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16. ABSTRACT

This project examined the role that road shoulders play in the stormwater runoff process. The goal of the research was to determine the type of shoulder treatment that yields the least quantity of runoff of the highest quality. Three types of shoulder materials were tested: conventional asphalt, gravel, and porous asphalt. Porous asphalt allows water to penetrate and flow through the pavement to a sublayer, and it can be used in place of conventional asphalt on low-traffic roadways. Each of the three shoulder materials were tested in duplicate on a heavily traveled, two-lane road north of Redmond, Washington. Stormwater runoff from the road flowed onto the shoulder test sections and was collected in a stormwater collection system at the base of the test sections. Flow-weighted composite samples were collected, and both runoff quantity and quality were evaluated.

On the basis of results from 11 storms monitored between November 1995 and August 1996, several trends were identified. The porous asphalt shoulders demonstrated a greater potential to reduce runoff volumes and peak discharge rates than gravel and conventional asphalt shoulders. During typical wet season storms (0.76 cm [0.3 in]), the porous asphalt and gravel shoulder test sections reduced runoff volumes by approximately 85 and 30 percent, respectively, in comparison to the conventional asphalt test sections. The ability of the porous asphalt shoulders to reduce pollutant loads far exceeded that of the gravel and conventional asphalt shoulders. During typical wet season storms the solids and pollutant loads from the porous asphalt shoulders were more than 90 percent lower than the loads from the conventional asphalt shoulders. The gravel shoulders yielded load reductions ranging from 10 to 70 percent lower than the conventional asphalt, although ortho-phosphorus loads exceeded those of the conventional asphalt shoulder by nearly 30 percent.

Removal rates were highest for those pollutants that were correlated with total suspended solids ($0.70<r^2<0.95$), indicating that physical mechanisms of settling and filtration were critical in removing pollutants from the runoff over both porous asphalt and gravel shoulders. The porous asphalt shoulders were more efficient at removing soluble pollutants, particularly ortho-phosphorus, than the conventional asphalt and gravel shoulders. After one year of use the porous asphalt shoulders showed no signs of clogging, maintaining infiltration rates of 4445 cm/hr (1750 in/hr).

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Research Project T-9903, Task 45
Storm Water Runoff Control

EFFECT OF ROAD SHOULDER TREATMENTS ON HIGHWAY RUNOFF QUALITY AND QUANTITY

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July 1997

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TABLE OF CONTENTS

EXECUTIVE SUMMARY ... xi

CHAPTER ONE: INTRODUCTION AND RESEARCH APPROACH ... 1
Statement of the Research Problem ... 1
Research Goals and Objectives ... 2
Research Hypotheses ... 3
Relevance of the Research in Context of the Research Problem ... 3
Urban Runoff Mitigation ... 6
  Washington Department of Ecology's Stormwater Program ... 6
  Puget Sound Highway Runoff Program ... 7
  Best Management Practices for Stormwater Mitigation ... 7
    Infiltration BMPs ... 8
    Porous Pavements ... 10
Experimental Design ... 15
  Monitoring Site Location and Description ... 16
  Site Preparation and Shoulder Test Section Installation ... 20
  Stormwater Sampling and Collection System ... 21
  Sampling Protocol ... 28
    Water Quality Analysis ... 28
    Bioassay Procedures ... 29
  Quality Assurance/Quality Control ... 30
  Rain Gauge Monitoring ... 30
  Rain Simulation/Overland Flow Experiments ... 30
  Probabilistic Load Estimation ... 32
  Roadside Ditch Vegetative Cover and Composition Survey ... 34

CHAPTER TWO: FINDINGS AND DISCUSSION ... 36
Introduction ... 36
Hydraulic Behavior of Shoulder Treatments ... 36
  Rain Simulation/Overland Flow Experiment Results ... 38
  Infiltration Experiments ... 42
QA/QC Results ... 42
Individual Pollutant Data—Seasonal Summaries ... 45
  Summary of All Water Quality Parameters ... 47
  Total Suspended Solids ... 49
  Turbidity ... 52
  Chemical and Biochemical Oxygen Demand ... 54
  Total and Ortho Phosphorus ... 58
  Metals—Lead, Zinc, and Copper ... 63
  Petroleum Fractions—Oil and Grease, Heavy Oil Range, and Diesel Range . 67
Bioassay Results ... 70
  Acute and Chronic Toxic Effects ... 71
  Biostimulatory Response ... 73
  Reasons for Toxic and Biostimulatory Effect ... 76
Roadside Ditch Survey Results ... 78
  Vegetative Cover ... 79
  Vegetative Composition ... 81
  Summary and Conclusions ... 83
Highway Pollutant Removal ... 84
  Transport Pathways ... 84

Dry Period Transport Pathways 84
Wet Period Transport Pathways 85
Pollutant Removal Mechanisms By Shoulder Treatments 86
Settling/Sedimentation 86
Filtration and Soil Incorporation 87
Adsorption and Ion Exchange 88
Correlations Between Specific Pollutants and Removal Mechanisms 88
Association Between Solids and Pollutants 88
Removal of Soluble Pollutants 90
Implication of Results for First Flush Capture by Porous Asphalt Shoulder 91
Comparison of Pollutant Removal Rates To Previous Studies 92
Clogging of Porous Pavements 93

CHAPTER THREE: CONCLUSIONS 96

CHAPTER FOUR: RECOMMENDATIONS/IMPLEMENTATION 100

REFERENCES 103

APPENDIX A—Data Sets for Individual Water Quality Parameters and Bioassay Summaries A-1

APPENDIX B—QA/QC DATA SUMMARIES B-1

APPENDIX C—Absolute Loads C-1

Appendix D—Porous Asphalt Road Shoulder Hydraulics Model D-1

LIST OF FIGURES

Figure		Page
1.1:	Typical Cross-Section of a Full-Depth Porous Pavement	12
1.2:	Vicinity and Monitoring Location of Road Shoulder Runoff Study Site	17
1.3:	Plan View of Road Shoulder Test Sections and Stormwater Runoff Collection System	19
1.4:	Schematic of Composite Flow Splitting Device	24
1.5:	Plan and Elevation Views of Composite Flow Splitting Device	26
1.6:	Slot Drain Runoff Collection System	27
1.7:	Schematic of Rain Simulation/Overland Flow Experiment System	32
2.1:	Relationship Between Storm Size and Shoulder Runoff Coefficient	39
2.2:	Relationship Between Storm Intensity and Shoulder Runoff Coefficient	40
2.3:	Relationship Between Storm Intensity and Runoff Coefficient	41
2.4:	Comparison of Relative Total Suspended Solids Loads for Various Seasons	52
2.5:	Comparison of Relative Chemical Oxygen Demand Loads for Various Seasons	57
2.6:	Comparison of Relative Biochemical Oxygen Demand Loads for Various Seasons	57
2.7:	Comparison of Relative Total Phosphorus Loads for Various Season	62
2.8:	Comparison of Relative Ortho-Phosphorus Loads for Various Seasons	62
2.9:	Comparison of Relative Lead Loads for Various Seasons	66
2.10:	Comparison of Relative Zinc Loads for Various Seasons	66
2.11:	Comparison of Relative Copper Loads for Various Seasons	67
2.12:	Relative Wet Season Loads: Oil and Grease, Heavy Oil Range, and Diesel Range	70
2.13:	Daily Algal Growth Potential Test Results	75
2.14:	Comparison of Total Vegetative Cover in Roadside Ditches Adjacent to Different Roadside Shoulders	80
2.15:	Vegetative Cover on the Road-Side of Ditches	80
2.16:	Vegetative Cover on the Bottoms of Roadside Ditches	81
2.17:	Percentage of Cover of Grasses and Herbs versus Other Vegetation in Ditches Adjacent to Gravel Shoulders Wider Than Four Feet	82
2.18:	Percentage of Cover of Grasses and Herbs versus Other Vegetation in Ditches Adjacent to Gravel Shoulders Narrower Than Three Feet	82
2.19:	Percentage of Cover of Grasses and Herbs versus Other Vegetation in Ditches Adjacent to Paved Shoulders	83
D.1:	Modified Porous Asphalt Hydraulics Model	D-3
D.2:	0.05 Inch/Hour Storm Simulation Results	D-7
D.3:	0.25 Inch/Hour Storm Simulation Results	D-7

LIST OF TABLES

Table		Page
1.1:	Pollutant Removal Efficiency of Porous Pavement Installations	14
1.2:	Results of Woodinville-Duvall NE Shoulder Soils Analysis	20
1.3:	Asphalt Gradations and Mix Properties Used by Various Agencies	22
1.4:	Water Quality Test Parameters and Analysis Protocols	29
2.1:	Summary of Storms Monitored	37
2.2:	Summary of Experimental Conditions and Runoff Coefficient Results for Rain Simulation/Overland Flow Experiments	39
2.3:	Field Duplicate Relative Percentage Difference (RPD) Results	43
2.4:	Treatment Replicate Relative Percentage Difference (RPD) Summary	44
2.5:	Runoff Coefficients Used for Load Estimations	46
2.6:	Total Suspended Solids Summary	50
2.7:	Tukey's Honestly Significant Difference Test Results on Wet Season Total Suspended Solids Concentrations	51
2.8:	Turbidity Summary	53
2.9:	Tukey's Honestly Significant Difference Test Results on Wet Season Turbidity Levels	54
2.10:	Chemical Oxygen Demand Summary	55
2.11:	Biochemical Oxygen Demand Summary	55
2.12:	Tukey's Honestly Significant Difference Test Results on Wet Season Chemical Oxygen Demand Concentrations	56
2.13:	Total Phosphorus Summary	59
2.14:	Ortho-Phosphorus Summary	59
2.15:	Tukey's Honestly Significant Difference Test Results on Wet Season Total Phosphorus Concentrations	60
2.16:	Tukey's Honestly Significant Difference Test Results on Wet Season Ortho-Phosphorus Concentrations	60
2.17:	Lead Summary	63
2.18:	Zinc Summary	63
2.19:	Copper Summary	64
2.20:	Tukey's Honestly Significant Difference Test Results on Wet Season Lead Concentrations	64
2.21:	Tukey's Honestly Significant Difference Test Results on Wet Season Copper Concentrations	65
2.22:	Oil and Grease Summary	68
2.23:	Heavy Oil Range Summary	68
2.24:	Diesel Range Summary	68
2.25:	Tukey's Honestly Significant Difference Test Results on Wet Season Heavy Oil Range Concentrations	69
2.26:	Summary of 96-Hour *Selenastrum capriocornutm* Chronic Toxicity Test Results for April 1, 1996, Storm	72
2.27:	Summary of 96-Hour *Selenastrum capriocornutm* Chronic Toxicity Test Results for February 5, 1996, Storm	72
2.28:	Tukey's Honestly Significant Difference Test Results for 96-Hour*Selenastrum capriocornutm* Chronic Toxicity Data from February 5, 1996 Storm	73
2.29:	*Selenastrum capriocornutm* (Algal Growth Potential) Test Results for February 5 and April 1, 1996, Storms	74
2.30:	Results of the 7-Day *Lemna minor* Growth Potential Tests on the February 5 and April 1, 1996, Storms	76

2.31: Comparison of February 5, 1996 Metal Concentrations to Water Quality Criteria 77
2.32: Correlation Between Total Suspended Solids and Various Pollutants 89
C.1: Wet Season Storm (0.5") Loads C-1
C.2: Wet Season (November to April) Loads C-2
C.3: Sanding Event Storm (0.8") Loads C-2
C.4: Summer Event Storm (1.5") Loads C-3
D.1: Equations for Modified Porous Asphalt Hydraulics Model D-4

EXECUTIVE SUMMARY

BACKGROUND

This summary describes a one-year monitoring study of roadside shoulder runoff quality and quantity. The study, cosponsored by the King County Roads and Engineering Division and the Washington State Department of Transportation, investigated the role that road shoulders play in the highway runoff process. Traditionally, roadside shoulders have been designed to increase traffic safety and to facilitate roadway operating benefits. With suitable information, roadside shoulders could also be designed to serve environmental functions, such as reducing runoff volumes and increasing runoff water quality, as well. Though extensive research has been done on the quality and quantity of runoff from highways in general, no studies have examined the role of the road shoulder in this process.

In King County, Washington, road shoulders are constructed of both gravel and conventional asphalt. This study evaluated the performance of gravel, conventional asphalt, and porous asphalt road shoulders. The hydraulic, hydrologic, runoff water quality, and operational characteristics of the three shoulder materials were evaluated at a monitoring site along a heavily traveled two-lane road north of Redmond, Washington.

Current environmental regulations are based on the assumption that gravel road shoulders allow significant stormwater infiltration, thereby reducing the quantity and improving the quality of the highway runoff. Transportation agencies, on the other hand, typically want to pave road shoulders on the assertion that paved shoulders enhance traffic safety and provide roadway operation and maintenance benefits. In addition, transportation agencies contend that gravel shoulders, because of their highly compacted nature, actually allow only minimal infiltration. They also believe that gravel shoulders may, in fact, act as a source for pollutants through release of fines to runoff. However, before this study, no research had been done to support or refute these assumptions and assertions.

Porous asphalt pavement has been cited as a potential substitute for conventional asphalt pavement on parking areas and low-traffic roadways, provided that suitable conditions exist. Porous asphalt pavements consist of an open-graded coarse aggregate held together by asphalt cement. They allow water to penetrate and flow through the pavement to a sublayer. Because of these characteristics, porous asphalt pavements can attenuate runoff, thereby providing the following potential benefits:

- reduce water puddling that can cause automotive hydroplaning and headlight glare
- reduce traffic noise
- reduce both the volume and rate of stormwater runoff
- remove pollutants in stormwater runoff as a result of physical and chemical mechanisms associated with infiltration
- increase groundwater recharge rates.

In addition to these potential advantages, there could be important drawbacks associated with porous asphalt pavements. The porous nature of these pavements makes them susceptible to clogging, which could directly impede the achievement of the benefits associated with the material. In addition, porous asphalt pavements require somewhat more care than the conventional material to install, and with traffic loading, porous pavements are prone to rutting from wear and raveling. Few studies have analyzed the water quality benefits provided by porous asphalt, and no study has reviewed their use on road shoulders.

The primary research task in this study was to determine whether porous asphalt road shoulders can simultaneously provide both the environmental and roadway operational benefits desired by regulatory and transportation agencies in Washington. The study objectives were

1. to determine the relative water quality of runoff from gravel, conventional asphalt, and porous asphalt shoulder treatments and road runoff controls

2. to determine the hydraulic behavior of gravel, conventional asphalt, and porous asphalt shoulder treatments under various conditions of storm intensity and storm duration
3. to determine the operational benefits and drawbacks of the three types of shoulder treatments
4. to make recommendations regarding the use of the three types of shoulder materials.

RESEARCH METHODS

Test Site

To test the performance of the three shoulder materials, an experimental monitoring site was installed to collect runoff from gravel, conventional asphalt, and porous asphalt shoulder test sections. The monitoring site was constructed along the south shoulder of the NE Woodinville-Duvall Road, north of Redmond, Washington, and adjacent to Cottage Lake Park. NE Woodinville-Duvall is a heavily traveled, two-lane road with a three-day average daily traffic rate of approximately 9,000 vehicles in each direction. The three shoulder materials were tested in duplicate along with two road controls that sampled runoff directly from the roadway (no shoulder treatment). Each of the shoulder test sections was 2.4 meters (8 ft) wide by 14.6 meters (48 ft) long, with 6-meter (20-ft) buffers between the shoulder sections. The road lane adjacent to the shoulder was 3.6 meters (12 ft) wide.

NE Woodinville-Duvall Road and its adjacent road shoulder are relatively level, and the road is crowned, allowing an even distribution of sheet flow from the road surface to the shoulder test sections. The use of a water truck to simulate an intense rain storm confirmed that the runoff flowed primarily in a sheet-like pattern perpendicular to the road shoulder. Soil tests performed prior to installation of the shoulder treatments determined that the shoulder drainage was suitable for installing the gravel and porous asphalt test sections. The shoulder soil is composed largely of gravel and sand fill with only minimal fines. The water table is approximately 1.2 meters (4 ft) below the surface of the shoulder.

Each of the shoulder treatments was installed directly on top of the graded shoulder. The gravel test sections were typical of gravel shoulders used in King County, consisting of 1.3- to 1.9-cm (1/2- to 3/4-inch) diameter crushed gravel, compacted to a depth of 7.6 cm (3 inches). The conventional asphalt test sections were paved with Washington State Department of Transportation (WSDOT) Class A asphalt according to typical King County paving standards. The conventional asphalt was applied and compacted to a depth of 7.6 cm (3 inches). The porous asphalt test sections consisted of a modified Arizona DOT mix. The porous asphalt mix was applied and lightly compacted to a depth of approximately 8.9 cm (3.5 inches) and had an estimated void volume of 15 percent. The road was conventional asphalt (WSDOT Class A mix).

Monitoring

Continuous composite samples of the runoff from the road controls and shoulder treatments were collected to determine total runoff volumes and relative runoff water quality. Flow splitter samplers were installed to collect flow-weighted composite samples from each test section. Runoff from the road controls and shoulder test sections flowed into slot drains, which directed the runoff to the flow splitters. A known "split" of the runoff was collected in 121-L (32-gallon) enclosed sampling containers.

