Applications and Volcanic Ashfall)

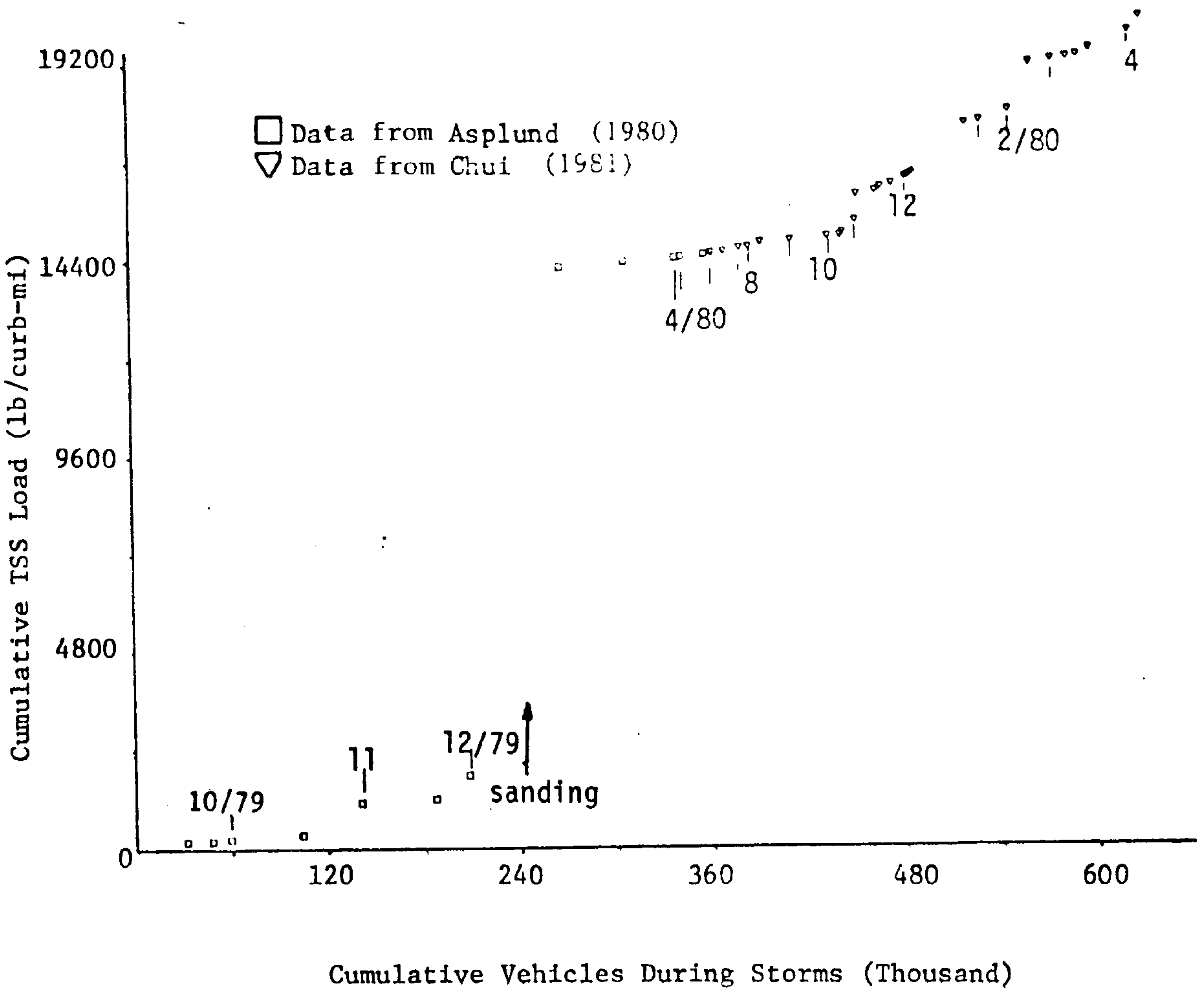


Figure 2: Cumulative TSS Load Versus Cumulative Vehicles During Storms for the Snoqualmie Pass Site (Including Sanding Applications)

impact of sanding was observed at Snoqualmie Pass, as shown in Figure 2. A large jump was observed in TSS accumulation at this site at the beginning of December 1980. The station was then inoperable from January 1980 to March 1980 because an ice block formed in the composite tank. Much smaller steps are visible following sanding during the milder 1980 - 81 winter.

Studded tires are allowed by law in Washington State between November 1 and April 1. These dates coincide with those when gradual slope changes in the cumulative TSS load versus VDS curves were observed at several sampling sites, as may be seen in Figure 3. It is hypothesized that the slope changes in November 1980 and April 1981 in the I-5 graph were caused by the installation and then the removal of studded tires. There was little or no sanding to obscure this effect in 1980 - 81, whereas sanding probably explains the more prominent slope changes during the previous winter.