Storms that produced at least 0.6 cm (0.25 inch) of precipitation over a period of at least 12 hours generated adequate runoff volumes for collection and sampling. A tipping bucket rain gauge with an ISCO 3230 data recorder was installed at the site to monitor rainfall depth and intensity. In addition to determining the volumes of runoff associated with each test section, the runoff samples were analyzed by the Municipality of Metropolitan Seattle (Metro) Environmental Laboratory for a variety of water quality variables, including suspended solids, petroleum fractions, total and ortho-phosphorus, chemical and biochemical oxygen demand, metals, and semivolatiles. Acute and chronic toxicity and biostimulation tests were performed on stormwater samples from each test section for several storms. The regular internal quality assurance/quality control (QA/QC) procedures of the Metro Environmental Laboratory were followed, and requirements were met for every storm. Random field duplicates of 5 percent of the samples were collected and analyzed.

The test sections and stormwater collection system operated well and facilitated the successful monitoring of 11 storms between November 1995 and August 1996. Ten of the 11 storms that were monitored occurred between November and April, a period consistent with the wet season in the Pacific Northwest. However, one of these 10 storms was preceded by a lengthy cold period during which the King County Road Maintenance Division applied sand to the roads. Consequently, the water quality of the runoff from this "sanding event" storm was considerably different from the other nine wet season storms. One storm was monitored in early August 1996 and was preceded by a 13-day period of no rain, representing a fairly typical "summer event" storm.

Debris (sand, leaves, and pine needles) transported by the runoff and deposited in the flow splitters interrupted uniform flow and resulted in uncertain runoff quantities. To describe the hydraulic characteristics of the shoulder treatments with confidence, rain simulation experiments were conducted. Under controlled conditions, "storms" of varying size and intensity were simulated, and the entire volume of runoff was collected. Water was applied to the shoulder test sections and distributed through a perforated diffuser pipe. A barrel with a ball valve at its base was used to discharge the "rain" into the diffuser pipe, and the storm intensities were manipulated by varying the water level in the barrel and the setting of the ball valve.

Six rain simulation experiments produced consistent results, providing a clear picture of the hydraulic characteristics of the shoulder treatments. The runoff coefficient, a unitless parameter that expresses the fraction of rainfall volume that is converted into storm runoff volume, was determined for each of the shoulder treatments under varying storm conditions. The runoff coefficient for the conventional asphalt shoulders was approximately 0.9 for all storm conditions tested. The runoff coefficients for the porous asphalt and gravel shoulders, however, appeared to be a function of storm size but were not affected by differences in storm intensity. The average storm size at the Cottage Lake site for the 1995-1996 water year was approximately 0.76 cm (0.3 inch). The runoff coefficients for the gravel and porous asphalt shoulders associated with storms of this size (± one standard error) were 0.65 (± 0.016) and 0.12 (± 0.010), respectively. However, during larger storms [≥ 1.27 cm (0.5 inch)], the runoff coefficients for the gravel and porous asphalt shoulders were approximately 0.8 and 0.4, respectively.

Infiltration rates of the gravel and porous asphalt shoulders were determined by single-ring infiltrometer experiments. The gravel shoulders had an average infiltration rate of 31.2 cm/hr (12.3 inch/hour). The infiltration rate of the porous asphalt surface course was 74.2 cm/minute (29.2 inch/minute) or, if continued at this rate, 4445 cm/hr (1750 inch/hour).

RESULTS

Runoff Water Quality and Quantity

The runoff water quality results of the shoulder treatments and road controls showed striking trends for the nine wet season storms, the single sanding event storm, and the single summer event storm. For purposes of statistical analysis the individual pollutant data from the nine wet season storms were pooled, and an average concentration for each treatment was determined. On average, the standard error was less than 15 percent of the mean for each treatment for the wet season storms.

Several general observations regarding all of the water quality variables were made. During the wet season storms, the runoff from all three of the shoulder treatments had lower average concentrations of pollutants than did the road runoff. Thus from a surface water quality standpoint, all three shoulder materials provided some reduction in pollutant concentrations. The concentrations of pollutants from all of the test sections were 3 to 15 times higher after the sanding event storm than the average wet season concentration. Sanding operations, routinely performed by the King County Road Maintenance Division during freezing conditions, clearly have a significant effect on highway runoff water quality.

The most striking trend in the data was that the porous asphalt shoulders consistently performed better than the gravel and conventional asphalt shoulders in reducing pollutant concentrations during most of the wet season and sanding event storms. The concentrations of pollutants in the runoff from the porous asphalt shoulders were typically 30 to 60 percent lower than the concentrations from the conventional asphalt shoulders during the wet season. During the sanding event storm the pollutant concentrations from the porous asphalt shoulders were also 40 to 50 percent lower than those from the conventional asphalt shoulder. The average runoff concentrations of total suspended solids (TSS), total phosphorus (TP), and ortho-phosphorus (OP) from the gravel shoulders, on the other hand, were higher than those concentrations from the conventional asphalt shoulders during the wet season. Statistical analysis (Analysis of Variance and Tukey's Honestly Significant Difference Test) indicated that the porous asphalt runoff concentrations of TSS, TP, OP, and the metals lead and copper were significantly different from those concentrations from the conventional asphalt and gravel shoulders ($P<0.001$).

The decrease in pollutant concentrations from the porous asphalt shoulders, coupled with the reduction in runoff volumes, have important pollutant loading implications. During the wet season the porous asphalt shoulders consistently reduced TSS, TP, OP, metals, and petroleum fraction loads by at least 90 percent in comparison to those loads from the conventional asphalt shoulders. During the sanding event storm the porous asphalt shoulders reduced the TSS, TP, OP, and metals loads by at least 75 percent. During the sanding event storm the pollutant concentrations were all elevated; thus load reductions of 75 percent are noteworthy.

The load reductions from the gravel shoulders were neither as large nor as consistent as those from the porous asphalt shoulders. The TSS, TP, metals, and petroleum fraction loads from the gravel shoulders were generally between 20 to 50 percent lower than the conventional asphalt loads during wet season and sanding event storms. However, the OP loads were up to 30 percent higher than the conventional asphalt loads.

There was a close correlation between some of the pollutants [TP, metals, and to a lesser extent chemical oxygen demand (COD)] and solids. This correlation indicated that the concentrations of these pollutants in the runoff are due in part to the presence of solids. Most likely these pollutants are adsorbed to suspended solids in the runoff. Furthermore, the major fraction of TP, metals, and COD seem to be in the particulate form. The pollutant removal efficiency of both the gravel and porous asphalt shoulders was greatest for those pollutants that were closely correlated with solids. Physical mechanisms of settling, filtration, and soil incorporation are most likely the dominant removal mechanisms functioning in the gravel and porous asphalt shoulders.

The removal efficiency of petroleum fractions and those pollutants known be relatively soluble fraction [particularly OP and biochemical oxygen demand (BOD)] was lower than the removal efficiencies of pollutants associated with particulates. There was minimal difference in BOD concentrations among all three shoulder treatments. The concentrations of OP in the runoff from the porous asphalt shoulders were only 30 percent lower than the concentrations from the conventional asphalt shoulder during the wet season in comparison to a nearly 60 percent reduction of TP. The average concentration of OP in the runoff from the gravel shoulders during the wet season was actually 75 percent higher than the concentration in the average conventional asphalt runoff. Clearly the gravel and porous asphalt shoulders were less efficient at removing these soluble pollutants. However, the porous asphalt shoulders demonstrated the greatest capacity to remove the soluble pollutants, indicating that adsorption and soil incorporation, mechanisms known to remove soluble pollutants, were at work.

Bioassays were conducted on one of the wet season storms and the sanding event storm to evaluate the toxic or biostimulatory effect of the shoulder runoff on aquatic organisms. The runoff from each of the shoulders was not toxic but was somewhat biostimulatory for each of the shoulder treatments. The biostimulatory effect was attributed to TP concentrations that were above threshold levels associated with eutrophic conditions. There were no significant differences in biostimulation among the various shoulder treatments.

Operational Aspects

Generally, the three shoulder materials all operated well. The gravel shoulders however, did erode somewhat. Erosion of the gravel appeared to be accelerated by vehicles straying onto the shoulder because of its proximity to the entrance to Cottage Lake Park. Inspection of porous asphalt core samples revealed that there was no ice or frost damage. Finally, the porous asphalt shoulders showed no signs of clogging throughout the monitoring period. The 1996 winter season had some extensive cold periods, during which time the King County Road Maintenance Division applied approximately 113 kg (248 pounds) of sand to the road adjacent to each test section (15.2 lane-meters or 50 lane-feet). Despite this heavy sand loading, the porous asphalt shoulders maintained average infiltration rates of 4445 cm/hr (1750 inch/hour). This infiltration rate is for the porous asphalt surface course and equals or exceeds those infiltration rates reported for other porous asphalt installations.

To evaluate one component of the operational characteristics of gravel and conventional asphalt shoulders, a roadside ditch vegetative cover and composition survey was conducted. The objective of the survey was to determine how road shoulder type affects vegetative cover and composition in roadside ditches, factors known to serve biofiltration functions. A total of 48 ditches along county roads in King and Snohomish counties, Washington, were surveyed. The results of the survey showed no dominant trends. Although ditches adjacent to paved shoulders appeared to have a slightly higher total percentage of vegetative cover than ditches adjacent to gravel shoulders, the vegetative composition in these ditches was quite mixed. These results indicate that paved shoulders are not more advantageous than gravel shoulder for biofiltration .

CONCLUSIONS AND RECOMMENDATIONS

The results of this road shoulder monitoring study show promise for the use of porous asphalt on road shoulders along county highways. Porous asphalt shoulders appear to provide both the environmental and road operations benefits desired by regulatory and transportation agencies. The pollutant removal rates of the porous asphalt shoulders, particularly during the wet season, equaled or exceeded the removal rates reported in other studies on porous pavement installations, as well as removal rates of infiltration basins and constructed wetlands.

Though current installation costs of porous asphalt shoulders may be somewhat higher than the costs associated with gravel and conventional asphalt installation, the long-term cost savings may be significant. The porous asphalt shoulders demonstrated the greatest ability to reduce runoff volumes, particularly during small storms (0.75 cm or 0.3 inch) typical for the Pacific Northwest. Given the operational characteristics of porous asphalt, it seems that the porous asphalt shoulders have the greatest potential to reduce peak runoff discharge rates. The use of porous asphalt road shoulders may therefore reduce the need for and number of road runoff detention facilities, which would result in an important cost savings.

The potential for porous asphalt shoulders to clog should be quantitatively evaluated. If clogging occurs, the water quality benefits of the material will diminish. Controlled experiments should be conducted to determine the length of time before clogging occurs in porous asphalt shoulders when they are exposed to typical annual sanding and highway runoff conditions. Assuming that the results of clogging experiments do not suggest that the porous asphalt shoulders will become completely clogged within five years, it is recommended that a program to install porous asphalt shoulders be implemented. Even if the pollutant removal capacity of porous asphalt shoulders decreases over time, its benefits will still exceed those of conventional asphalt and gravel shoulders.

The study results indicate that gravel shoulders are quite inadequate with regard to several important pollutants. *Ortho-phosphorus* is environmentally significant, as it is typically the limiting nutrient that causes algal blooms in receiving waters. The ortho-phosphorus loads from the gravel shoulders were consistently higher than the loads from both the porous and conventional asphalt shoulders. Furthermore, most storms during the wet season yielded *total suspended solids* concentrations that were higher in the runoff from the gravel shoulders than in the runoff from the porous and conventional asphalt shoulders.

If gravel shoulders are to be used in the future, it is recommended that extractions be conducted on the gravel mix to determine whether the gravel mix is a source of phosphorus. It is possible that phosphorus-containing materials could be excluded from the mix, thereby reducing phosphorus loads from gravel shoulders.

CHAPTER ONE: INTRODUCTION AND RESEARCH APPROACH

STATEMENT OF THE RESEARCH PROBLEM

Research over the last two decades has revealed that urban development has a profound effect on the hydrology, water quality, morphology, and biodiversity of urban streams (Booth and Reinelt 1993, Washington Department of Ecology 1992). The quality of an urban stream depends on the interaction of many physical, chemical, and biological processes, and these processes are inextricably linked to urbanization. The most notable manifestation of urban development is the increase in the amount of impervious surfaces that cover the land. The percentage of impervious area in a landscape has become a useful indicator by which to measure the impacts of development on aquatic systems. Research indicates that there is a general negative relationship between impervious cover and surface water quality associated with stormwater runoff (Schueler 1984).

The amount of transport-related imperviousness (roads and parking lots) often exceeds other forms of imperviousness (Schueler 1984). In a study on impervious surfaces in the City of Olympia, Washington, transport-related imperviousness comprised 63 to 70 percent of the total impervious cover at 11 residential, multifamily, and commercial sites where it was measured (City of Olympia 1995). Seven of the 19 recommendations made by the City of Olympia regarding impervious surface reduction addressed vehicle-oriented pavement issues (City of Olympia 1995). Despite the fact that most efforts to control urbanization focus on zoning codes that regulate the number of dwelling units per area, significant opportunities clearly exist to reduce the share of transport-related imperviousness.

In western Washington a debate has been ongoing over one facet of transport-related imperviousness: road shoulders. Current environmental regulations are based on the assumption that gravel shoulders allow significant stormwater infiltration. Because infiltration can reduce the volume and peak flow rate of runoff from impervious areas, as well as improve the quality of the runoff (Washington Department of Ecology 1992), environmental agencies assume that gravel shoulders provide environmental benefits not met by paved shoulders. Transportation agencies, on the other hand, argue that paved shoulders enhance traffic safety and provide roadway operation and maintenance benefits. Furthermore, transportation agencies challenge that gravel shoulders do not in fact provide significant infiltration. Despite these differing opinions, no research has examined the performance and operation of different shoulder materials.

This study, which is cosponsored by the King County Roads and Engineering Division and the Washington State Department of Transportation (WSDOT), was designed to investigate the role that road shoulders play in the stormwater runoff process. Specifically, the research examined the hydraulic, hydrologic, surface water quality, and operational characteristics produced by road shoulders treatments to determine whether road shoulders can simultaneously provide both ecological and roadway operational benefits.

RESEARCH GOALS AND OBJECTIVES

This research attempted to answer the following question: how do shoulder treatments affect the quantity and quality of runoff during its flow over the shoulder?

The goal of this research was to determine the type of shoulder treatment that yields the least quantity of runoff of the highest possible quality. Three types of shoulder materials were tested: gravel, conventional asphalt, and porous asphalt. This research examined the effects of shoulder materials on runoff quantity and quality from a heavily traveled, two-lane road in western Washington.

The study objectives of this research were as follows:

1. to determine the relative water quality of runoff from gravel, conventional asphalt, and porous asphalt shoulder treatments

2. to determine the hydraulic behavior of gravel, conventional asphalt, and porous asphalt shoulder treatments under various conditions of storm intensity and storm duration
3. to determine the operational benefits and drawbacks of the three types of shoulder treatments
4. to make recommendations regarding the use of the three types of shoulder materials.

RESEARCH HYPOTHESES

The hypotheses posed in this research were as follows:

1. The porous asphalt treatment will yield runoff of the highest water quality in comparison to the gravel and conventional asphalt treatments.
2. The greatest degree of infiltration can be obtained from the porous asphalt shoulder treatment, in comparison to the gravel and conventional asphalt treatments, for the range of storm intensities and durations typical of the Pacific Northwest.
3. The operational benefits of porous asphalt shoulders will match those of conventional asphalt and exceed those of gravel shoulders.

RELEVANCE OF THE RESEARCH IN THE CONTEXT OF THE RESEARCH PROBLEM

A fairly extensive study of highway runoff water quality was completed in Washington state in the early 1980s (Mar et al. 1982, Horner and Mar 1982). Neither this study, nor others of its kind, examined the role of road shoulders on highway runoff water quality. This dearth of information has led to the conflict existing between environmental and transportation agencies.

The belief by environmental agencies that gravel shoulders allow significant stormwater runoff infiltration has led to regulations promoting such uses. In the Puget Sound Basin infiltration has been highlighted as the preferred method of stormwater treatment and disposal where conditions for such a practice are suitable (Washington

Department of Ecology 1992). Infiltration can provide multiple benefits, including pollution removal, control of streambank erosion, flood control, and groundwater recharge. However, infiltration systems have the highest failure rates of any stormwater management alternatives (Horner et al. 1994). Although the potential benefits and concerns of infiltration are not disputed, the belief that gravel shoulders provide significant infiltration has never been scientifically tested.

Transportation agencies, meanwhile, pursue shoulder paving programs under the assertion that paved shoulders enhance pedestrian and bicycle travel, create road construction and maintenance advantages, give lateral structural support to the roadway base and surface, and are safer than gravel shoulders. Transportation personnel further contend that infiltration into gravel shoulders is negligible. This belief is based in part on the theory that compacted gravel is not very pervious and in part on common evidence of erosion on gravel shoulders. Finally, transportation personnel speculate that gravel shoulders may in fact be a source of pollutants produced by the erosion of gravel and accompanying fines, in addition to contaminants transported by solids. Despite these conflicting beliefs, however, no research has examined the potential benefits or drawbacks of gravel road shoulders.