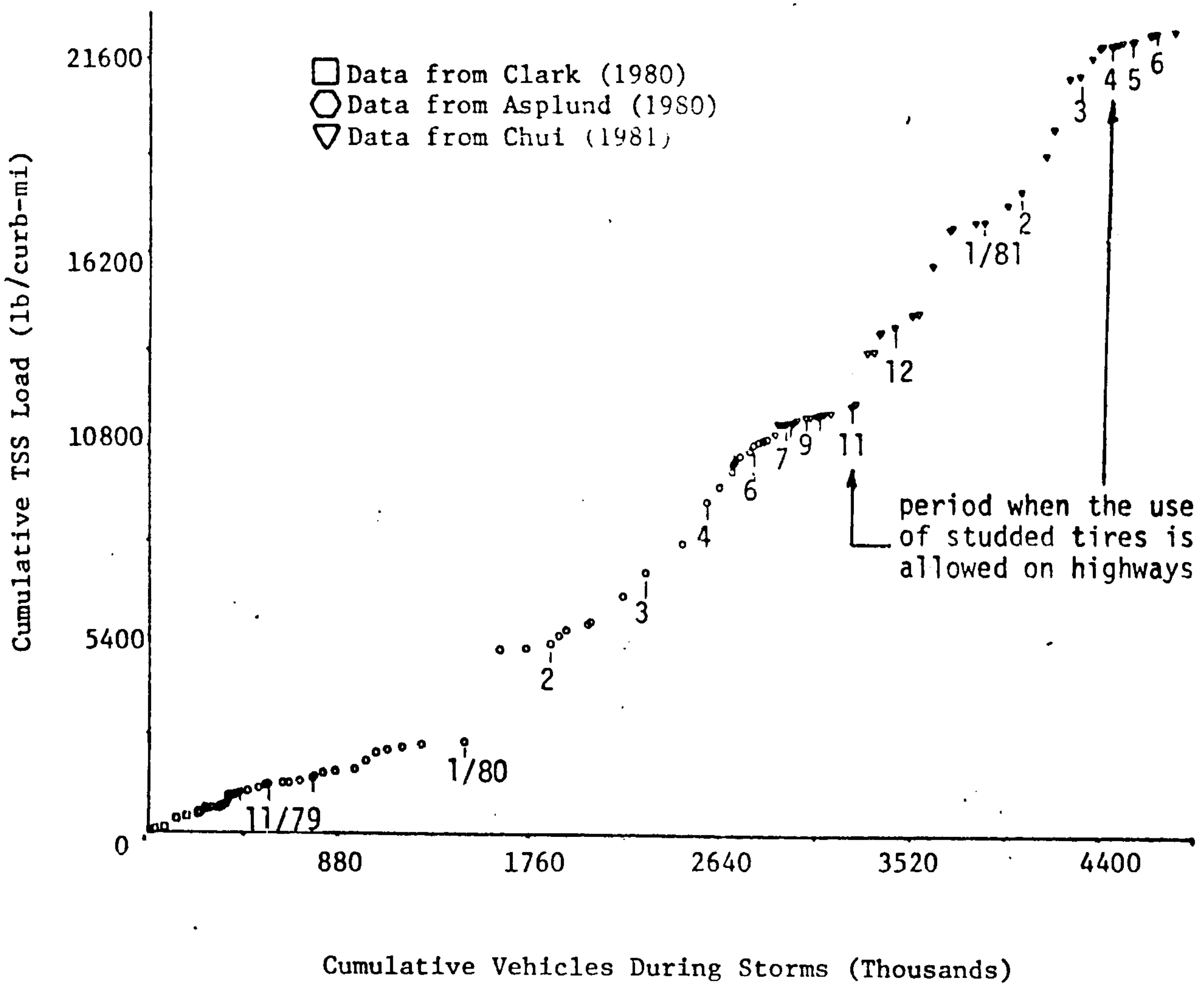


Figure 3: Cumulative TSS Load Versus Cumulative Vehicles During Storms for the I-5 Site (Including Sanding Applications and Solids Settled in the Upstream Flume)

LOADING MODEL VERIFICATION AND EXPANSION

TSS Loading

Analysis of data from other runoff sites experiencing ashfall and sanding suggested that satisfactory linear relationships between cumulative TSS and VDS could be developed regardless of the stair-step behavior. Table 5 summarizes the results of linear regressions of cumulative TSS load on cumulative VDS for each site.

In spite of the success of the derived regressions in explaining variance, it was decided that, in order to resolve the role of VDS, runoff data influenced by sanding and ashfall should be eliminated from the analysis. Results could then serve as a loading model for normal highway operations, and sanding loads could be estimated separately.

With the deletion of data involving sanding and ashfall, along with a few points from occasions when the composite tank overflowed, the cumulative TSS load versus VDS relationship is more nearly linear over an extended time span. Figure 4 illustrates a typical plot for this case, using the I-5 data set (excluding grit settled in the upstream flume). Table 6 summarizes the results of linear regressions conducted with this data subset for all runoff sites.

A further result of the analysis of Asplund (1980) and Asplund, et al. (1980, 1981) was the observation of a linear relationship between TSS runoff rate (lb/curb-mi/1000 VDS) and average annual runoff coefficient at Western Washington sites. TSS runoff rates and average annual runoff coefficients taken from Table 6 are plotted for all runoff sites in Figure 5. TSS runoff rates at the Eastern Washington sites are substantially higher than those at Western Washington locations, seemingly because regular and relatively strong winds move loose soil from the semi-arid surrounding lands onto highway surfaces.

Table 5: Summary of Linear Regression of Cumulative TSS Load versus Cumulative Vehicles During Storms for all Runoff Sites (including sanding applications and volcanic ashfall).

			Linear Regression			End-Points	
Site	No. Cases	Average Annual Runoff Coefficient	Intercept (lb TSS/curb mi)	Slope (lb TSS/curb-mi-1000 VDS)	R^2	Cumulative VDS (1000 veh.)	Cumulative TSS Load (lb/curb-mi)
I-5 w/Grit(1)	69	.72	-537	6.75	.993	2,687	16,623
I-5	129	.72	-380	3.21	.997	4,727	14,256
I-5*	25	.77	-317	3.44	.989	859	2,601
SR-520	43	.70	-514	7.03	.991	1,243	7,726
Vancouver	93	.43	-197	5.78	.990	594	3,128
Snoqualmie Pass	42	.72	-1173	37.02	.943	628	20,261
Montesano	68	.73	-4981	42.04	.980	1,182	40,364
Pasco	35	.80	-501	32,18	.933	103	2,875
Spokane	10	.64	-2551	16.73	.929	703	10,085
Pullman-9	22	.58	457	46.76	.795	52	2,553

Note: (1) Includes large particles which settled in flume upstream of flow splitter and were collected for analysis.

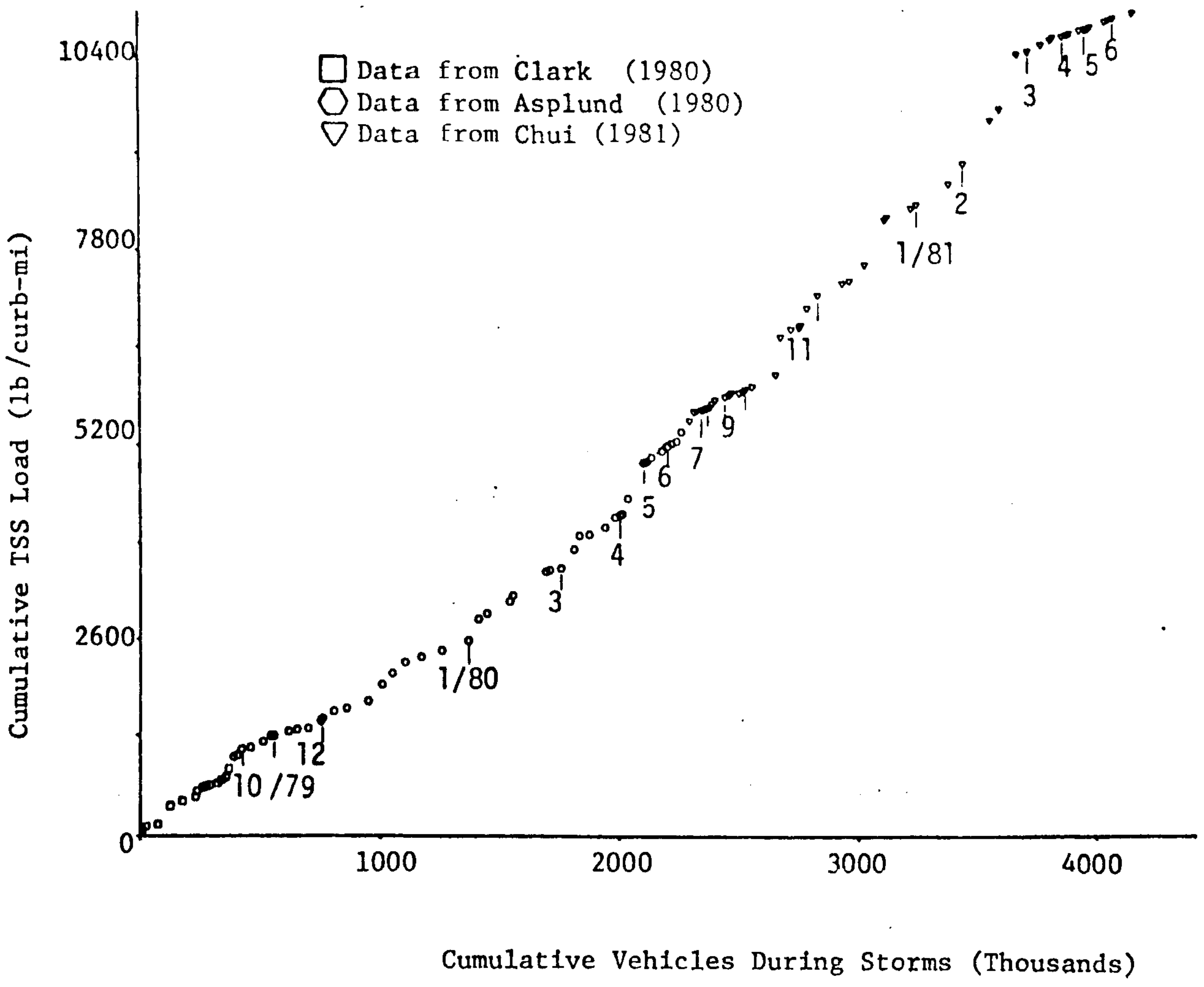


Figure 4: Cumulative TSS Load Versus Cumulative Vehicles During Storms for the I-5 Site (Excluding Winter Sanding and Solids Settled in Flume)

Table 6: Summary of Linear Regression of Cumulative TSS Load versus Cumulative Vehicles During Storms for all Runoff Sites (excluding sanding applications and volcanic ashfall).

			Linear Regression			End-Points	
Site	No. Cases	Average Annual Runoff Coefficient	Intercept (lb TSS/curb-mi)	Slope (lb TSS/curb-mi/1000 VDS)	R^2	Cumulative VDS (1000 veh.)	Cumulative TSS Load (lb/curb-mi)
I-5 w/Grit(1)	67	.72	-888	6.72	.992	2,574	15,463
I-5	120	.72	-553	2.75	.992	4,134	10,982
I-5*	25	.77	-317	3.44	.989	859	2,601
SR-520	34	.70	-100	4.14	.998	849	3,455
Vancouver	78	.43	-38	3.40	.992	520	1,818
Snoqualmie Pass	29	.72	-286	4.86	.950	418	1,987
Montesano	29	.73	-316	7.02	.975	463	3,198
Pasco	22	.80	-14	20.42	.880	60	1,081
Spokane	10	.64	-2551	16.73	.929	704	10,085
Pullman-9	17	.58	-100	18.46	.965	28	468

Note: (1) Includes large particles which settled in flume upstream of flow splitter and were collected for analysis.