Porous asphalt pavement has been cited as a potential substitute for conventional asphalt pavement on parking areas and low-traffic roadways, provided suitable conditions exist (Washington Department of Ecology 1992, Cahill Associates 1993, Isenring et al. 1991, Hossain and Scofield 1991, Balades et al. 1995). Porous asphalt pavement allows water to penetrate and flow through the pavement to a sublayer. By acting as an attenuation and runoff reduction device, porous pavement systems offer the following potential advantages (Washington Department of Ecology 1992, Cahill Associates 1993, Schueler 1987, Hossain and Scofield 1991):

1. Hydroplaning and skidding occur up to 15 percent less on porous pavement surfaces than on conventional asphalt pavement.

2. There is less puddling due to infiltration, which reduces headlight reflectivity.
3. Tire noise is reduced in comparison to conventional asphalt pavement.
4. The hydraulic functions offered by porous pavements can reduce both the volume and rate of stormwater runoff.
5. Groundwater recharge rates are enhanced.
6. Porous pavement installations can potentially remove stormwater runoff pollutants through various physical and biological mechanisms.

In addition to the potential advantages of porous pavements, there are noteworthy disadvantages (Washington Department of Ecology 1992, Cahill Associates 1993, Schueler 1987, Hossain and Scofield 1991):

1. The greatest concern regarding the use of porous pavements is their capacity to clog. Fine grained particles from construction sites, road sanding practices, automobiles, and stormwater runoff can accumulate in the voids of the porous asphalt, reducing its infiltrative capacity and overall performance.
2. A high level of workmanship is required throughout the construction process in order to retain the pavement's porous properties.
3. Because of their porous nature, porous asphalt pavements are susceptible to rutting and other forms of structural failure.

Whereas the structural and hydraulic performance of porous asphalt pavements have been studied fairly extensively (see review by Doell 1995), data on the pollutant removal efficiency of porous pavement installations are limited, and no data exist on their performance in road shoulder applications. This study attempts to determine whether porous asphalt pavements could perform the infiltration functions desired by environmental agencies, as well as the structural and operational functions preferred by road maintenance agencies.

Ideally, transportation system design and operation, and environmental law, regulation, and implementation should be mutually compatible and capable of accomplishing the goals of both disciplines. This study provided the comprehensive data on the ecological and roadway operations performance of gravel, porous asphalt, and conventional asphalt shoulder treatments necessary to solve this debate. Though the study was performed in the Pacific Northwest to resolve an issue that developed in King County, Washington, the results may have regional, statewide, and national implications. Stormwater management requirements are being implemented on local and regional scales in Washington state, and a similar progression is occurring in other states. Results regarding the road shoulder treatment that provides both environmental and road operations benefits could be applied to thousands of miles of roads in this state and tens of thousands nationwide.

URBAN RUNOFF MITIGATION

Washington Department of Ecology's Stormwater Program

Because of the pervasive changes to basin hydrology, it is nearly impossible to eliminate the impacts of urban development. However, the economic and environmental consequences of the changes to the hydrologic regime of the urban landscape have prompted a number of jurisdictions to adopt stormwater management programs designed to assess and reduce the impacts of urbanization. The requirements of the Puget Sound Water Quality Management Plan (PSWQMP 1992) established the foundation of the stormwater program developed by the Washington Department of Ecology (1992). The PSWQMP and Ecology's stormwater programs apply to the cities and counties, as well as the Washington State Department of Transportation, in the Puget Sound basin.

The plan requires all 111 local jurisdictions in the Puget Sound basin to implement stormwater management programs that include, but are not limited to, the following guidelines (Washington Department of Ecology 1992):

- ordinances for all new development and redevelopment that address control of off-site water quality, the use of source control best management practices, the effective treatment of the water quality design storm, the use of infiltration where appropriate, the protection of stream channels and wetlands, and erosion and sediment control

- operation and maintenance programs for new and existing public and private stormwater systems
- coordination with provisions of the Growth Management Act, where appropriate.
- basin planning
- identification and ranking of potentially significant pollutant sources and their relationship to the drainage system and water bodies through an ongoing assessment program

<u>Puget Sound Highway Runoff Program</u>

The Washington Department of Ecology (WDOE) worked with the Washington State Department of Transportation (WSDOT) to adopt a rule and develop a program to control the quality of runoff from state highways in the Puget Sound basin. The Puget Sound Highway Runoff Program includes previsions that WSDOT will

- adopt a technical manual to use as guidance for managing highway runoff
- adopt a vegetation management program
- include best management practices as part of new construction projects.

<u>Best Management Practices for Stormwater Mitigation</u>

The Washington Department of Ecology's stormwater program includes the use of best management practices (BMPs) for stormwater mitigation. BMPs are described as physical, structural, and/or managerial practices that, when used singly or in combination, prevent or reduce pollution of water. Three classes of BMPs are identified that address different, though overlapping, stormwater management objectives: pollution prevention is accomplished through the use of **source control BMPs**; pollutant treatment is accomplished through the use of **runoff treatment BMPs**; and protection of stream ecosystems from erosion and sedimentation is accomplished through the use of

streambank erosion control BMPs. Although critical for the protection of surface and ground water quality, source control BMPs are not discussed in this review.

Runoff treatment BMPs are designed to remove pollutants contained in runoff. Treatment BMPs utilize a variety of physical, chemical, and biological mechanisms, including sedimentation, filtration, plant uptake, ion exchange, adsorption, and bacterial decomposition, to remove pollutants from stormwater. The goal for runoff treatment BMPs, as stated by the WDOE (1992), is to provide effective treatment for at least 90 percent of the runoff generated by development. To achieve this goal, treatment BMPs are developed to treat the 6-month, 24-hour design storm.

Streambank erosion control BMPs are designed to prevent or control the excessive erosion that typically occurs in streams located in urbanizing watersheds. The goal for streambank erosion control BMPs, as stated by the WDOE (1992), is to replicate, to the extent possible, the pre-existing hydrologic regime in streams by attenuating runoff from development sites and slowly releasing it back to the natural drainage system. The 2-year return period storm is identified as the key event for controlling streambank erosion.

Infiltration BMPs

WDOE (1992) has highlighted infiltration as the most effective BMP for both runoff treatment and streambank erosion control when site conditions are appropriate. Infiltration is the only structural BMP that has the potential to reduce both the peak runoff rates and runoff volumes from urban development. In addition, infiltration BMPs can reduce contaminant concentrations and loads in runoff when runoff percolates in a soil column in which physical and chemical mechanisms operate (Horner et al. 1994). This advantage is especially important for soluble pollutants, which are not effectively treated by surface devices but which soils can effectively capture during percolation (Minton 1987).

Infiltration BMPs include a variety of devices with different management objectives (Horner et al. 1994). *Infiltration basins* impound water in a surface pond until it infiltrates the soil. Excess runoff that can not be contained by the basin is discharged to a conveyance device. *Infiltration trenches* receive runoff in a shallow excavated trench that is backfilled with stone to form a below-grade reservoir. Water enters the underlying subsoil according to its infiltration rate. *Perforated pipes* are used to distribute runoff into the subsoil. *French drains* consist of a pervious material, such as gravel, and disseminate inflowing water into the surrounding soil. Finally, *porous pavements* permit precipitation and runoff to drain through coarse-graded concrete, asphalt, or specially cast blocks with a pervious opening. Porous pavements are discussed in more depth below.

An important distinction must be made, however, between infiltration BMPs designed for runoff treatment and those designed for streambank erosion control. Infiltration BMPs designed for runoff treatment utilize the ability of soils and vegetative root systems to bind, decompose, and/or trap pollutants contained in stormwater runoff (WDOE 1992). Therefore, for runoff treatment to be successful, soils must have an adequate, though not rapid, infiltration rate, contain sufficient organic matter with suitable cation exchange capacity, and maintain aerobic conditions. Streambank erosion control, on the other hand, is accomplished by infiltration BMPs that utilize excessively drained soils. Though there may be some instances when a soil can be used for both runoff treatment and streambank erosion control, this is rare.

Despite their considerable potential, infiltration systems have the highest failure rates of any stormwater management alternative. A study on infiltration system failures in the mid-Atlantic region reported that 50 to 100 percent of infiltration basins had failed within five years of construction (Schueler et al. 1992). The five year failure rates for infiltration trenches and porous pavements were approximately 50 and 75 percent, respectively. The leading cause of infiltration system failures is clogging from sediments brought in with runoff. Microorganism growth in poorly drained soils and oils in runoff can also cause failure (Horner et al. 1994). In the Puget Sound region, the proximity of the seasonal water table to the surface is a leading cause of failure. Furthermore, the presence of a shallow glacial till soil layer increases the possibility of failure. Horner and coworkers

(1994) made several recommendations for successful infiltration systems. These systems should be built on deep to excessively drained soils and should not be near seasonal high water tables or low spots in drainage catchments. To prevent clogging, infiltration facilities should have a pretreatment device to settle larger solids and reject runoff from eroding sites.

Porous Pavements

Porous pavements have been identified as a suitable infiltration BMP. (For a more in-depth review of porous pavement design and operational characteristics, see review by Doell 1995.) Porous pavements allow runoff to infiltrate through a coarse-graded material with a pervious opening. There are two types of porous pavements (WDOE 1992). *Porous asphalt pavement* consists of an open graded, coarse aggregate held together by asphalt cement, forming a coherent mass, with sufficient interconnected voids to permit a high rate of permeability. *Pervious concrete* consists of a specially formulated mixture of Portland cement, uniform open graded coarse aggregate, and water. The material can be combined with various agents that improve the entrainment of water. Conventional asphalt pavements, on the other hand, consist of densely graded asphalt mixes containing a bituminous binder in conjunction with well-graded aggregates that contain a significant amount of fines. The use of fine-graded aggregates in conventional asphalt pavements increases compactability and strength but decreases the void ratio that restricts infiltration. Porous asphalt pavements are used most commonly among porous pavements and are reviewed below.

Porous pavements have been cited as a substitute for conventional asphalt pavement on a variety of applications:

1. parking lots, especially fringe or overflow parking areas
2. parking aprons, taxiways, and runway shoulders at airports
3. emergency stopping and parking lanes and vehicle cross-overs on divided highways

4. low-traffic volume roads.

Partial Depth Versus Full Depth Porous Pavements. Porous pavements have typically been used either as a partial depth pavement overlay or a full depth porous pavement (Schueler 1987). The partial depth pavement overlay consists of the open-graded asphalt surface course described above and is designed to allow water to penetrate and flow through the pavement to the underlying soil layer. The partial depth porous pavement acts as an attenuation and runoff reduction device. In addition to permitting water to infiltrate the pavement, the voids in the porous pavement provide temporary storage of water. The capacity of the partial depth pavement to reduce the volume of surface runoff is dependent on the infiltration capacity and percolation rate of the underlying soil.

Full depth porous pavement devices allow surface water to drain through a series of layers (Figure 1.1). Beneath the surface course of the full depth porous pavement is a crushed stone-filled storage/recharge layer designed to receive all incident rainfall and runoff. The crushed stone layer increases the storage capacity of this device, and the stormwater stored in this layer percolates into the native soil subbase. As with the partial depth porous pavement device, the rate of outflow depends on the soil properties.

Advantages of Porous Pavements. There are a number of distinct advantages of porous pavement devices (Cahill Assoc. 1993, Schueler 1987, WDOE 1992, Hossain and Scofield 1991, U.S. EPA 1980). The friction coefficient on porous pavements increases under wet conditions, which results in up to 15 percent less hydroplaning and skidding on porous pavements than on conventional asphalt pavements. Because of the infiltrative capacity of porous pavements, there is less puddling, which reduces headlight reflectivity and other potential driving dangers. In addition, studies have reported that tire noise is decreased with porous pavements.

The principle hydraulic functions of porous pavement devices are to reduce both the volume and rate of stormwater runoff, and in turn to recharge the groundwater. These devices have the capacity to replicate predevelopment hydrologic characteristics, allowing infiltration to be broadly and evenly distributed (Cahill Assoc. 1993). The infiltrative capacity, and the associated decrease in surface runoff volume and increase in groundwater recharge, provided by porous pavement installations is a function of the void space volume of the crushed stone reservoir base course in full-depth porous pavement installations and of the porous asphalt surface course in partial depth installations. The soil properties of the underlying native soil subbase determines the overall infiltration capacity.

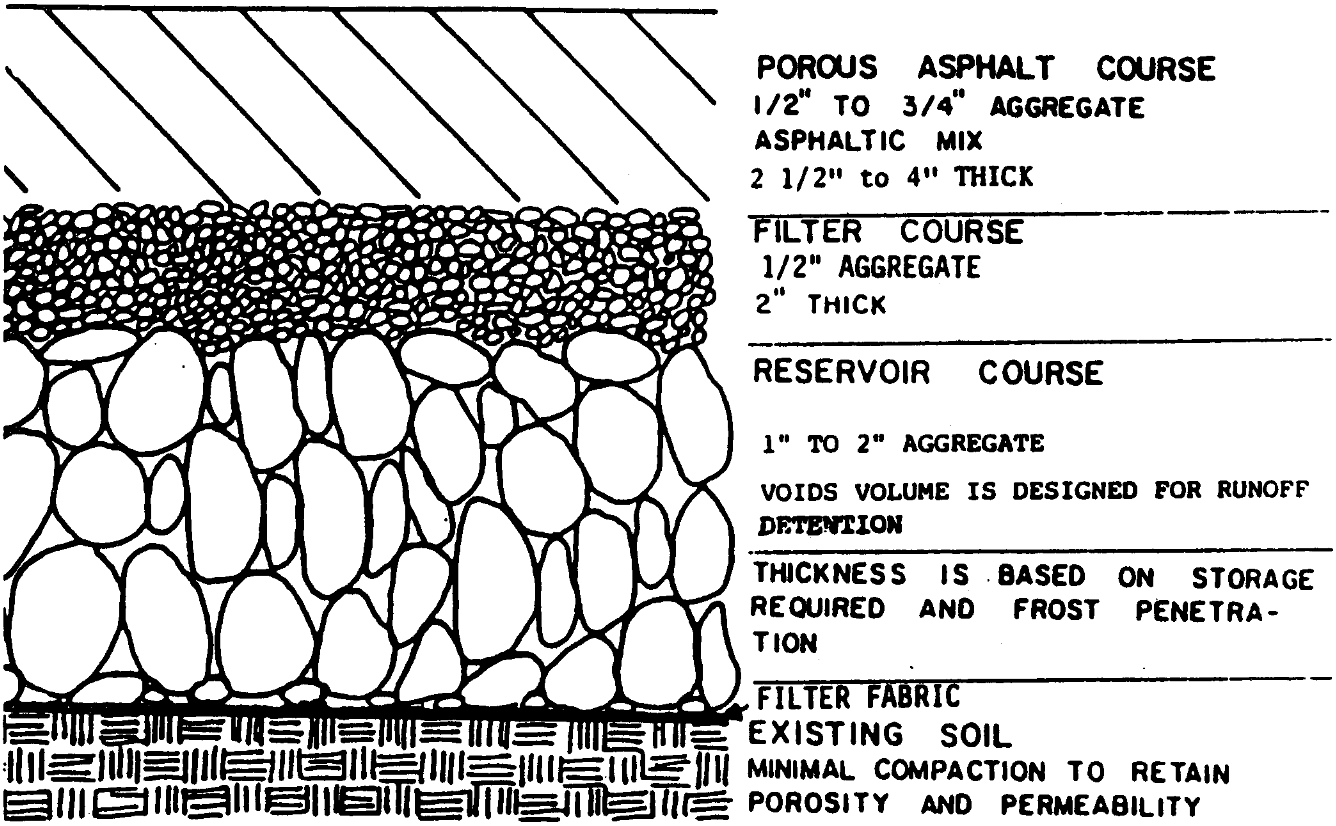

Figure 1.1 Typical Cross-Section of a Full-Depth Porous Pavement
From U.S. EPA 1980.

In addition to this runoff quantity reduction function, porous pavements can improve the water quality of surface and ground water. Porous pavements have the potential to reduce contaminants in runoff through several physical and biological mechanisms. Though few data exist on the pollutant removal capacity of porous pavement systems, knowledge of the mechanisms by which pollutants are removed in other infiltration systems can be applied to porous pavement systems.

Fine-grained particulates, including solids, BOD, and pathogens, as well as contaminants associated with such particulates, can be filtered or trapped in void spaces within both the porous pavement and the underlying soil column. Soluble pollutants may be removed in the soil column via adsorption (as dissolved phosphorus, metals, and synthetic organics) or ion exchange (dissolved metals). The ability of soils to remove pollutants is dependent on sorption, whereby both particulate and soluble forms of nonpoint pollutants become bound to soil particles through ion exchange (Cahill Assoc. 1993). As is the case with runoff quantity control, soil characteristics determine the pollutant removal efficiency of porous pavement systems.

Pollutant removal can also be achieved biologically in soils (Brock and Madigan 1991). Under aerobic conditions in the upper layers of the soil, pollutants are oxidized by soil bacteria that use oxygen dissolved in the surface water and soil moisture as the electron acceptor. Under anaerobic conditions, other electron acceptors such as nitrate and nitrite are utilized by soil bacteria to oxidize pollutants. The process of oxidation reduces COD, petroleum hydrocarbons, and synthetic organics to more benign forms.