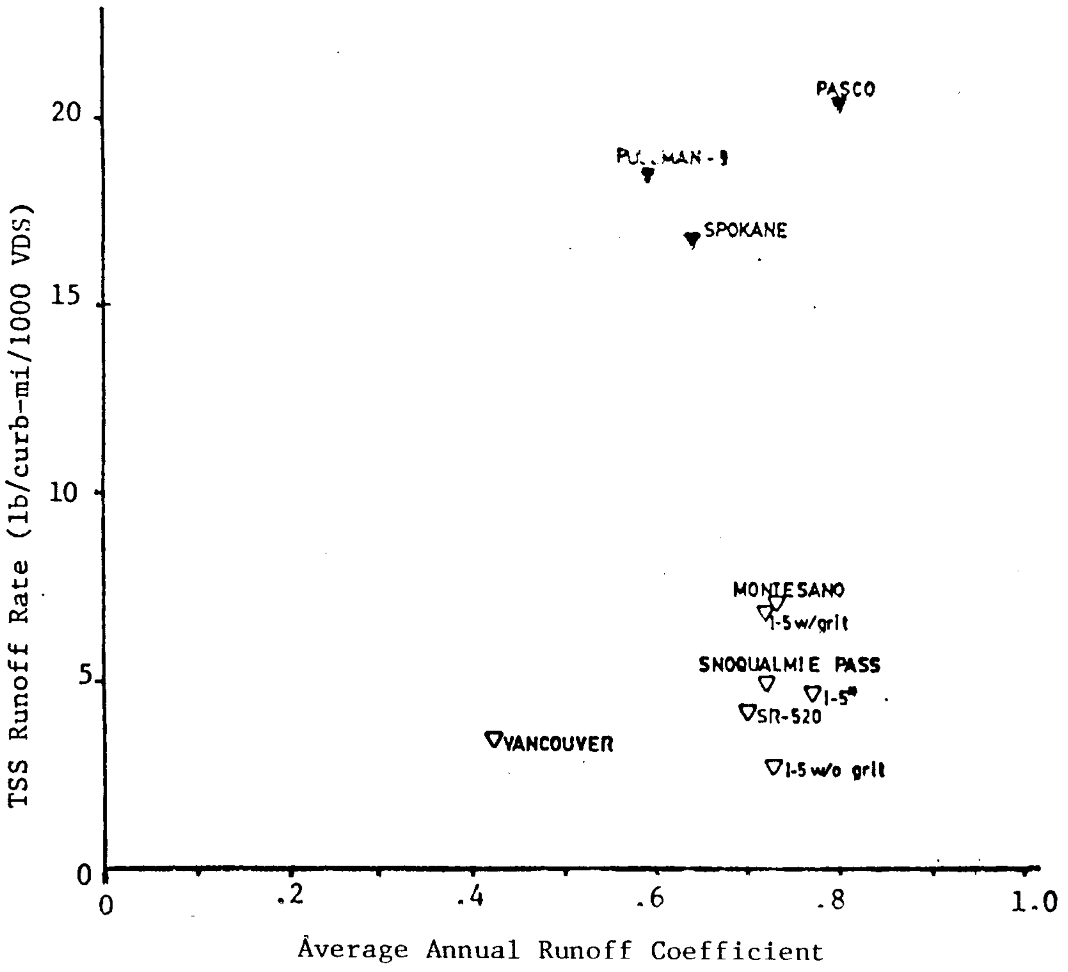


Figure 5: TSS Runoff Rate Versus Average Annual Runoff Coefficient for All Sites

The direct relationship between TSS runoff rate and runoff coefficient can be explained by recalling that the TSS load (lb/curb-mi) is the product of the runoff TSS concentration times runoff volume. If the concentration of runoff from a highway segment is not altered by volume losses, such as splashing from the roadway, leakage between bridge segments or leakage in cracks in the roadway, then the TSS load should be proportional to the runoff coefficient (the more volume, the more TSS). The value of the TSS runoff rate (lbs/curb-mi/1000 VDS) for a runoff coefficient of 1, the constant K in the proposed Washington State loading model, may then be estimated by:

$$K_{RC=1} = \frac{K_{RC=n}}{n}$$

where: n = any measured or estimated value of average runoff coefficient

Asplund _et al._, (1980, 1981) judged on the basis of 1979 - 80 data that K should be taken as approximately 6.4 lb TSS/curb-mi/1000 VDS for the conditions prevalent in Wastern Washington. Inspection of Figure 5, based on the full 1979 - 81 data set, validates that judgment. For Eastern Washington conditions, a choice for K of 25 - 30 lb TSS/curb-mi/1000 VDS appears to be appropriate. Because this judgment is based on many less observations than available for Western Washington conditions, it is a major objective for the final monitoring year (1980 - 81) to more firmly calibrate the model for application to Eastern Washington.

The proposed solids loading model was evaluated for application to individual storm estimates by comparing its predictions to observed TSS loads from all storms monitored at the I-5, I-5* and SR-520 sites. The error was estimated according to the difference between predicted and observed loadings as a percentage of the observed value.

Table 7 summarizes the performance of the runoff model in individual storm cases. Errors average in the vicinity of 200 percent and range as large as an order of magnitude. Large errors are usually associated with storms following sanding operations. There is also a tendency for the error to oscillate from positive to negative. This tendency suggests that considerable pollutant quantities remain on highway surfaces after small storms (low intensity and small volume) and are later removed by heavy storms. The oscillating phenomenon seems to be associated with frontal systems which first bring low intensity storms, followed by heavier storms and then low intensity storms again before the systems pass. If runoff from an entire frontal system could be composited, the error in solids prediction may be reduced.

Table 7. Comparison of Observed TSS Loadings Versus Those Predicted by the Washington State Runoff Model for Individual Storm Cases.

	Percentage Error				
Site	Mean	Standard Deviation	Minimum	Maximum	No. Cases
I-5 (1979-81 Data)	219	284	0.3	1649	129
I-5 (1979-80 Data)	190	257	0.3	1369	77
I-5 (1980-81 Data)	261	317	3.9	1649	52
I=5* (1980 Data)	170	220	0.3	972	25
SR-520 (1979-80 Data)	98	113	2.6	537	43

Note: (1) The I-5 data analyzed excludes large particles settled in the upstream flume.

Highway runoff pollutant loadings, and likewise concentrations, in a given locale are thus highly variable in the short time frame but more constant, when normalized for traffic and average runoff coefficient, in the longer span. Consequently, the loading model in its present form is valid and applicable for predictions over the long-term (monthly or annually). Little precision results if it is applied on a storm-by-storm basis, however.

Loadings of Other Pollutants

The classical assessment of pollutants other than TSS in stormwater is to use a ratio of a specific pollutant to the total solids or total suspended solids loads (Zison, 1980; Donigian and Crawford, 1977). Ratios of each pollutant to TSS (K_p) were computed for each sampling site and evaluated according to the correlation demonstrated and 95 percent confidence limits. These results are presented in Tables 8 - 10.

For VSS, COD and TOC, the ratios from site-to-site for each pollutant are generally of the same order within a factor of 2-3, have overlapping confidence bands and represent high degrees of correlation ($R > 0.83$ in all but one case). Levels of these contaminants are thus largely controlled by the solids, regardless of traffic and meteorological conditions. A single K_p may be selected to serve for predictive modeling with a known amount of error at any Washington State location.

The ratios are much more variable for the other constituents, and correlation coefficients are lower overall. $NO_3 + NO_2 - N$ is very poorly correlated with TSS, as expected since this quantity is present in solution. A tabulation of the ratios (rounded to less significant figures) with traffic, Table 11, may be inspected to note some associations between certain specific pollutant ratios and ADT. Linear regression analyses were conducted

Table 8: Specific Pollutant:TSS Ratios for Organics (excluding volcanic ashfall but including sanding applications)

		Site	R	No.Cases	Kp (x10^{-1})	95% Confidence Interval Lower Limit (x10^{-1})	Upper Limit (x10^{-1})
K_{VSS}	VSS(lb)/TSS(lb)	I-5	.831	128	1.66	1.38	1.93
		I-5*	.981	25	2.62	2.02	3.22
		SR-520	.972	43	2.00	1.82	2.17
		Vancouver	.938	91	1.90	1.69	2.11
		Snoqualmie Pass	.995	43	1.13	1.05	1.21
		Montesano	.937	66	1.33	1.10	1.55
		Pasco	.875	36	2.37	1.44	3.29
		Spokane	.979	11	1.85	1.41	2.30
		Pullman-9	.886	21	1.30	0.05	2.54
K_{COD}	COD(lb)/TSS(lb)	I-5	.934	128	4.12	3.73	4.51
		I-5*	.932	25	7.01	3.88	10.13
		SR-520	.978	43	4.88	4.50	5.25
		Vancouver	.735	91	5.89	4.27	7.50
		Snoqualmie Pass	.928	43	2.04	1.46	2.62
		Montesano	.858	66	2.66	1.94	3.38
		Pasco	.932	36	5.04	3.56	6.52
		Spokane	.979	10	4.89	3.73	6.06
		Pullman-9	.873	21	4.08	(1)	
K_{TOC}	TOC(lb)/TSS(lb)	I-5	.849	40	.392	.313	.471
		I-5*					
		SR-520	.919	16	.612	.468	.757
		Vancouver	.856	27	.760	.575	.944
		Snoqualmie Pass	.946	8	.214	.148	.280
		Montesano	.965	11	.609	.493	.725
		Pasco	.983	9	.665	.562	.767
		Spokane	.890	4	.089	.005	.173

Note: (1) Negative lower limit.

Table 9: Specific Pollutant:TSS Ratios for Heavy Metals (excluding volcanic ashfall but including sanding applications)

	Site	R	No.Cases	Kp	95% Confidence Interval	
					Lower Limit	Upper Limit
				$(x10^{-1})$	$(x10^{-1})$	$(x10^{-1})$
K_{PB} PB(lb)/TSS(lb)	I-5	.978	116	4.58	4.34	4.81
	I-5*	.985	19	4.87	3.90	5.84
	SR-520	.992	42	4.17	3.98	4.36
	Vancouver	.609	70	0.55	0.34	0.76
	Snoqualmie Pass	.987	31	0.60	0.54	0.67
	Montesano	.887	48	1.06	0.81	1.31
	Pasco	.501	29	1.70	(1)	
	Spokane	.997	9	0.98	0.91	1.06
	Pullman-9	.934	14	0.48	0.14	0.82
K_{ZN} ZN(lb)/TSS(lb)	I-5	.960	116	1.66	1.54	1.78
	I-5*	.903	19	2.27	1.03	3.51
	SR-520	.975	42	1.01	0.93	1.10
	Vancouver	.812	60	0.56	0.44	0.67
	Snoqualmie Pass	.951	27	0.44	0.34	0.54
	Montesano	.838	45	0.36	0.25	0.46
	Pasco	.566	29	0.96	(1)	
	Spokane	.931	9	5.71	3.14	8.28
	Pullman-9	.526	11	0.26	(1)	
K_{CU} CU(lb)/TSS(lb)	I-5	.924	115	1.95	1.75	2.15
	I-5*	.970	19	3.03	2.16	3.90
	SR-520	.976	42	1.63	1.50	1.76
	Vancouver	.654	67	1.31	.86	1.76
	Snoqualmie Pass	.986	31	1.20	1.06	1.35
	Montesano	.803	47	0.87	0.58	1.16
	Pasco	.875	29	0.65	0.39	0.90
	Spokane	.986	10	0.77	0.63	0.92
	Pullman-9	.835	13	0.83	(1)	

Note: (1) Negative lower limit.

Table 10: Specific Pollutant:TSS Ratios for Nutrients (excluding volcanic ashfall but including sanding applications).

		Site	R	No.Cases	Kp	95% Confidence Interval	
						Lower Limit	Upper Limit
					$(x10^{-1})$	$(x10^{-1})$	$(x10^{-1})$
K_{TKN}	TKN(lb)/TSS(lb)	I-5	.864	72	3.30	2.83	3.78
		I-5*	.898	6	1.77	0.77	2.77
		SR-520	.860	34	2.29	1.80	2.78
		Vancouver	.195	58	17.66	(1)	
		Snoqualmie Pass	.969	16	2.04	1.67	2.40
		Montesano	.885	29	2.12	1.62	2.63
		Pasco	.929	12	5.23	3.67	6.70
		Spokane	.987	7	10.49	8.56	12.41
		Pullman-9	.931	8	7.10	1.97	12.23
$K_{NO_3+NO_2-N}$	NO_3+NO_2-N(lb)/TSS(lb)	I-5	.406	95	2.12	0.94	3.30
		I-5*	.769	6	1.28	0.06	2.51
		SR-520	.746	40	0.99	0.67	1.31
		Vancouver	.506	59	3.52	1.74	5.30
		Snoqualmie Pass	.592	24	0.59	0.03	1.16
		Montesano	.174	41	0.44	(1)	
		Pasco	.557	25	0.81	(1)	
		Spokane	.876	8	2.37	0.87	3.87
		Pullman-9	.414	14	2.50	1.97	12.23
K_{TP}	TP(lb)/TSS(lb)	I-5	.982	92	2.27	2.18	2.35
		I-5*	.943	23	1.91	1.13	2.69
		SR-520	.966	37	1.76	1.59	1.93
		Vancouver	.894	74	1.85	1.58	2.13
		Snoqualmie Pass	.997	28	2.06	1.96	2.17
		Montesano	.953	56	1.64	1.40	1.87
		Pasco	.924	23	1.17	0.83	1.52
		Spokane	.871	9	2.22	0.78	3.66
		Pullman-9	.949	13	2.68	1.05	4.32

Note: (1) Negative lower limit.

Table 11: Summary of Average Daily Traffic and the Specific Pollutant Ratios at Each Sampling Site.

Site	ADT (thousands)	Specific Pollutant Ratios								
		VSS	COD	TOC	Pb ($\times 10^{-3}$)	Zn ($\times 10^{-3}$)	Cu ($\times 10^{-4}$)	TKN ($\times 10^{-3}$)	NO_3-NO_2-N ($\times 10^{-3}$)	TP ($\times 10^{-3}$)
Western Washington:										
I-5	57	.2	.4	.7	4.6	1.7	2.0	3.3	2.1	2.3
I-5*	57	.3	.7		4.9	2.3	3.0	1.8	1.3	1.9
SR-520	42	.2	.5	.8	4.2	1.0	1.6	2.3	1.0	1.8
Vancouver	9	.2	.6	.7	.6	.6	1.3	17.7	3.5	1.9
Snoqualmie Pass	8	.1	.2	.9	.6	.4	1.2	2.0	.6	2.1
Montesano	11	.1	.3	.9	1.1	.4	.9	2.1	.4	1.6
Eastern Washington:										
Pasco	2	.2	.5	1.0	1.7	1.0	.7	5.2	.8	1.2
Spokane	17	.2	.5	.8	1.0	5.7	.8	10.5	2.4	2.2
Pullman-9	3	.1	.4		.5	.3	.8	7.1	2.5	2.7

with these data to explore the strength of these associations. Table 12 presents the most satisfactory regression equations that were derived.