Research on the pollutant removal efficiency of porous pavement installations is not extensive. However, the few studies that have been conducted demonstrated compelling results. Schueler (1987) summarized the pollutant removal capabilities of a porous pavement installation (Table 1.1) and compared the results with those of other BMPs. Schueler estimates that porous pavement systems can capture 80 to 99 percent of total suspended solids, total nitrogen, chemical oxygen demand, zinc and lead, and 65 percent of phosphorus; however, the actual capture depends on soil characteristics. On the basis of Schueler's (1987) comparison, porous pavements appear to perform better than most other BMPs, especially when the total array of nonpoint source pollutants is taken into considered.

Table 1.1 Pollutant Removal Efficiency of Porous Pavement Installations

Pollutant	Removal Efficiency (%)
Sediment	> 95 %
Total Phosphorus	60 %
Ortho Phosphorus	> 50 %
Total Nitrogen	88 %
Nitrate + Nitrite Nitrogen	> 70 %
Total Kjeldahl Nitrogen	> 90 %
Extractable Lead	> 95 %
Extractable Zinc	> 99 %
Chemical Oxygen Demand	83 %

From Schueler 1987.

Disadvantages of Porous Pavements. As stated above, infiltration system BMPs have the highest failure rates of any stormwater management alternative, and porous pavements are no exception. The greatest concern regarding porous pavement failure is their susceptibility to clogging by fine-grained particles that can accumulate in the voids in the porous asphalt surface course (Schueler et al 1992). In full-depth porous pavement installations clogging can also occur in the void spaces of the crushed stone layer. As the voids get filled, the infiltrative capacity declines reducing the overall performance of the system. Once a porous pavement has been clogged it is difficult and costly to rehabilitate and often must be completely replaced (WDOE 1992, Schueler 1987).

Because of their porous nature, porous pavements lack the structural stability provided by conventional asphalt pavements (Cahill Assoc. 1993). Consequently the amount of wheel rut deformation in porous pavements is slightly higher than that in conventional pavements (WDOE 1992). The completely porous nature of the full depth porous asphalt pavement installations further increases their structural instability. Somewhat more care is required to install porous asphalt than conventional asphalt to retain the porous properties desired. Most pavement engineers and contractors lack expertise in working with these materials (WDOE 1992), and, therefore, the likelihood of failure is increased.

Considerations for Porous Pavement Installation. Given the cited advantages and disadvantages of porous pavements, several factors should be evaluated when a porous pavement installation is considered. The British Columbia Research Corporation (1992) developed several guidelines, outlined below, that incorporate the considerations necessary when the relevance of a porous pavement installation is evaluated. Porous pavements are feasible for one-half to three hectare catchments and are marginally feasible for catchments of up to 6.5 hectares. Porous pavements are applicable on sites with sand, loamy sand, sandy loam, and loam soils. The minimum infiltration rate of subsoils feasible for porous pavements is about 13 mm/hr (0.5 in/hr). Factors that may preclude the use of porous pavements include slope, proximity to the high water table, bedrock, foundations, space consumption, maximum space limitations, and high sediment input.

EXPERIMENTAL DESIGN

The goal of this research was to determine the type of shoulder treatment that yields the least quantity of runoff of the highest quality. Therefore, the experimental design involved sampling flow-weighted composite samples of runoff from the three shoulder treatments: gravel, conventional asphalt, and porous asphalt. The inputs to the experimental system were the runoff from the road and rainfall falling on the treatment sections. The measured output was the surface runoff from the individual treatment sections. This design assumed the following:

- The quantity of runoff entering each shoulder section from the road is the same for each treatment.
- The quantity and intensity of rainfall falling on each shoulder section is the same for each treatment.
- The quality of runoff entering each section from the road is the same for each treatment.
- The quality of rainfall falling on each shoulder section is the same for each treatment.

This research was carried out in two phases. Phase I involved collecting flow-weighted composite samples of stormwater runoff from the test sections during storms greater than or equal to 0.25 inches. In addition to analyzing the runoff samples being analyzed for a variety of water quality parameters, the quantity of runoff was measured to determine the runoff coefficient associated with the shoulder treatments. Because of a design error in the flow splitter sampling device, accurate runoff quantities were not obtained for the storms sampled. Therefore, Phase II of the research involved determining the runoff coefficients of the shoulder treatments under controlled conditions. Finally, several experiments were conducted to test a culvert sampling device under low flows, and a survey was conducted to compare vegetative cover in roadside ditches with gravel shoulders with the vegetative cover in ditches with conventional asphalt shoulders. Doell (1995) provided a thorough discussion of the experimental procedures and installation of the test sections and stormwater collection system. The most important features are repeated here.

Monitoring Site Location and Description

The monitoring site was located on the south shoulder of the NE Woodinville-Duvall road north of Redmond, Washington, adjacent to Cottage Lake Park (Figure 1.2). The King County Department of Public Works, Road Services Division, conducted a traffic study of Woodinville-Duvall NE at Cottage Lake Park in November 1995 and

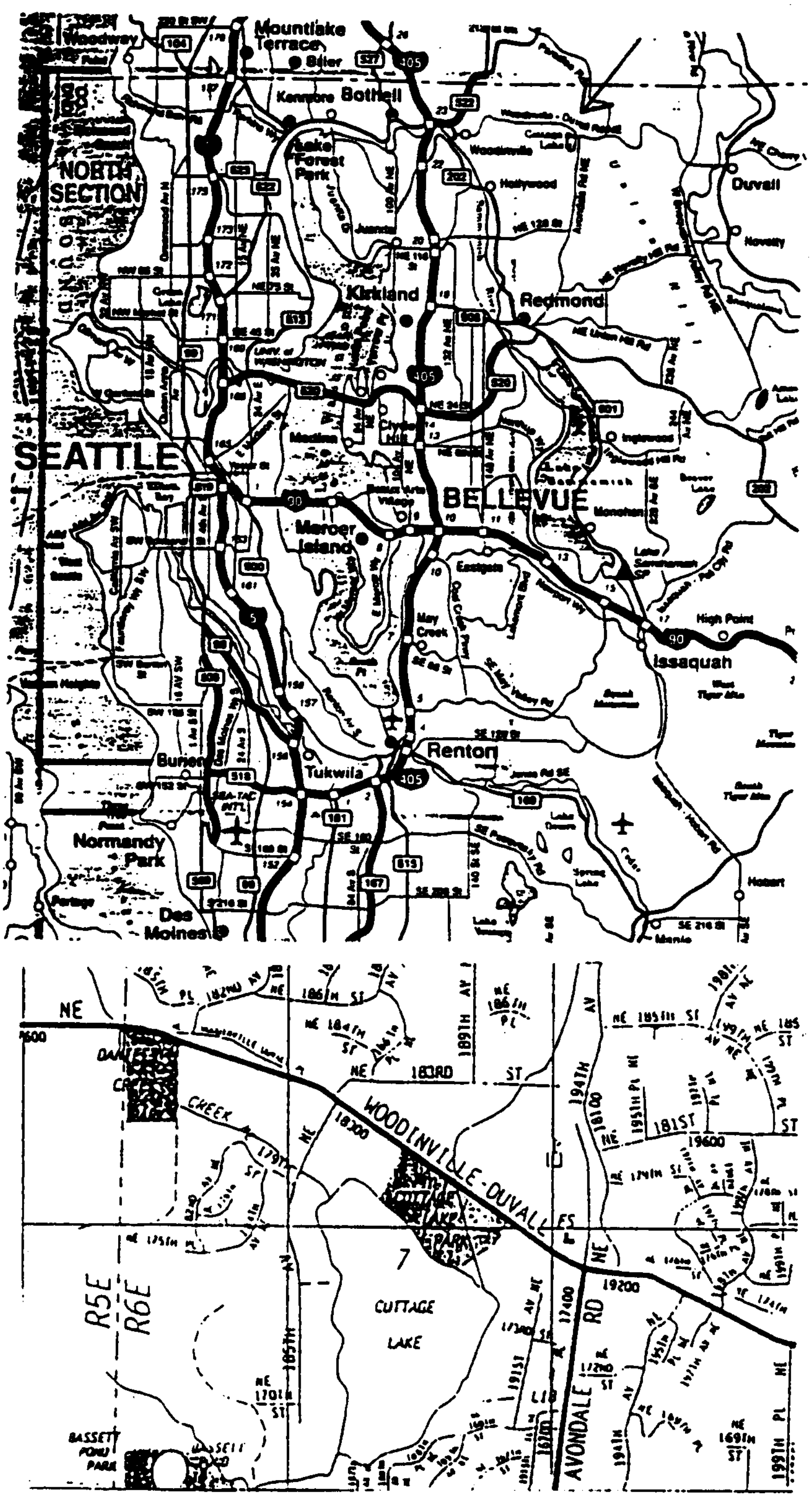

Figure 1.2 Vicinity and Monitoring Location of Road Shoulder Runoff Study Site
From Thomas Brothers 1995

determined that the 3-day average daily traffic (ADT) was approximately 9,000 vehicles in each direction (King County Department of Public Works 1995). The site encompasses the entire shoulder adjacent to Cottage Lake Park (approximately 3 meters [10 ft] wide by 183 meters [600 ft] long) and an area adjacent to the road just inside the park boundary (approximately 4.5 meters [15 ft] wide by 183 meters [600 ft] long). Each shoulder treatment was tested in duplicate, along with two controls that sampled runoff directly from the road (Figure 1.3). The road lane was 3.6 meters (12 ft) wide, and the road test sections were 14.6 meters (48 ft) in length. Each of the shoulder test sections (six total including replicates) was 2.4 meters (8 ft) wide by 14.6 meters (48 ft) long, with 6-meter (20-ft) buffers between each shoulder section. The total contributing area for each of the shoulder test sections was 87.6 m^2 (960 ft^2), whereas the area of the road sections was 52.6 m^2 (576 ft^2). The area inside the park securely housed the stormwater collection equipment.

NE Woodinville-Duvall and its adjacent road shoulder are relatively level. In addition, the road is crowned. These two conditions allowed for an even distribution of sheet flow from the road surface to the shoulder sections and restricted any runoff from entering from the sides of the shoulder sections. To confirm that the site met these hydraulic requirements, a water truck was used to simulate an intense rain storm. When water was sprayed onto the roadway surface, the runoff flowed primarily in a sheet-like pattern perpendicular to the edge of the road (Doell 1995).

Prior to the installation of the shoulder treatments, soil tests were performed to determine the composition of the shoulder soil and to determine the depth of the water table (Doell 1995). These tests were conducted to verify that the soils underlying the porous asphalt and gravel shoulders would adequately drain the water that had percolated through the respective treatments. Soil samples were taken at three depths: surface, 35.6 cm (14 inches), and 91.4 cm (36 inches) below the surface. All of the soil samples were taken from a single 1.2-meter (4-ft) deep hole dug at the west end of the site. Because the entire shoulder was composed of the same fill material imported when the road was built, it was

Figure 1.3. Plan View of Road Shoulder Test Sections and Stormwater Runoff Collection System
From Doell 1995

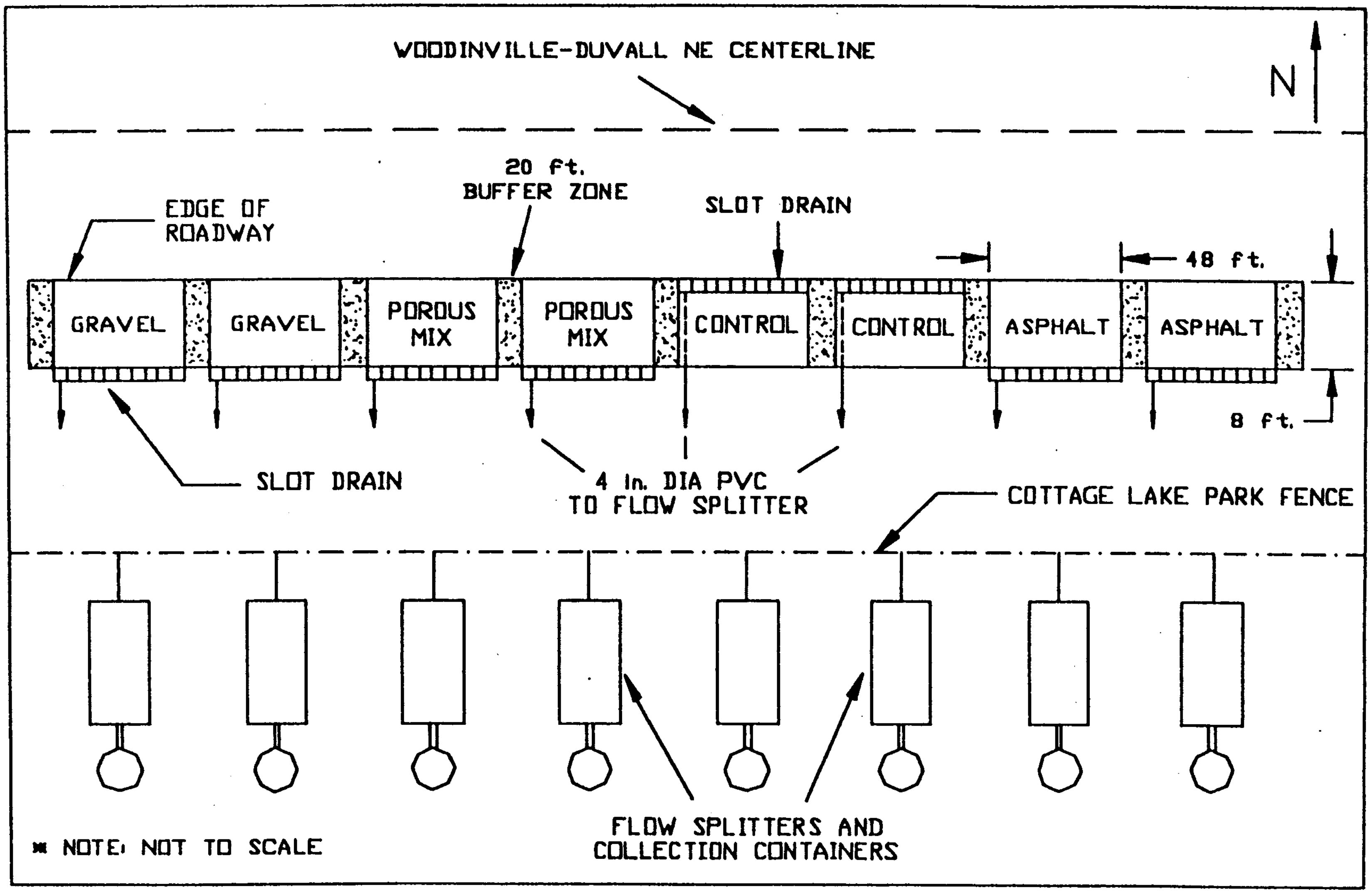

Figure 3.2 Plan View of Road Shoulder Test Sections and Stormwater Runoff Collection System

From Doell 1995

assumed that the soil test results from the single location were representative of the entire shoulder site. Results from the soil tests revealed that the soils are composed largely of gravel and sand with only minimal fines (Table 1.2), indicating that drainage should be adequate. The water table was found at a depth of approximately 1.2 meters (4 ft). The researchers concluded that even with seasonal variations in the water table, infiltration from the porous asphalt and gravel shoulders would be adequate.

Table 1.2 Results of Woodinville-Duvall NE Shoulder Soils Analysis

Sample Depth	% Gravel	% Sand	% Fines [a]	USCS Classification [b]
Surface	29.9	63.7	6.4	SP-SM
14 Inches	31.8	60.5	7.7	SP-SM
36 Inches	30.3	61.2	8.5	SW-SM

From Doell 1995.
[a] Fines include both silt and clay, though no distinction between the two was available.
[b] SP-SM is poorly graded sand with silt and gravel.
SW-SM is well graded sand with silt and gravel.

Site Preparation and Shoulder Test Section Installation

Before the shoulder test sections were installed, the entire length of the shoulder was graded, and approximately 5.0 to 7.5 cm (2 to 3 inches) of surface material was removed. This material was removed to ensure uniform slope and texture of the shoulder, and to ensure that the test sections were flush with the road surface.

The gravel, conventional asphalt, and porous asphalt shoulder treatments were installed during the week of October 9, 1995. Each of the shoulder treatments was installed directly on top of the graded shoulder according to the following specifications (Doell 1995):

Gravel: 1.3- to 1.9-cm (1/2- to 3/4-inch) diameter crushed gravel was applied and compacted to a depth of 7.6 cm (3 inches) for both of the gravel test sections. This gravel mix is consistent with that typically used on non-paved roads and road shoulders.

Conventional Asphalt: The two conventional asphalt test sections were paved with Washington State Department of Transportation (WSDOT) Class A asphalt according to typical paving specifications. The conventional asphalt was applied and compacted to a depth of 7.6 cm (3 inches). The aggregates used in the WSDOT Class A mix are densely graded (Table 1.2). The asphalt binder was specified as AR-4000 and constituted 3.5 to 4.0 percent of the mix by weight.

Porous Asphalt: The porous asphalt mix used for this study was based on the design developed by Arizona DOT (Hossain and Scofield 1991). Under the advice of the contractor installing the asphalt test sections, some alterations were made to the Arizona DOT design. The AR-4000 binder was used instead of the AR-8000 binder specified for the Arizona mix, and the asphalt content was reduced from 5.5 to 3.5 or 4.0 percent of the mix by weight. All other specifications of the porous asphalt mix, namely aggregate gradation, remained the same as that specified in the Arizona DOT mix (Table 1.3) The porous asphalt mix was applied and lightly compacted to a depth of approximately 8.9 cm (3.5 inches) for both of the porous asphalt test sections.