The data base used to derive the reported K_p expressions includes winter sanding. Asplund (1980) gathered some evidence that the pollutant:TSS ratios decline with large sand applications, in excess of the solids required to sorb essentially all of the other contaminants present. Because of the mild 1980-81 winter and minimal sand applications, this tentative conclusion could not be further explored. Extending the model to more effectively cover sanding is an objective of ongoing research.

Sulfur-Extended Pavement Study

A section of SR-270 just west of Pullman (designated station Pullman-9) was paved with sulfur-extended asphalt, while a nearby section was paved with conventional asphalt to serve as a control. The main objective of the overall study is to monitor relative pavement wear. The presence of the test section is also being used to advantage in the Runoff Water Quality project to check for differences in sulfur compounds in runoff from the two sections. To date, only sulfate has been measured in the samples, and Pullman-Control results had to be discarded because of problems resulting from heavy volcanic ashfall at the site. The control site sampling station has been repaired, and total sulfur will be monitored along with sulfate during the current year.

Figure 6 illustrates the relationship between sulfate runoff rate and average annual runoff coefficient for Pullman-9 and a limited number of samples from other sites analyzed for sulfate for comparison. Sulfate runoff rate for Pullman-9 was notably higher than at other sites in the state. In the absence of good control data, however, final conclusions must be withheld

Table 12: Expressions of Specific Pollutant Ratios Recommended for Use with Washington State Highway Runoff Model

Pollutant	Expression	R^2	Specifications
VSS	$K_{VSS} = .2$	--	For all sites
COD	$K_{COD} = .4$	--	For all sites
TOC	$K_{TOC} = .8$	--	For all sites
Pb	$K_{Pb} = 2x10^{-5}+(8.55x10^{-8})*(ADT)$	.987 --	For all sites except Pasco
Zn	$K_{Zn} = 4.48x10^{-4}+(2.37x10^{-8})*(ADT)$	.820	For all sites except Spokane
Cu	$K_{Cu} = 7.05x10^{-5}+(2.89x10^{-9})*(ADT)$	.888	For all sites
TKN	$K_{TKN} = 2x10^{-3}$	--	For Western Washington sites
	$K_{TKN} = 5.36x10^{-3}+(3.06x10^{-9})*(ADT)$	.995	For Eastern Washington sites
NO_3+NO_2-N	$K_{NO_3+NO_2-N} = 2x10^{-3}$	--	For all sites
TP	$K_{TP} = 2x10^{-3}$	--	For all sites

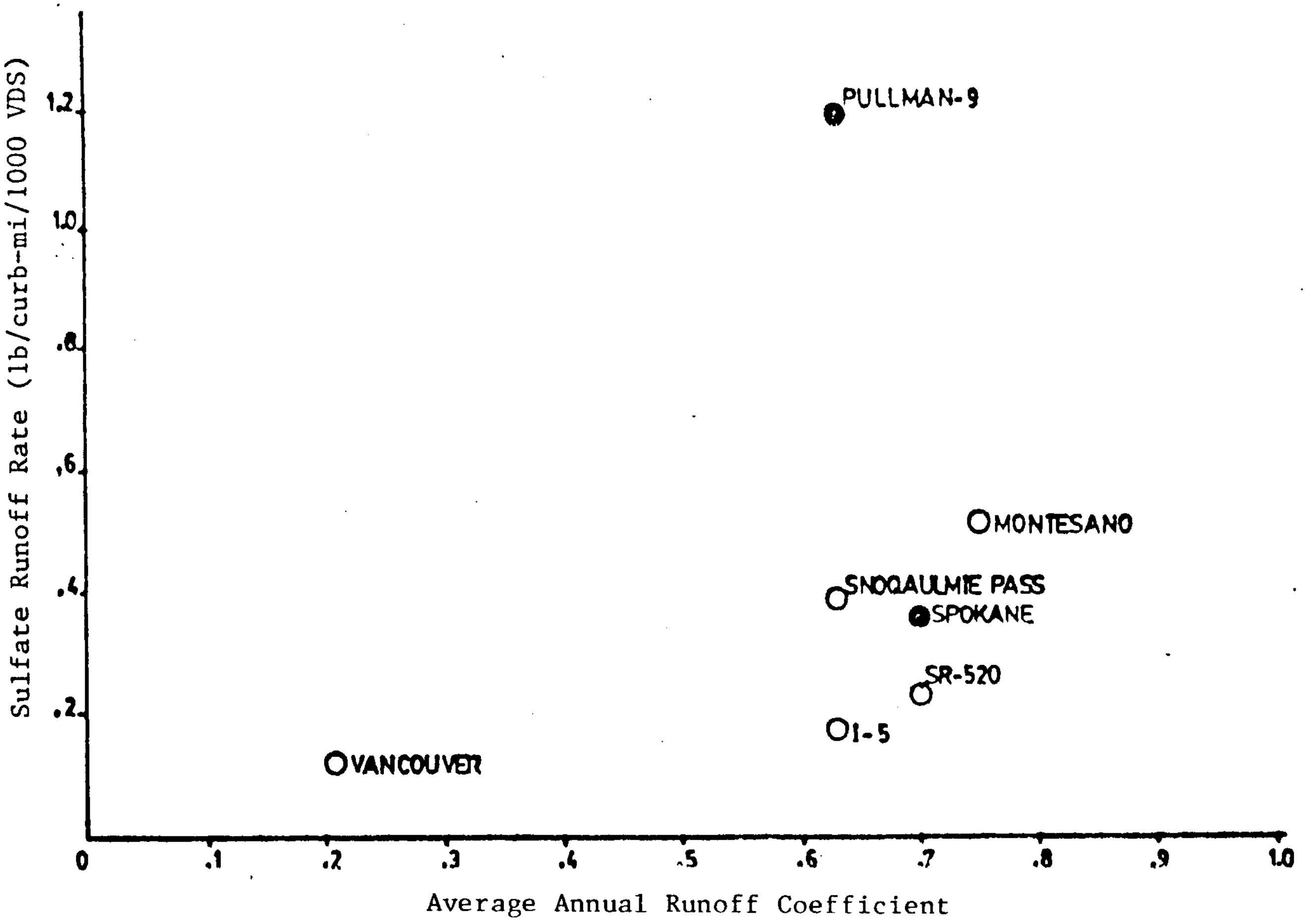


Figure 6: Sulfate Runoff Rate Versus Average Annual Runoff Coefficient for Seven Sampling Sites

pending the final year's results. What data exist show a poor correlation between sulfate and TSS, as expected considering the normal presence of sulfate in solution.