Stormwater Sampling and Collection System

Because of large variations in pollutant concentrations that occur during runoff events (Whipple et al 1983) and dynamic flow conditions of urban runoff (Horner et al. 1994), characterizing pollutant concentrations during runoff events is quite difficult. The accepted practice is to determine an event mean concentration (EMC), which is obtained by collecting a flow-proportional composite sample. A single sample is analyzed that is composited from a series of samples taken throughout the runoff event and combined in proportion to the flow rate existing at the time of sampling (Horner et al. 1994). The more frequently a sample is collected and contributed to the composite, the more accurate the estimate of the runoff pollutant concentrations will be (Whipple et al 1983). Therefore, continuous composite sampling techniques provide the best estimate of the event mean concentration.

Table 3.2 Asphalt Gradations and Mix Properties Used by Various Agencies

Sieve size % passing	1"	3/4"	1/2"	3/8"	1/4"	No. 4	No. 8	No. 10	No. 16	No. 40	No. 200	Asphalt Content (% by weight)	Asphalt Void Volume (%)
B-mix (ODOT)	99-100	92-100	75-91	—	50-70	—	—	21-41	—	6-24	2-7		
OGEM (ODOT)	—	100	95-100	—	15-40	—	—	—	—	—	—		
E-mix (ODOT)	—	99-100	95-100	—	52-72	—	—	5-15	—	—	1-5	4-8	
F-mix (ODOT) [2].	99-100	85-96	60-71	—	17-31	—	—	7-19	—	—	1-6	4-8	15-20
FHWA (WDFD)	—	—	—	100	33-47	—	7-13	—	—	—	2-4		
Australia	—	—	100	96	29	—	12	—	—	—	4		
Arizona DOT	—	—	100	95-100	19-46	—	0-28	—	—	0-16	0-5	5.5	22
EPA (1980)	—	—	100	90-100	—	35-50	15-32	—	2-15	—	0-3	5.5-6	16
Virginia	—	—	100	90-100	—	30-50	10-30	—	0-20	—	0-4	7-11	21-31
WSDOT A-mix	—	100	90-100	75-90	55-75	—	—	30-42	—	11-24	3-7	3.5-4	
WSDOT D-mix	—	—	100	97-100	—	30-50	5-15	—	—	—	2-5		

From Doell 1995

Flow splitter composite samplers were used at the monitoring site for this study, both to measure runoff volumes and to collect stormwater samples. The composite flow splitters used were based on the original design developed by Clark and Mar (1980). The flow splitter consists of a rectangular channel through which the entire volume of runoff is directed. Vertical dividers (or veins) are placed parallel to the direction of flow at the outlet end of the rectangular channel (Figure 1.4). The total volume of runoff is divided, or split, by the veins, and the fraction of the flow that is diverted is collected in a sample container. The width of the entire splitter and the width of the vertical dividers determine the fraction of the total flow that is collected. Therefore, the total volume of runoff is calculated on the basis of the ratio of these widths.

Design of composite flow splitters is based largely on three important principles (Clark and Mar 1980):

1. The projected runoff volume generated from the design storm determines the fraction of the flow to be split, which is controlled by the number of dividers at the channel outlet and the width of these dividers.
2. The splitter must be long enough that flow disturbances are dissipated before reaching the dividers.
3. A supercritical slope is required to prevent flow disturbances upstream and settling of solids.

A two-year recurrence storm lasting 6 hours is estimated to produce approximately 1.0 inch of rain in the general Seattle area, and this storm size was used to design the composite flow splitters for this study. The flow splitters were designed to split 5.4 percent (1/18.5) of the flow. A thorough description of the design, construction, and calibration of the composite flow splitters used in this study is presented by Doell (1995) and is not repeated here. The flow splitters were built to the following specifications:

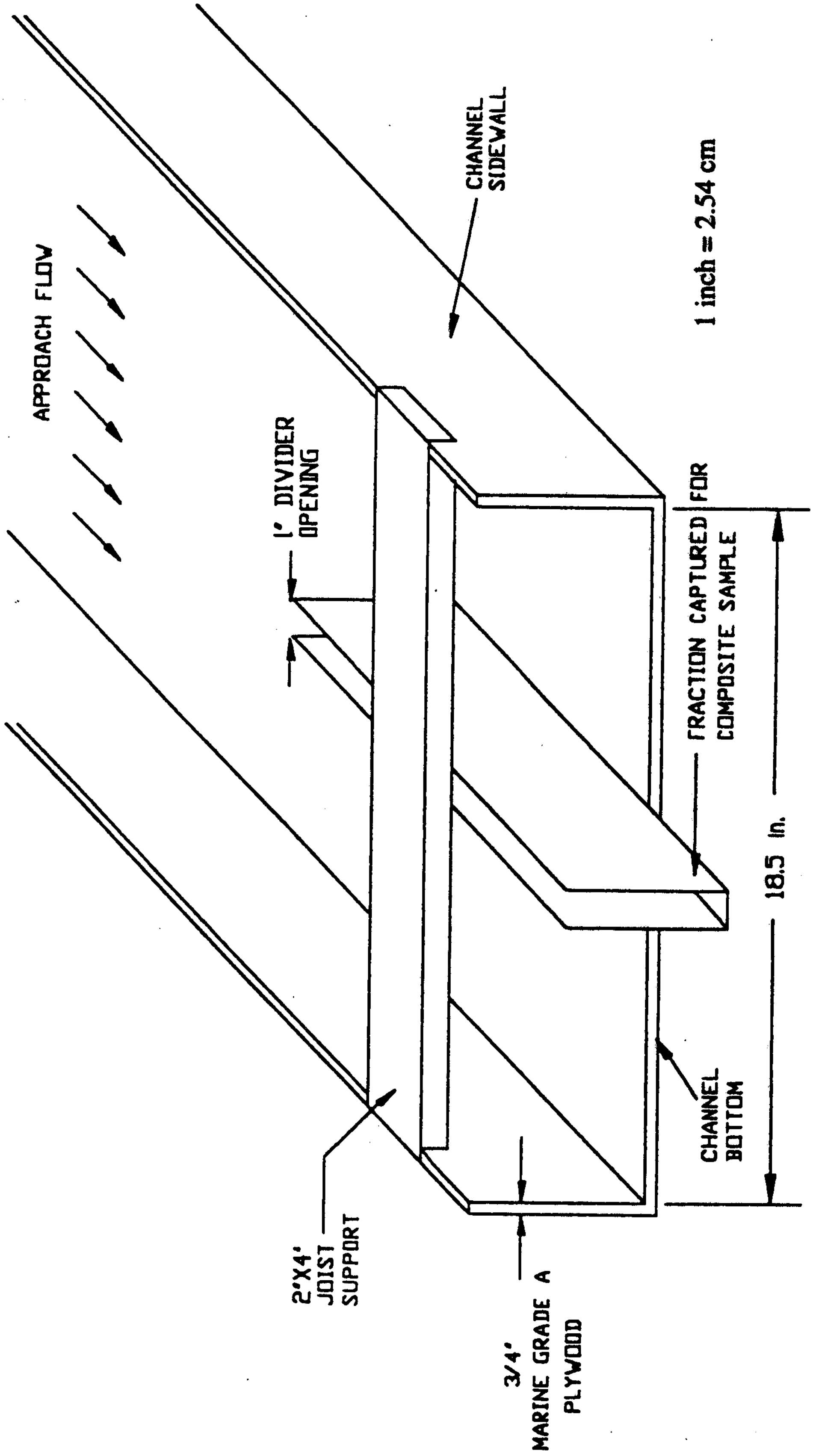

Figure 1.4 Schematic of Composite Flow Splitting Device
1 inch = 2.54 cm
From Doell 1995

- The flow splitter channel was 2.4-m (8-ft) long and had interior and exterior widths of 47 and 51 cm (18.5 and 20.0 inches), respectively (Figure 1.5). The channel sidewalls and bottom were constructed of 1.9 cm (3/4 inch) Marine Grade A plywood, with the Grade A side facing the interior of the channel. All interior surfaces were sanded, and a marine spar varnish was applied to prevent decay and lower the frictional resistance.
- The flow divider (vein) was constructed of gauge 11 (1/8 inch) stainless steel. The width of the vein was 2.5 cm (1 inch), and the upstream edges of the dividers were beveled at 45° angles to minimize frictional resistance.
- Wooden frames were constructed to house the splitters. The frames were constructed so that the splitters were level horizontally but maintained a 2.54-cm/0.3m (1-inch/ft) vertical slope.

Slot drains were installed at the base of the shoulder test sections and at the edge of the road for the two control sections to collect the surface runoff. The slot drain (Dura Channel System) was a plastic, U-shaped channel 15 cm (6 inches) wide at the top and supported a plastic grate through which the stormwater entered the drain (Figure 1.6). The drains were fabricated in 1.2-m (4-ft) sections pieced together with coupling segments to form a 14.6-m (48-ft) long channel. A 10-cm (4-inch) diameter pipe was attached to the outlet of each drain and directed the runoff into the flow splitters located inside Cottage Lake Park.

Rectangular PVC gutter material was used to convey the sampled stormwater from the flow splitter vein to a 121-L (32-gallon) enclosed sampling container. A detachable PVC section was installed to facilitate sampling from the container. The sampling containers were lined with plastic garbage bags, and the bags were changed between storms. Prior to installation, the sampling containers were calibrated to provide a water depth to sample volume relationship (Doell 1995).

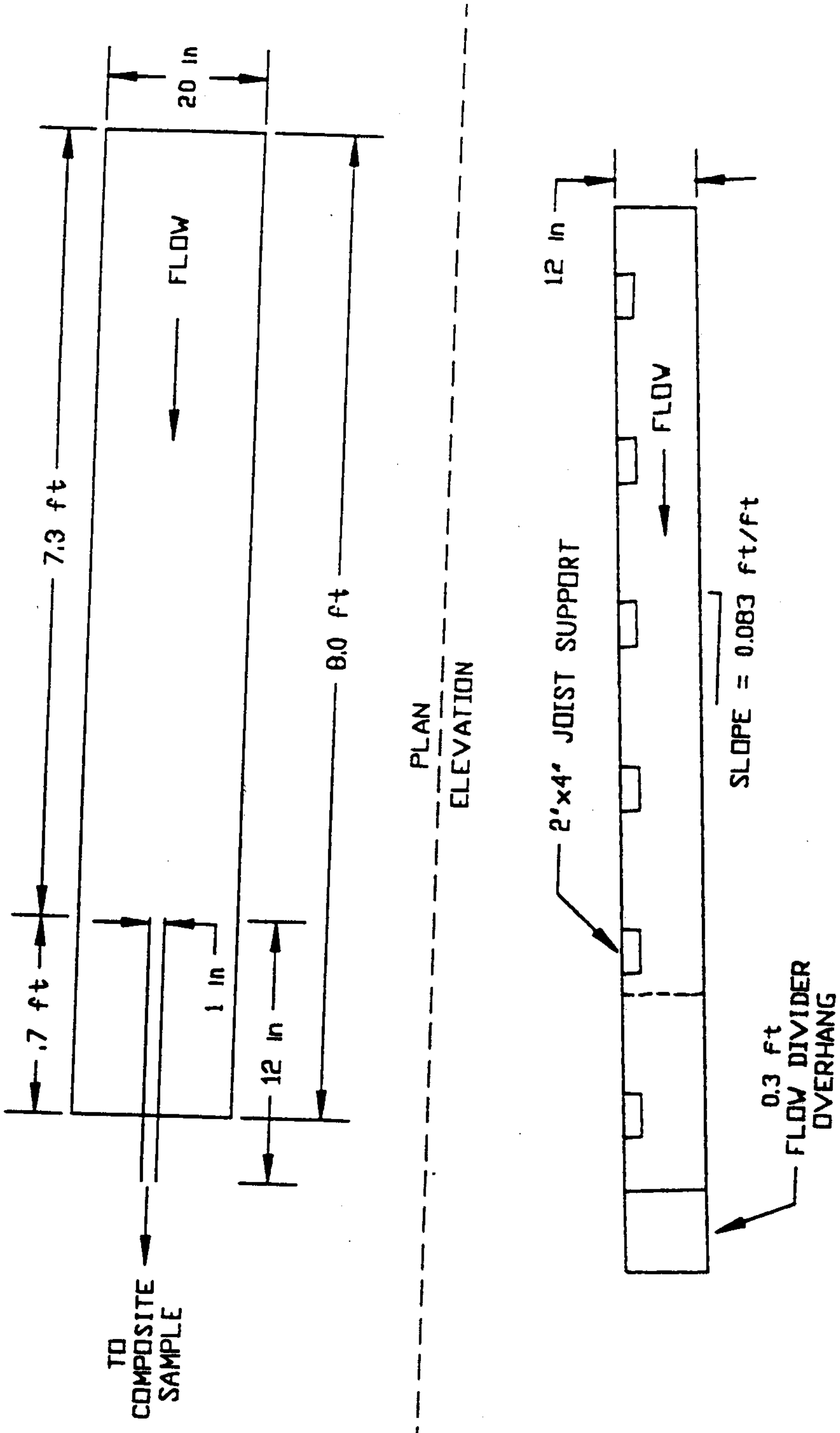

Figure 1.5 Plan and Elevation Views of Composite Flow Splitting Device
1 inch = 2.54 cm
From Doell 1995

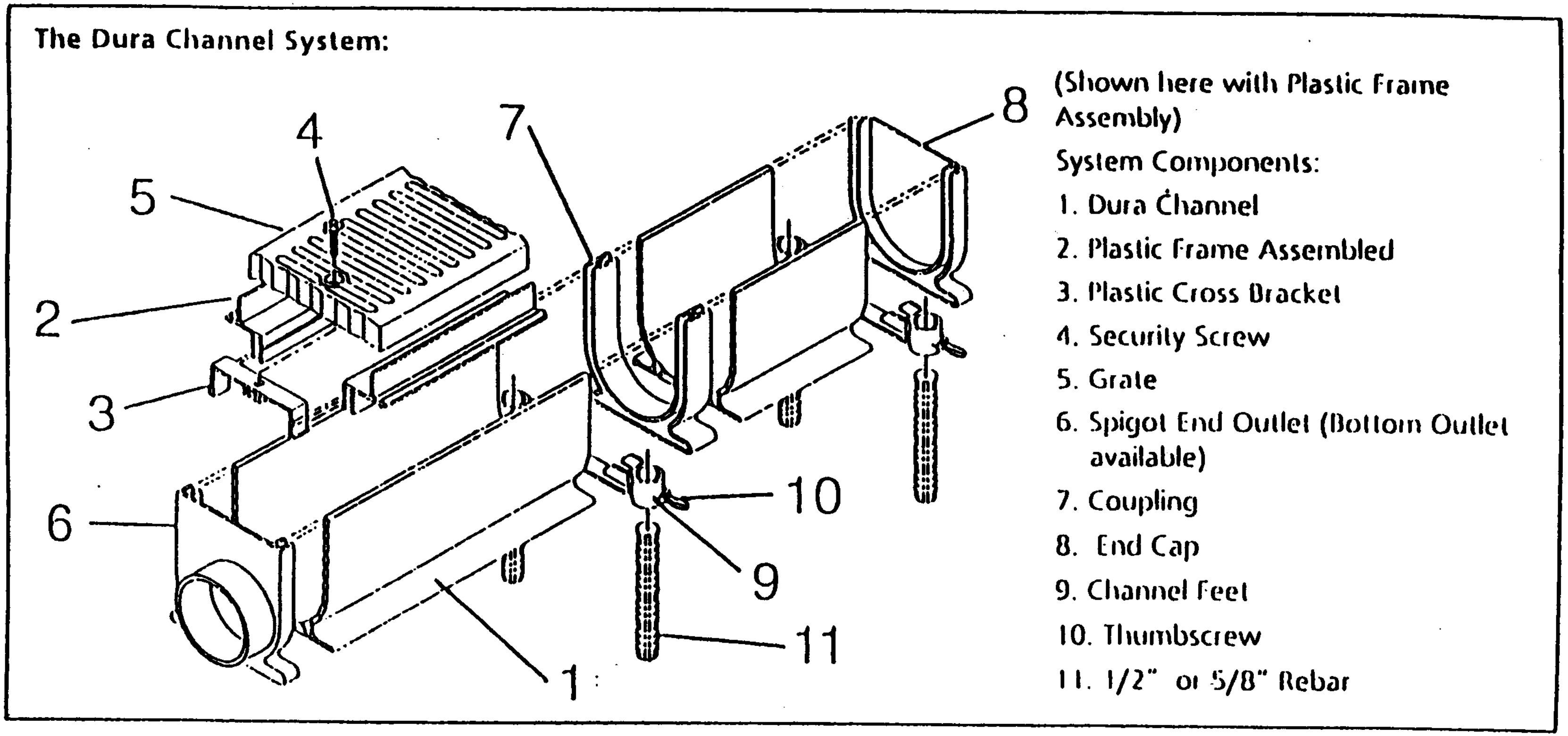

Figure 1.6 Slot Drain Runoff Collection System
From Doell 1995

Sampling Protocol

As described in the experimental design section, the objectives of the study were to determine the volume of runoff generated from each shoulder test section and the relative water quality of this runoff. Storms producing approximately 0.6 cm (0.25 inches) or more of precipitation over a period of at least 12 hours were considered to be sufficient to produce adequate runoff volume. These criteria were based on regional storm characteristics and were considered to be sufficient for the purposes of determining representative pollutant event mean concentrations and loading estimates (Bellevue Utilities Department 1995).