EXPLORATORY STUDIES

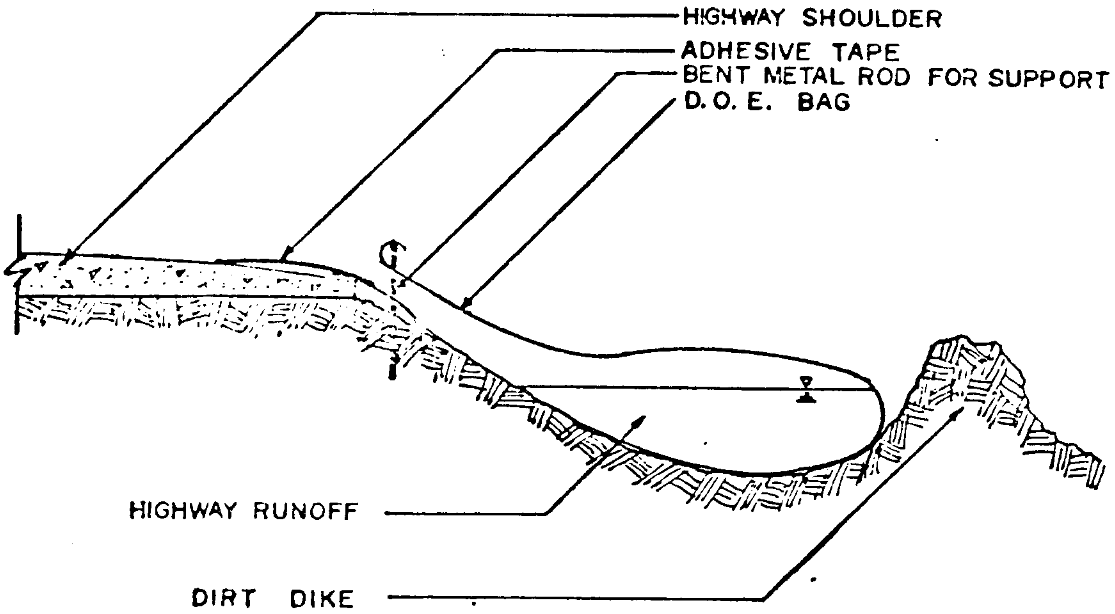
Over-the-Shoulder Runoff Sampling

Asplund (1980) pointed out that "curbing, or the lack of it, is probably the single most influential factor in determining the amount of pollutants removed via the runoff". Over-the-shoulder (in the absence of curbing) runoff has not been previously sampled; thus, exploratory studies were undertaken during the 1980-81 sampling year.

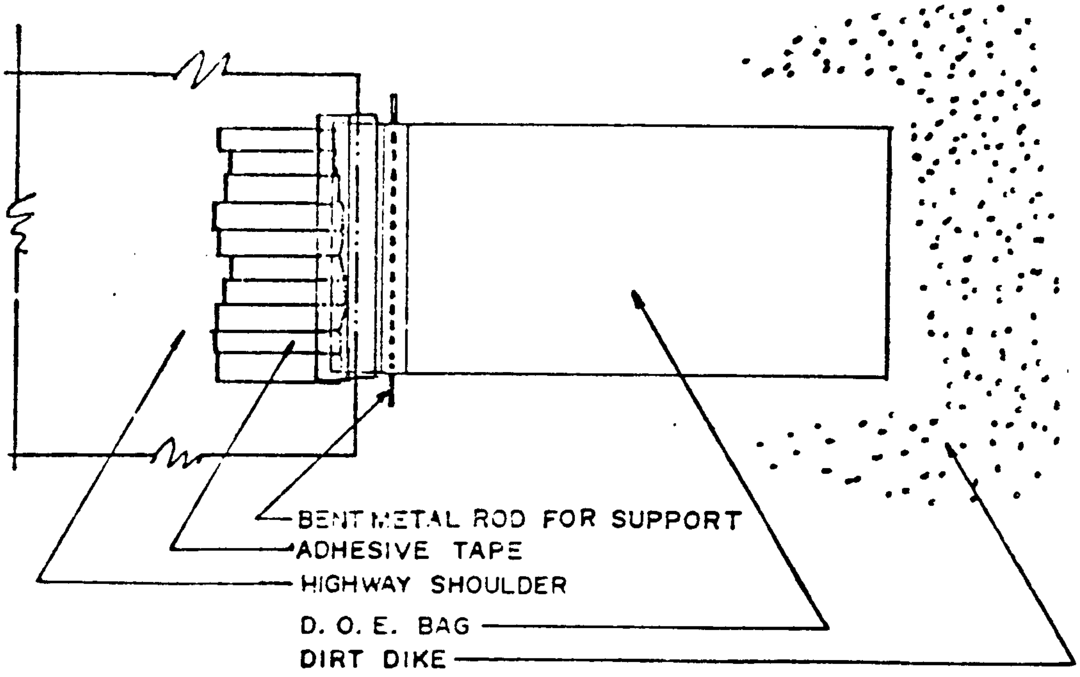
A very simple collection system was employed. Heavy-duty garbage bags issued by Washington State Department of Ecology (WSDOE) were taped down at the edge of the highway shoulder in order to allow stormwater to drain over the shoulder into the bag. Figure 7 illustrates the sampling system schematically. The sampling sites were located along I-5 northbound lanes about one-half mile north of the regular I-5 sampling site.

Sampling equipment consisted of a plastic bucket of constant cross-sectional area, measuring yard stick and one liter container. The WSDOE bag filled with runoff was first lifted from the shoulder gently. The stormwater was then stirred thoroughly to resuspend particles, and a water sample was taken with the one liter container. The remainder of the runoff was emptied into the bucket, the depth in which provided an estimate of the amount of runoff.

Table 13 presents the results of the bag studies. The available data demonstrate that stormwater runoff from highway sections without curbing has much higher pollutant concentrations than runoff from areas with curbing. The apparent explanation is that over-the-shoulder runoff carries practically all of the solids off the highway, whereas flow along curbing for a distance results in some sedimentation, especially of the larger particles.



SIDE VIEW



PLAN VIEW

FIGURE 7: SCHEMATIC DIAGRAM OF THE OVER-THE-SHOULDER SAMPLING SYSTEM (NOT TO SCALE)

There is then a reasonably good chance that this material will be removed from the drainage by wind scatter or sweeping before the occurrence of a large, high velocity flow, capable of transporting it in the runoff.

Table 13: Pollutant Concentrations in Over-the-Shoulder Runoff Compared to Composite Samples from an I-5 Curbed Section.