The following protocol was used to collect samples from the composite sample containers:

1. The depth of water in the composite sample containers was measured and recorded.
2. The water in the containers was stirred with a wooden paddle to resuspend particulate matter.
3. Stormwater runoff samples were collected in appropriate sample bottles provided by the Municipality of Metropolitan Seattle (Metro) Environmental Laboratory according to criteria established by the Laboratory.
4. Observations were noted regarding weather conditions, flow splitter operation, and shoulder test section characteristics (i.e., gravel erosion, etc.).
5. Samples were delivered to the Metro Environmental Laboratory within 1 to 2 hours of sampling for analysis.

Water Quality Analysis

Composite samples from each test section (eight total, including replicates) were analyzed by the Metro Environmental Laboratory for the water quality variables shown in Table 1.4. Table 1.4 also outlines the analytical methods used for the respective water quality parameters.

Table 1.4 Water Quality Test Parameters and Analysis Protocols

Test Parameter	Analysis Protocol
TPH Diesel	WDOE-WTPH-D
TPH Gasoline	WDOE-WTPH-G
TPH	WDOE-WTPH-418.1
Total Phosphorus	EPA 365.3
Ortho Phosphorus	EPA 365.3
Turbidity	EPA 180.1
Chemical Oxygen Demand	EPA 410.1/410.2
Biochemical Oxygen Demand	EPA 405.1
Conductivity	EPA 120.1
Total Suspended Solids	EPA 160.2
Total Oil and Grease	EPA 413.1
Metals by ICP/MS	EPA 200.8/6020
BNA (Semivolatiles)	EPA 625

Bioassay Procedures

Bioassays were performed by Metro on stormwater samples from each shoulder test section for three storms, including one preliminary test. The preliminary test was conducted to evaluate which testing procedures were appropriate for the water quality conditions specific to the shoulder treatments runoff. Acute and chronic toxicity tests were conducted to supply information about the toxicity of the runoff from the shoulder test sections to aquatic organisms. In addition, biostimulation tests were run to determine the nutrient status of the runoff as it affects aquatic plant growth. Assays were performed with full-strength runoff, runoff diluted with lake water, and lake water controls.

The *Daphnia pulex* acute toxicity tests were conducted as outlined in Weber (1989). The chronic toxicity tests on *Selenastrum capricornutum* were conducted as outlined in Weber *et al.* (1989). A modified algal growth potential test, based on the S. capricornutum Bottle Test described by Miller et al. (1978), was run on *Selenastrum capricornutum.* This procedure does not attempt to determine which nutrient in particular limits algal growth, but it simply determines the maximum standing crop of the algae. Finally, biostimulation tests on *Lemna minor* were conducted according to ASTM (1989).

Quality Assurance/Quality Control

The regular internal quality assurance/quality control (QA/QC) procedures of the Metro Environmental Laboratory were followed. These procedures include, but are not limited to, the use of laboratory blanks, laboratory positive controls, laboratory duplicate samples, and laboratory spiked samples. In addition, field duplicates of 5 percent of the samples were sampled using a random numbers table to pick the duplicate sites.

Rain Gauge Monitoring

A tipping bucket rain gauge was installed at the monitoring site inside Cottage Lake Park. The rain gauge consisted of a tipping bucket and an ISCO 3230 data recorder that recorded rainfall (in inches) every 10 minutes. The rain gauge was installed and monitored by King County Road Maintenance Division personnel. In addition to the on-site rain gauge, King County Surface Water Management Division monitored a rain gauge near the corner of NE Woodinville-Duvall and Avondale Road NE (site 02W). Data from both gauges were used for determining storm-specific and annual rainfall depths.

Rain Simulation/Overland Flow Experiments

As discussed in the Findings section, the flow splitter composite samplers did not provide accurate measurements of the runoff volumes. Because determinations of the runoff coefficients associated with the shoulder treatments was crucial to meeting the goals of the study, experiments were conducted under controlled conditions to evaluate the hydraulics of the shoulder treatments.

To determine the runoff coefficients associated with the shoulder treatments, it was necessary to collect the volume of runoff that was generated when a known volume of water was applied to the site at a known rate. In effect, a storm of known size and intensity was simulated, and the runoff from the test sections was collected. Under natural storm conditions the shoulder test sections received runoff from the adjacent road, as well as receiving direct rainfall. The rain simulation/overland flow experiments attempted to simulate these conditions.

Water was applied to the shoulder test sections and distributed through a perforated diffuser pipe. A 1.9-cm (3/4-inch) PVC pipe with 0.2-cm (5/64th-inch) holes at 0.61-m (2-ft) intervals was used to distribute the "rain" across the road-side edge of the shoulder test sections (Figure 1.7). The total volume of water applied through the diffuser pipe for each experiment represented the volume associated with the runoff generated from the adjacent road section plus the volume associated with the rainfall onto the shoulder section for a given storm size. It was assumed that the runoff coefficient from the asphalt road was 1.0, and therefore all of the rainfall on the road was contributed to the shoulder as runoff.

A 170-L (45-gallon) barrel with a 1.3-cm (1/2-inch) ball valve at the barrel's base was used to discharge the "rain" into the diffuser pipe. The discharge rates from the diffuser pipe (representing storm intensity) were controlled by manipulating the height of the water level in the barrel and by altering the opening of the ball valve. The discharge rate was held constant by maintaining the water level in the barrel (that is, maintaining a constant head). This was accomplished by allowing a garden hose to flow into the barrel at the same rate as the discharge rate. In this manner both storm size and rainfall intensity could be tested as they affected the runoff coefficient of the shoulder treatments. All of the runoff that was generated from these simulated rain storms was collected in the slot drains at the base of the shoulder test sections and was conveyed to collection containers.

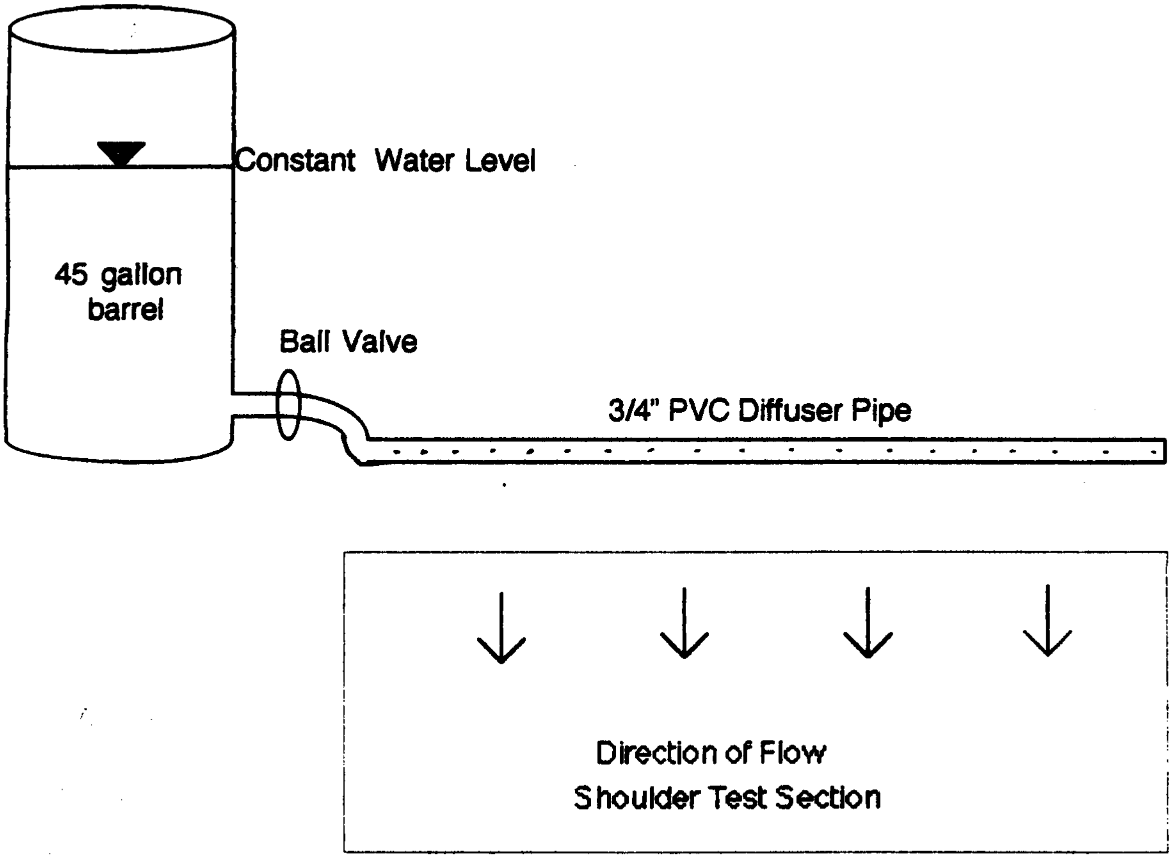

Figure 1.7 Schematic of Rain Simulation/Overland Flow Experiment System

Probabilistic Load Estimation

Marsalek (1990) described a modified direct average method for evaluating annual runoff pollution loads that was based on simulated runoff volumes and probabilistic distributions of constituent concentration derived from limited field data. This method is similar to direct average methods, but it leads to a better evaluation of uncertainties in the load estimates arising from variations in the concentration data.

The annual load is estimated as:

$$L_1 = N \sum V_i C_i/n \qquad \text{(Eq. 1)}$$

or

$$L_2 = NVC = RC \qquad \text{(Eq. 2)}$$

where L is the annual load, V is the event runoff volume, C is the event mean concentration, subscript $i = 1,2,3...,N$ denotes individual events during the year, n is the number of events sampled, $V = \Sigma V_i/N$, $C = \Sigma C_i/n$, and $R = \Sigma V_i$. Since the annual runoff, R, can be determined fairly accurately by measurement or computer simulation, the main task is determining the mean concentration, C.

It is advantageous to approximate EMCs by a statistical distribution model that can serve to draw inferences about sample statistics. It is generally recognized that urban runoff EMCs are lognormally distributed (EPA 1983, Driscoll 1986). Assuming $(\ln C_i)$ is normally distributed with mean μ and variance s^2, then $C_i = \exp(\ln C_i)$ is lognormally distributed with mean a and variance b^2:

$$a = \exp(u + s^2/2) \qquad \text{(Eq. 3)}$$

$$b^2 = a^2 (\exp s^2 - 1) \qquad \text{(Eq. 4)}$$

For the lognormal mean a, an approximate confidence interval can be estimated (Horner et al. 1994):

$$\text{C.I.} = a{*}e \; +/- \text{Ø}(s^2/n + s(s^2)^3/(n-1))^{0.5} \qquad \text{(Eq. 5)}$$

where e is base of the natural logarithms, + is used for the upper confidence limit, - is used for the lower confidence limit, Ø equals 1.96 for a 95 percent confidence interval and 1.69 for a 90 percent confidence interval, and n is the number of EMC values used to find μ.

The total flow volume for the loading estimate period is multiplied by the mean EMC to get the loading. Then, that volume is multiplied by the upper and lower confidence limits to get the estimate bounds:

$$R{*}a_{lower}\,\text{C.I.} < L < R{*}a_{upper}\,\text{C.I.} \qquad \text{(Eq. 6)}$$

This probabilistic load estimation method was used in the present study.

Roadside Ditch Vegetative Cover and Composition Survey

One objective of this study was to evaluate the operational characteristics of the three shoulder materials. One aspect of this objective was to determine how road shoulders effect vegetative cover and composition in roadside ditches. Therefore, a survey was conducted to evaluate the vegetative composition and cover on roadside ditches adjacent to both gravel and paved shoulders.

Ditches along county roads in King and Snohomish counties, Washington, were evaluated. Each sample site was 3 m (10 ft) long by the width of the given ditch. Attempts were made to randomly pick "test section" ditches. The primary variable used to pick ditches to survey was ease of pulling off the road. At a given ditch location, second and third sites were evaluated that were 50 paces apart from one another.

Vegetative cover was subjectively estimated by making visual estimates of percentage of cover according to the Braun-Blanquet scale (Chapman 1976). The Braun-Blanquet scale distinguishes cover on the basis of the following categories: Less than 1%, 1-5%, 6-25%, 26-50%, 51-75%, and 76-100%. This cover scale was used to determine total percentage of cover of the ditch site (3 m [10 ft] long by the width of the given ditch), as well as to distinguish the percentage of cover on the roadside of the ditch and the percentage of cover on the bottom of the ditch.

The composition of the vegetation was also determined. Vegetation was classified as grasses and low-growing herbs or "other." The criteria used to determine whether the plant was an herb were stem width and plant height. Plants with stem widths of less than or equal to 2 mm (0.08 in) and plant heights of less than 0.3 m (1 ft) were classified as herbs. All plants not fitting this classification were considered "other." The premise for this classification was that grasses and low-growing herbs provide the most biofiltration of pollutants (Horner et al. 1994). The percentage of cover of each of the two vegetation classifications was determined. At each site the width of the respective ditch was measured, and a simple sketch of the site was drawn to note the type and width of the shoulder. Finally, observations were noted as to the conditions of the shoulder and ditch.

CHAPTER TWO: FINDINGS AND DISCUSSION

INTRODUCTION

Construction and installation of the road shoulder test sections and stormwater runoff collection system was completed in early November 1995. Despite some initial setbacks following installation, which are described by Doell (1995), the system operated well and *facilitated* the successful monitoring of 11 storms between November 1995 and August 1996. Table 2.1 summarizes the storms that were monitored. Ten of the 11 storms occurred between November and April, a period consistent with the wet season in the Pacific Northwest. However, one of these 11 storms was preceded by a lengthy cold period during which the King County Road Maintenance Division applied sand to the roads. Consequently, the water quality of the runoff from this February 5, 1996, storm was considerably different from the other 10 wet season storms. The final storm occurred in early August 1996 and was preceded by a 13-day period of no rain.

This chapter presents a summary of the compiled data from the monitored storm events. It describes the hydraulic behavior of the shoulder treatments and the evaluation of quality of the runoff. The report compares the relative pollutant loads from the three shoulder treatments. Results from the roadside ditch survey and the low-flow sampler experiments are also presented. Following the presentation of the results, the relationships between shoulder treatment and runoff quantity and quality are discussed.

HYDRAULIC BEHAVIOR OF SHOULDER TREATMENTS

A primary objective of this study was to describe the hydraulic behavior of the gravel, conventional asphalt, and porous asphalt shoulders, particularly the runoff coefficients associated with the treatments. As described in the preceding chapter, the flow splitter composite samplers were to provide a flow-weighted composite sample, which would represent both the water quality conditions during the entire runoff event and, by extrapolation, the entire quantity of runoff.

Table 2.1 Summary of Storms Monitored

Date	Storm Size (Inches)	Storm Duration (hr)	Conditions Prior to Storm	Duration and Size of Storm before Sampling
11/7/95*	1.50	24	Lt rain -- 0.3" over 3 days	Unknown
11/8/95*	1.00	24	Hvy rain -- 1.2" in 24 hrs	Unknown
11/18/95*	0.30	24	No rain during 24 hrs preceding	Unknown
11/27/95*	0.60	48	No rain during 24 hrs preceding	Unknown
1/16/96	1.75	32	Lt rain -- 0.2" over 36 hrs	Sampled entire storm
1/21/96	1.60	40	No rain during 55 hrs preceding	14 hrs -- 0.7"
2/5/96	0.81	12	0.42" over 28 hrs preceding	Sampled entire storm
2/21/96	0.30	4	No rain during 24 hrs preceding	Sampled entire storm
4/1/96	1.04	26	Intermittent lt rain over 8 days preceding	4 hrs -- 0.06"
4/16/96	1.02	25	Intermittent lt rain over 8 days preceding	6 hrs -- 0.22"
8/2/96	1.48	19	No rain during 13 days preceding	Sampled entire storm

* = Storm monitored prior to rain gauge installation; therefore, estimated conditions are presented.

The water flowing down the flow splitter had to be evenly distributed across the width of the channel so that a uniform and consistent "split" of the flow would be provided. Observation of the flow splitters during storm events revealed that they were not performing as designed. The flow was often not uniformly distributed across the channel bottom, which resulted in a nonuniform and inconsistent split of the flow volume.

Typically, debris (sand, leaves, and pine needles) was deposited at the top of the channel and impeded uniform flow down the length of the channel. In addition, the channels were designed too wide for the volume of runoff generated by the shoulder test sections during most storms available to monitor.

These problems compounded to produce inconsistent and questionable runoff quantity results from the monitored storms. Inconsistent performance of the flow splitters is not the only reason for variable runoff coefficient data. Factors such as traffic volumes during the storm, the storm's physical characteristics (precipitation intensity and duration and prevailing winds), and evaporation can affect the rainfall-runoff relationship (Asplund 1980). For instance, natural cross winds and/or traffic-generated vortex winds can blow spray, which may affect the quantity of runoff from shoulder test sections.