Date of Sampling	Over-the-Shoulder TSS	Over-the-Shoulder VSS	Over-the-Shoulder COD	Composite TSS	Composite VSS	Composite COD
11/14/80	180	51		67	25	
	190	56				
	188	41				
02/01/81	1412	261	1141	65	22	124
	1081	267	359			
02/12/81	358	98	213	159	30	83
	79	23	126			
	93	33	134			

Note: Units of all concentrations are mg/ℓ.

Coupon Study of Acquired Pollutants

Asplund (1980) suggested that there are two types of traffic-related pollutants found in highway runoff:

> "Primary source pollutants are from the normal operation and frictional wear of the vehicles. Secondary acquired source pollutants can be any materials that are 'acquired' and carried by the vehicles for later deposition."

A study was instituted to estimate the contribution of secondary acquired pollutants. Small steel plates with six magnetized plastic coupons were attached by silicone sealant to the inside of the wheel-well of vehicles under study. The magnetic coupons were removed periodically to be analyzed for the amount of materials collected.

Figure 8 presents the results of the coupon study. Large variations were noted in the amount of solids collected on vehicles which had traveled the same distance. The type of driving the vehicles experienced governed the amount of solids collected. If the vehicle had been driven in a rural area (e.g., vehicle #3), the collection was many times that on vehicles driven on urban streets or highways. Highway driving produced a faster initial build-up than did city driving. There appeared to be a point at which coupons saturated. Beyond that point, gains and losses of materials occurred with little additional net build-up. On the basis of this study and knowledge gained in the regular sampling program, it is estimated that the secondary acquired source is responsible for 10-20 percent of the total TSS load on urban highways.

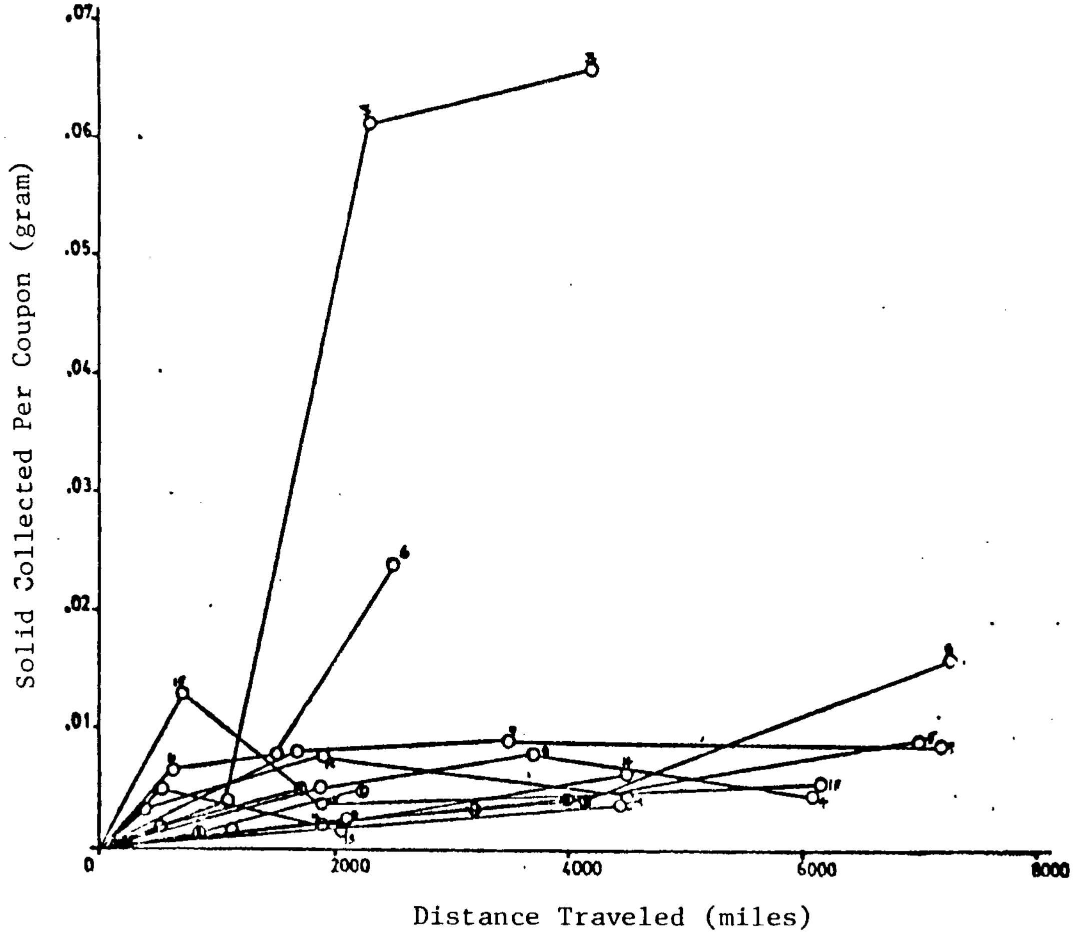


Figure 8: Accumulation of Secondary Aquired Pollutants With Distance

CONCLUSIONS

A pollutant loading model has been developed and tested for use in predicting highway runoff water quality in Washington State. The model is of the form:

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

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

where the quantities are as previously defined. The results of more than 400 storms sampled over a span of more than two years have established K, the TSS runoff rate, as about 6.4 lb TSS/curb-mi/1000 VDS under Western Washington conditions. A much smaller volume of data suggests that a K in the range of 25-30 applies to Eastern Washington. The specific pollutant ratios, K_p, are constants for VSS, COD, TOC, $NO_3 + NO_2 - N$ (in Western Washington) and TP and are linearly related to ADT in the cases of Pb, Zn, Cu and TKN (in Eastern Washington), as detailed in Table 12. The model as presently defined is capable of predicting loadings satisfactorily over an extended time span but is imprecise when applied to individual storms.

Winter sanding loads must be added to those accruing from normal operations as predicted by the TSS model. Sand particles transport other pollutants in approximately the same ratios as established for regular operations, up to a presently ill-defined point in especially heavy sanding applications.

Preliminary results indicate that sulfur-extended asphalt pavements contribute substantially greater sulfate loadings to runoff than other pavements. The magnitude of sulfate and total sulfur loads and their implications for receiving water quality will be evaluated in continuing research.

Exploratory studies have shown that runoff from uncurbed sections has considerably higher pollutant concentrations than that from curbed sections and that materials adhering to the undercarriage of automobiles could be a significant source of solids on rural highways.

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