Rain Simulation/Overland Flow Experiment Results

In order to estimate the runoff coefficients associated with the shoulder treatments, rain simulation/overland flow experiments were performed during the summer of 1996. A total of six experiments was conducted under varying conditions of storm intensity and storm size. Table 2.2 summarizes the experimental conditions and runoff coefficient results for the six experiments. The relationship between storm size and storm intensity on shoulder runoff coefficients are shown in Figures 2.1 and 2.2.

Several noteworthy observations were made during these experiments. At the lower "rainfall" intensities tested (0.13 cm/hr [0.05 in/hr]) the runoff on the gravel shoulders infiltrated within 0.3 to 0.6 m (1 to 2 ft) of the perforated diffuser pipe. However, pooling then occurred at the base of the gravel test sections before was flowed into the slot drains at the base of the shoulder test sections. At the higher "rainfall" intensities (0.25 to 0.64 cm/hr [0.1 to 0.25 in/hr]), overland flow was on the gravel shoulder test sections with the runoff flowing in small rivulets. Again, pooling occurred at the base of the gravel test sections before water flowed into the slot drains. In addition to the surface flow of runoff into the slot drains, subsurface flow trickled into the slot drain through seams in the drain. The drain was fabricated with 2.4-m (8-ft) sections, and no sealant was applied when the sections were connected, allowing subsurface flow to trickle into the drain.

Table 2.2 Summary of Experimental Conditions and Runoff Coefficient Results for Rain Simulation/Overland Flow Experiments

Storm size (inches) and storm intensity (inches/hour) are shown, along with the associated runoff coefficient [shown in brackets] for each experimental condition.

Experiment	Porous Asphalt	Gravel	Conventional Asphalt
1		0.46", 0.35"/hr [0.80]	0.13", 0.38"/hr [0.84]
2	0.20", 0.06"/hr [0.13]	0.17", 0.06 "/hr [0.63]	0.14", 0.06 "/hr [0.87]
3	0.20", 0.06 "/hr [0.10]	0.17", 0.06 "/hr [0.64]	0.10", 0.07 "/hr [0.88]
4	0.20", 0.10"/hr [0.10]	0.17", 0.10"/hr [0.64]	
5	0.20", 0.25"/hr [0.13]	0.20", 0.25"/hr [0.70]	
6	0.60", 0.25"/hr [0.38]		

1.0 inch = 2.54 cm.
The runoff coefficient is a unitless parameter and is the ratio of the runoff volume to the rainfall volume.

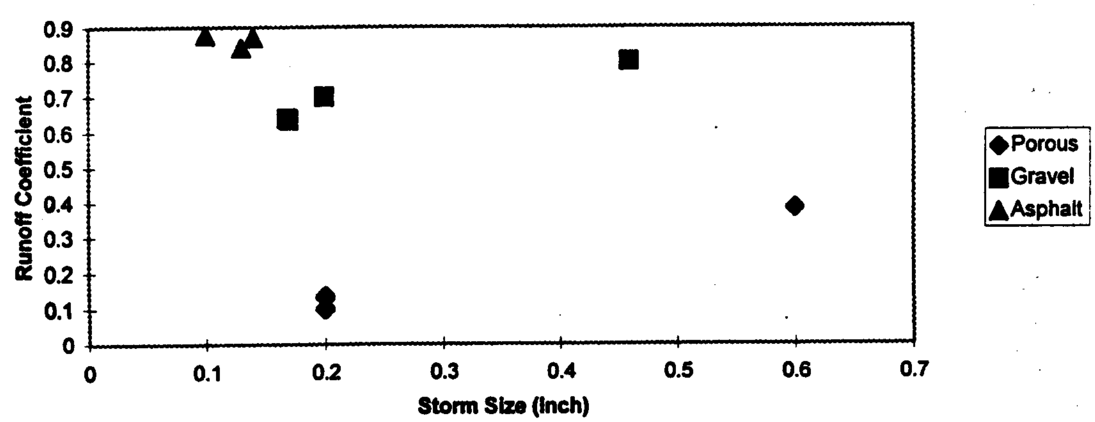

Figure 2.1 Relationship Between Storm Size and Shoulder Runoff Coefficient

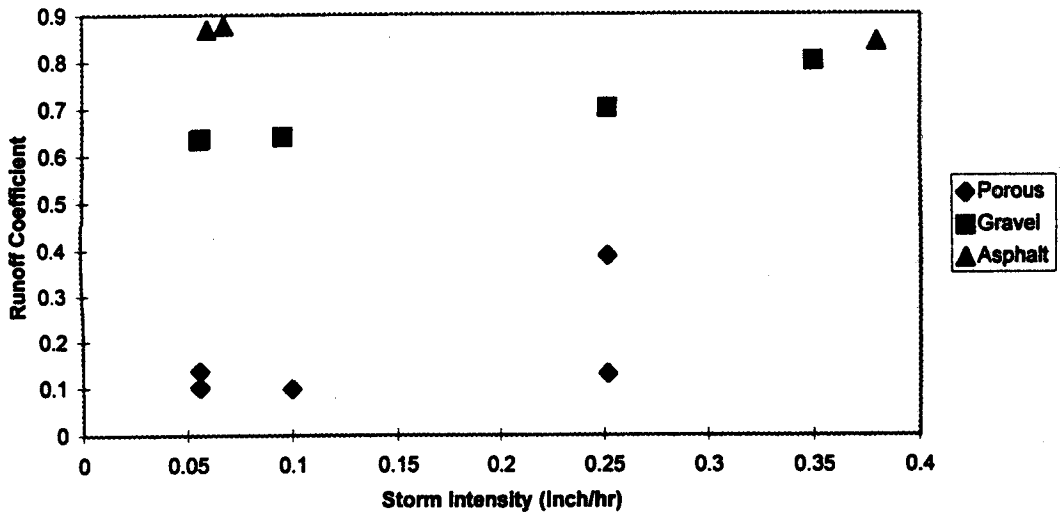

Figure 2.2 Relationship Between Storm Intensity and Shoulder Runoff Coefficient

Similar observations were made on the porous asphalt test sections. However, the "rainfall" infiltrated the porous asphalt within 0.3 to 0.6 m (1 to 2 ft) of the perforated diffuser pipe at all of the "rainfall" intensities tested (0.13 to 0.64 cm/hr [0.05 to 0.25 in/hr]). As with the gravel shoulders, pooling was observed at the base of the porous asphalt test sections, but in this case the pooling was never above ground, but rather just beneath the porous asphalt surface. Flow into the slot drains at these test sections occurred in the pooling locations, as well as through the seams in the slot drains. It became evident that the slot drains at these test sections were acting as a barrier to the subsurface flow. Therefore, the subsurface flow was getting backed up, and subsequently flowing through the seams of the slot drains or up and over the rim of the drains.

The term "runoff coefficient" implies surface runoff. In the case of the porous asphalt test sections, and to some degree the gravel test sections, there was no actual surface runoff but rather subsurface flow that was forced to the surface. The runoff coefficient results from the rain simulation/overland flow experiments reflected the total volume of runoff collected in the slot drains.

The runoff coefficient is a unitless parameter and is the ratio of the runoff to rainfall volumes. The runoff coefficient for the conventional asphalt shoulders was approximately 0.9 for all of the storm conditions tested, which is consistent with reported values for impervious surfaces (Schueler 1995, City of Olympia 1995, Horner et al. 1994). The runoff coefficients for the porous asphalt and gravel shoulders appeared to be a function of storm size. Figure 2.3 examines the relationship between storm intensity and runoff coefficient for the gravel and porous asphalt shoulders for 0.5-cm (0.2-in) storms. Apparently, the runoff coefficients for the gravel and porous asphalt shoulders were fairly constant over a range of storm intensities. However, the results of experiments 5 and 6 indicated that the runoff coefficient for the porous asphalt shoulder increased from 0.13 to 0.38 when the storm size increased from 0.5 to 1.5 cm (0.20 to 0.60 inches) and when storm intensity was constant (0.64 cm/hr [0.25 in/hr]).

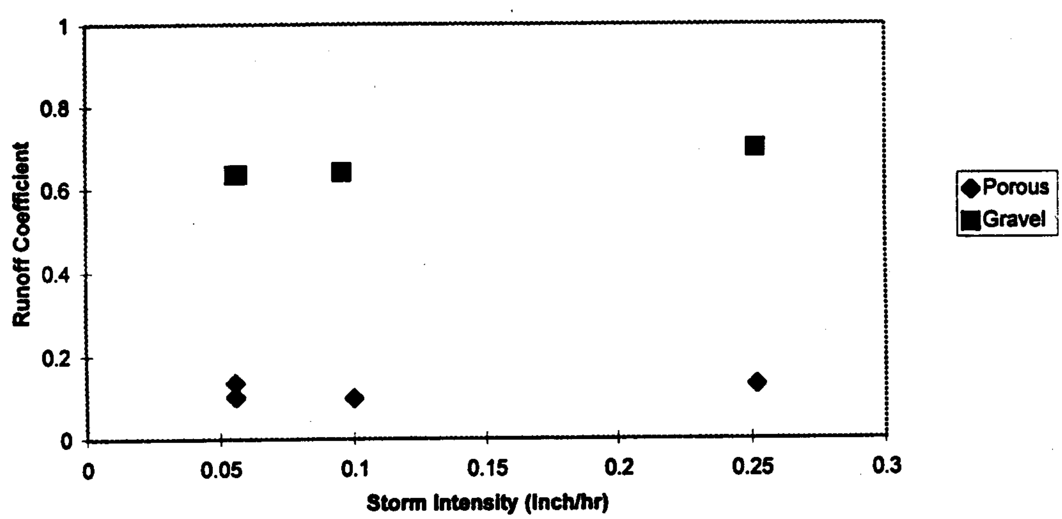

Figure 2.3 Relationship Between Storm Intensity and Runoff Coefficient (Storm size of 0.2 inches)

The average storm size at the Cottage Lake site for the 1995-1996 water year was approximately 0.76 cm (0.3 inches). Given the results of the rain simulation/overland flow experiments, the runoff coefficients for the gravel and porous asphalt shoulders associated with the typical storm size were 0.65 +/- 0.016 and 0.12 +/- 0.010, respectively (mean +/- 1 SE). The runoff coefficients for the gravel and porous asphalt shoulders associated with storms 0.5 inches or greater were 0.8 and 0.4, respectively.

Infiltration Experiments

Basic infiltration tests were conducted on the gravel and porous asphalt test sections using a single ring infiltrometer. The gravel shoulders were tested in five locations, producing an average infiltration rate of 31.2 cm/hr (12.3 in/hr). The porous asphalt shoulders were tested in triplicate, producing an average infiltration rate of 74.2 cm/minute (29.2 in/min) or, if continued at this rate, 4445 cm/hr (1750 in/hr).

Attempts were made to produce sheet flow on the porous asphalt test sections. Water was applied to the porous asphalt with a garden hose at a discharge rate of approximately 20 L per minute (5.3 gal/min). At first sheet flow occurred immediately. However, after the porous asphalt surface became wet, the water began to infiltrate. Within a minute all of the water was infiltrating the porous asphalt with no sheet flow. As the water was applied with greater force, infiltration occurred more quickly.

QA/QC RESULTS

The Municipality of Metropolitan Seattle Environmental Laboratory (Metro) conducted the water quality analyses for the study. Metro follows strict internal QA/QC guidelines, including the following procedures:

1. Laboratory control samples are analyzed.
2. All analytical results for conventionals are reported from batches in which the calibration curve and positive controls are within control windows (r = 0.995 or greater, and +/- 20 percent of the true value respectively).
3. Method blanks are used and expected to be less than method detection limits.

4. Laboratory duplicates are expected to be within 25 percent relative percentage difference.

5. Recovery of matrix spikes is expected to be within 70 to 130 percent.

QA/QC data summaries provided by the Metro laboratory for each storm are presented in Appendix B. For all but a few exceptions the data passed the internal QA/QC checks for accuracy and completeness, and the data were presented without qualification. The few instances in which method blank surrogates or positive control samples were below the recommended QC limits are highlighted in Appendix B. All of the bioassay analyses passed their respective precision tests.

In addition to the internal duplicates analyzed by the laboratory, field duplicates were sampled. The identities of the duplicates were not reported to the laboratory. Field duplicates were taken (using a random numbers table) during four of the eleven storms monitored (36 percent of the storms). A total of 1644 samples were analyzed throughout the monitoring period. Field duplicates were analyzed from 5 percent of the total number of samples. The average relative percentage difference for the field duplicates was 19 percent, which is within the guidelines Metro follows. Table 2.3 outlines the average and range of the relative percentage difference data for individual water quality parameters.

Table 2.3 Field Duplicate Relative Percent Difference (RPD) Results
Average relative percentage difference = 19%.
Average and range relative percentage difference for various parameters are shown.

Parameter	Average RPD	Range of RPD
TSS	28.0%	15-45%
BOD	8.2%	2-17%
COD	20.1%	5-31%
TP	15.6%	10-21%
OP	45.6%	0-100%
Metals (Pb, Cu, Zn)	18.0%	0-58%
DR, HOR, O&G	24.2%	1-100%

RPD = Relative percentage difference.

Each shoulder treatment and the road control were tested in duplicate; therefore, there were eight test sections, but only four treatments. The data from both test sections for each respective treatment were pooled to test for differences between the treatments. However, the relative percentage difference between the two test sections for each given treatment was calculated. Table 2.4 provides a summary of the mean and range of the relative percentage differences between treatment test sections for a variety of water quality parameters. The average relative percentage difference between the two road, conventional asphalt, gravel, and porous asphalt treatments were 40.4, 27.3, 33.4, and 48.4 percent, respectively. Although these averages are all above the recommended limit set by *Metro*, they indicate heterogeneity within each treatment. It is important to note that the relative percentage difference between the test sections of each treatment is also expressed in terms of sample variance, which is a primary factor considered in all statistical tests. Therefore, by pooling the data between test sections for a given treatment, the conclusions reached in statistical testing are valid because they incorporate treatment heterogeneity.

Table 2.4 Treatment Replicate Relative Percentage Difference Summary
The mean and (range) in relative percentage difference (%) for each treatment for a variety of water quality parameters are shown. The average relative percent difference between the two road, conventional asphalt, gravel, and porous asphalt treatments were 40.4, 27.3, 33.4, and 48.4%, respectively.

	TSS	BOD	COD	TP	OP	Pb	Cu	Zn
Road	56.2 (4-47)	32.0 (0-62)	32.8 (11-112)	37.2 (1-115)	37.7 (4-98)	48.4 (22-165)	43.7 (7-144)	34.9 (12-86)
Asphalt	26.0 (15-30)	22.6 (20-37)	28.3 (9-54)	21.0 (1-45)	42.1 (15-72)	29.4 (1-61)	21.7 (1-49)	27.7 (1-62)
Gravel	21.7 (13-30)	33.8 (7-57)	38.2 (5-67)	20.2 (6-44)	47.9 (16-109)	30.0 (3-54)	9.2 (2-23)	21.0 (5-49)
Porous	86.5 (38-170)	26.4 (3-11)	26.3 (0-66)	52.3 (2-107)	41.3 (0-100)	67.9 (6-156)	44.1 (0-99)	42.2 (13-85)

INDIVIDUAL POLLUTANT DATA—SEASONAL SUMMARIES

In this section water quality summaries of the runoff from the different test sections are presented for specific pollutants. The data are summarized in three categories: wet season, sanding event, and summer event. Nine of the 11 storms that were monitored occurred between November and April and were assumed to represent typical wet season conditions. The data from these nine storms were aggregated to present an average event mean concentration for each water quality parameter for the respective treatments. One storm occurred in early February and followed a heavy application of sand on the roads. This "sanding event" storm was considered separately. The final monitored storm occurred in early August following a 13-day period of no rain and represents a "summer event." Four days before the summer event storm the Woodinville-Duvall NE Road had been resurfaced with new asphalt.

Each treatment was tested in duplicate. In the following summaries the data from the duplicates for each treatment are pooled. Statistical analyses were performed on the wet season data to evaluate the equality of the means. No statistical analyses were performed on the sanding and summer events because of the small sample sizes associated with these storms. Though the data from the duplicates for each treatment were pooled, the relative percentage differences between the treatment duplicates are reported in the Quality Assurance/Quality Control Results section.

Urban runoff pollutant concentrations typically follow a log-normal distribution as suggested by the Nationwide Urban Runoff Program (USEPA 1983), Washington state highway runoff monitoring studies (Little 1982), and studies by the City of Bellevue, Washington (City of Bellevue 1995). Because of the relatively small sample sizes in the present study, it was not possible to confirm the distribution of this data set, though there was indication that the data were positively skewed for many of the parameters. If data follow a log-normal distribution, then analytic statistical determinations based on assumptions of normality are invalid. However, by using log-transformed data (that is, taking the natural logarithm of each data point), parametric testing procedures can be followed (Zar 1996). On the basis of these conditions, all statistical analyses for testing equality of means (ANOVA and Tukey's HSD) were performed on the log-transformed data. The raw data (concentrations), however, are reported in the untransformed state. In addition, the arithmetic means are reported, as those are not affected by assumptions of normality.

Absolute loads were calculated on the basis of the probabilistic method described by Marsalek (1990) and discussed in Chapter 1. The absolute loads are presented in Appendix C. For purposes of comparing the loads from the three shoulder treatments, the relative loads of the gravel and porous asphalt in comparison to those of the conventional asphalt shoulders are presented in this section. The relative loads for the gravel and porous asphalt shoulders were calculated according to the following equation:

$$RL_{G\ or\ P} = (AL_{G\ or\ P} * 100)/AL_{CA} \qquad \text{(Eq. 6)}$$

where: $RL_{G\ or\ P}$ is the relative load of the gravel or porous asphalt shoulder, $AL_{G\ or\ P}$ is the absolute load of the gravel or porous asphalt shoulder, and AL_{CA} is the absolute load of the conventional asphalt shoulder. The absolute loads presented in Appendix B and the relative loads presented in this section are based on the runoff coefficients outlined in Table 2.5.

Table 2.5 Runoff Coefficients Used for Load Estimations

Loading Period	Porous Asphalt	Gravel	Conventional Asphalt
Wet Season	0.12	0.65	0.9
Sanding Event	0.4	0.8	0.9
Summer Event	0.4	0.8	0.9

Several assumptions should be stated, and considerations made, regarding analysis of runoff concentrations from the road in comparison to analysis of runoff from the three shoulder treatments:

1) The pollutant load delivered from the road to the shoulder test sections is the same for each test section.

2) The rainfall onto the road and shoulder test section is uniform with respect to both quantity and quality.

3) The area of the road test sections (52.6 m^2 [576 ft^2]) is not the same as the area of the shoulder test sections (87.6 m^2 (960 ft^2) [Figure 1.3]).

Given these assumptions, we assumed uniform and equal inputs to the shoulder test sections. Therefore, comparisons of runoff characteristics could be made between the three shoulder treatments. However, because the area of the shoulder test sections differed from that of the road test sections, statistical comparisons should not be made between the road test sections and the shoulder treatments.

Summary of All Water Quality Parameters

Below are seasonal summaries of total suspended solids (TSS), turbidity, chemical oxygen demand (COD), biochemical oxygen demand (BOD), total and ortho-phosphorus (TP and OP), metals (lead, zinc and copper), and petroleum fractions. The complete data set for all of the parameters tested, as well as summaries for the metals cadmium, chromium, nickel, and arsenic, are presented in Appendix A. Several general observations regarding all of these parameters include the following:

1. **All three of the shoulder treatments had lower average wet season event mean concentrations (EMCs) of solids and pollutants than did the EMCs in the road runoff.**

The EMCs of the runoff from the shoulder treatments were from 23 to 88 percent lower than the EMC of the road runoff. Because the area of the shoulder test sections was larger than the area of the road test sections, lower pollutant concentrations in the runoff from the shoulder test sections may had been due in part to dilution.

The area that contributed to runoff from the shoulder test sections was approximately 1.7 times the area that contributed to runoff from the road test sections.

Therefore, all else being equal, the runoff concentrations from the shoulders would have been 59 percent of the runoff concentrations from the road. The observed decrease in concentration in the runoff from the shoulder treatments in comparisond to that of the road may have been due in part to this "dilution factor." Any differences in concentrations between the shoulder test sections and road that were greater than 59 percent can be attributed to pollutant removal mechanisms. Because the runoff from the shoulder test sections flowed over (or through) the conventional asphalt, porous asphalt, and gravel shoulders, respectively, there was opportunity for pollutant transfer from the water to the shoulder material.

2. **The EMCs of solids and pollutants from all of the test sections were 3 to 15 times higher after the sanding event storm than those of the average wet season.**

The sanding event storm occurred in early February 1996 after a lengthy cold period, during which time the King County Road Maintenance Division applied sand to the roads. During each pass by the sanding truck 0.624 cubic yards of sand are spread on the road per lane mile (Bob Richardson, King County Road Maintenance Division, personal communication). During a single sanding operation the sanding truck makes approximately four passes. Given these figures, it was assumed that approximately 0.6 cubic feet (62 pounds) of sand was applied to the road adjacent to each test section (50 lane feet) per sanding operation.

For nine days before this storm there were intermittent light showers. In the 24 hours immediately before the sanding event storm a low intensity storm lasted approximately 20 hours and produced 1.07 cm (0.42 in) of rain. The sanding event storm itself was relatively large, producing 2.06 cm (0.81 in) over 12 hours, with maximum intensities of 0.64 cm/hr (0.25 in/hr).

Research has documented that during larger storms, more solids and pollutants are removed in highway runoff than during low-intensity, small storms (Asplund 1980, Gupta et al. 1978). Because of the size of the sanding event storm and the preceding conditions, the increased solids and pollutant concentrations in the runoff from all of the test sections were not unexpected. A study on highway stormwater runoff in Washington state concluded that sanding operations during snowfall and freezing weather is the major contributing factor to winter TSS loads (Asplund 1980). Furthermore, this study determined that the highest individual storm loads result when a large winter storm follows a period of sanding operations.

3. **The EMCs of solids and pollutants from all of the shoulder test sections were up to 17 times higher during the summer event storm than during the average wet season.**

During dry periods the major mechanisms by which pollutants are removed from roads include prevailing surface winds or traffic-generated vortex winds, and mechanical scrubbing by tires (Asplund 1980). Highway flushing studies performed in 1980 on I-50 in Sacramento, California, found that approximately 87 percent of the total pollutant mass from the highway was deposited on the median and distress lanes, indicating the significance of pollutant transport off roads during dry periods. Prior to the summer event storm there were 13 days of no rain, a duration long enough to have accumulated substantial solids and pollutants on the shoulders. The summer event storm itself was relatively large, 3.9 cm (1.53 in) of rain in 20 hours, a size large enough to wash the solids and pollutants off the shoulder test sections.

Total Suspended Solids

Total suspended solids (TSS) seasonal summaries are presented in Table 2.6. Several general observation of the data include the following:

1. **Analysis of variance of the wet season data led to the conclusion that the average EMCs of TSS were significantly different between the three shoulder treatments: conventional asphalt, porous asphalt, and gravel (P<0.001).**

The average EMC of TSS in the runoff from the porous asphalt shoulders was 75 percent lower than the average EMC in the runoff from the conventional asphalt shoulder. By contrast, the gravel shoulders contributed solids to the runoff so that the runoff from the gravel shoulders was 10 percent higher than the average EMC in the runoff from the conventional asphalt shoulder. Results of Tukey's Honestly Significant Difference Test (Zar 1995) showed that the average wet season EMC of TSS from the porous asphalt shoulders was significantly different from those EMCs from the conventional asphalt and gravel shoulders (Table 2.7).

Table 2.6 Total Suspended Solids Summary

Site	# of Wet Season Samples	Wet Season Mean EMC +/- 1 SE (mg/L)	Sanding Event EMC (mg/L)	Summer Event EMC (mg/L)
Road	15	140.4 +/- 22.3	962.0	40.5
Asphalt	16	64.1 +/- 9.9	407.0	94.0
Gravel	16	71.3 +/- 11.6	229.0	112.0
Porous	15	16.6 +/- 3.8	211.5	72.2

EMC = Event Mean Concentration.
1 SE of the mean presented for the wet season data.

2. The relative wet season TSS loads from the gravel and porous asphalt shoulders were 74 and 3 percent of the load from the conventional asphalt shoulder, respectively.

Relative loads are presented in this section for the purpose of comparing the pollutant loading performance of the gravel and porous asphalt shoulder treatments to that of the conventional asphalt shoulder. The low runoff coefficient of the porous asphalt shoulder, coupled with the comparatively low TSS concentration in the porous asphalt shoulder runoff, yielded a TSS load that was 97 percent smaller than the conventional asphalt load, as shown in Figure 2.4. Despite the fact that the wet season TSS concentration from the gravel shoulder was higher than that of the conventional asphalt shoulder, the wet season load from the gravel shoulder was 26 percent smaller than the wet season conventional asphalt load. The smaller load was due to the lower runoff coefficient of the gravel shoulder.

Table 2.7 Tukey's Honestly Significant Difference Test Results on Wet Season Total Suspended Solids Concentrations

Shoulder:	Porous Asphalt	Conventional Asphalt	Gravel
Average EMC: (mg/L)	16.6	<u>64.1</u>	<u>71.3</u>

This table shows average wet season EMC of TSS for the three shoulder treatments. Underlines indicate those EMCs that were <u>not</u> significantly different ($\alpha = 0.05$) using Tukey's HSD Test (Zar 1996).

3. The relative sanding event TSS loads from the gravel and porous asphalt shoulders were 50 and 23 percent of the TSS load from the conventional asphalt shoulder, respectively.

Despite the higher TSS concentrations during the sanding event the porous asphalt shoulder removed nearly 80 percent of the TSS load in comparison to the load from the conventional asphalt shoulder (Figure 2.4). The gravel shoulder removed 50 percent of the load in comparison to the load removed by the conventional asphalt shoulder.

4. The relative summer event TSS loads from the gravel and porous asphalt shoulders were 106 and 34 percent of the TSS load from the conventional asphalt shoulder, respectively.

The average summer event TSS EMC from the gravel shoulder was nearly 20 percent higher than the EMC from the conventional asphalt shoulder. Despite the lower runoff coefficient associated with the gravel shoulder, the gravel TSS load was 6 percent higher than the conventional asphalt load (Figure 2.4). The TSS load from the porous asphalt was 66 percent lower than the load from the conventional asphalt shoulder.

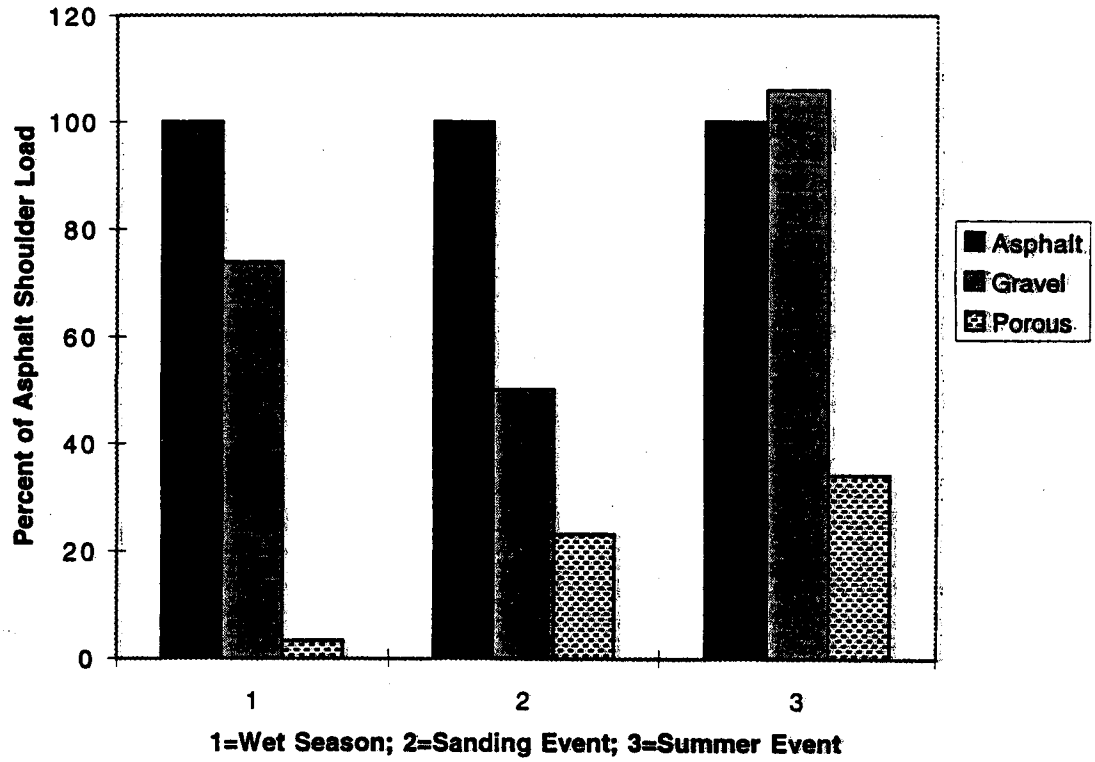

Figure 2.4 Comparison of Relative Total Suspended Solids Loads for Various Seasons

Turbidity

Summaries of the turbidity data are presented in Table 2.8. Turbidity is a measure of the degree to which a sample of water scatters light, and is reported in nephelometric turbidity units [NTU] (Sawyer, McCarry, and Parkin 1994). Turbidity may be caused by a variety of suspended materials, including organic and inorganic substances that range in size from colloidal to coarse dispersions. Several general observations of the turbidity data include the follows:

1. **The turbidity levels from all of the test sections over all of the storms monitored were fairly well correlated with the TSS concentrations.**

Turbidity and TSS data were fairly correlated, as determined by a scatter plot of turbidity levels versus TSS concentrations in the runoff from all of the test sections during all of the storms monitored. A linear regression of the plot with the y-intercept forced to zero generated a r^2 value of 0.79. Because of the correlation between turbidity and TSS, trends identified for the turbidity data were similar to those presented for the TSS data.

2. **Analysis of variance of the wet season data led to the conclusion that the average turbidity levels were significantly different between the three shoulder treatments ($P<0.001$).**

The average turbidity level in the runoff from the porous asphalt shoulder was over 50 percent lower than the level in the runoff from the conventional asphalt shoulder; however, because of large variance, these levels were not significantly different. The average turbidity level in the runoff from the gravel shoulder, on the other hand, was over two times higher than the level from the conventional asphalt shoulder, and these levels were significantly different (Table 2.9).

Table 2.8 Turbidity Summary

Site	# of Wet Season Samples	Wet Season Mean EMC +/- 1 SE (NTU)	Sanding Event EMC (NTU)	Summer Event EMC (NTU)
Road	15	29 +/- 2.3	520	29
Asphalt	16	20 +/- 1.5	340	34
Gravel	16	44 +/- 7.7	190	54
Porous	15	11 +/- 1.6	200	31

EMC = Event Mean Concentration. Turbidity is not actually measured as a concentration, but as a "unit." Regardless of this fact, the term event mean concentration is still used to indicate that the measurement is reflective of the conditions throughout the event.
NTU = Nephelometric turbidity units.
1 SE of the mean presented for the wet season data.

Table 2.9 Tukey's Honestly Significant Difference Test Results on Wet Season Turbidity Levels

Shoulder:	Porous Asphalt	Conventional Asphalt	Gravel
Average: (NTU)	11	20	44

This table shows average wet season levels of turbidity for the three shoulder treatments. Underlines indicate those levels that were not significantly different (α= 0.05) using Tukey's HSD Test (Zar 1996).
NTU = Nephelometric turbidity units.

Chemical and Biochemical Oxygen Demand

Summaries of the wet season, sanding event and summer event chemical oxygen demand (COD) and biochemical oxygen demand (BOD) data are presented in Tables 2.10 and 2.11. Although the two are similar, distinctions between the chemical oxygen demand and the biochemical oxygen demand are significant. The chemical oxygen demand is a measure of the total organic content in the wastewater and reflects the chemical oxidation of organics to carbon dioxide and water using a strong oxidizing agent under laboratory conditions. The biochemical oxygen demand, on the other hand, is a measure of the amount of dissolved oxygen required by microorganisms in the biochemical oxidation of organic matter. Generally, the COD of a waste is higher than the BOD because the COD test does not differentiate between biologically oxidizable and biologically inert organic matter (Sawyer, McCarty and Parkin 1994). The following observations can be made about the COD and BOD data:

1. **Although the majority of pollutant concentrations in the runoff from the three shoulder treatments were lower than the concentrations in the road runoff during the wet season, the BOD concentrations were an exception.**

Though not statistically different, the average wet season EMCs of BOD in the runoff from the gravel and porous shoulders were actually higher than the concentrations in the road runoff. The average EMC of BOD from the conventional asphalt shoulder, on the other hand, was slightly lower than that from the road. Oxygen is required by bacteria to metabolize organics, both soluble and insoluble materials. However, the bacteria themselves exert an oxygen demand. It is possible, though certainly not proven, that trapped organics and/or bacteria present in the gravel and porous asphalt shoulders were flushed off the shoulders during runoff events and contributed to the biological oxygen demand in the runoff from these sites.

Table 2.10 Chemical Oxygen Demand Summary

Site	# of Wet Season Samples	Wet Season Mean EMC +/- 1 SE (mg/L)	Sanding Event EMC (mg/L)	Summer Event EMC (mg/L)
Road	15	65.4 +/- 7.7	250.0	85.0
Asphalt	16	46.2 +/- 5.5	122.0	71.0
Gravel	16	28.9 +/- 3.4	71.0	72.0
Porous	15	22.5 +/- 4.3	63.5	64.5

EMC = Event Mean Concentration.
1 SE of the mean presented for the wet season data.

Table 2.11 Biochemical Oxygen Demand Summary

Site	# of Wet Season Samples	Wet Season Mean EMC +/- 1 SE (mg/L)	Sanding Event EMC (mg/L)	Summer Event EMC (mg/L)
Road	15	5.85 +/- 0.86	22.15	24.55
Asphalt	13	5.51 +/- 0.81	10.55	21.70
Gravel	12	6.08 +/- 1.07	7.00	22.10
Porous	6	6.72 +/- 2.13	11.15	32.75

EMC = Event Mean Concentration.
1 SE of the mean presented for the wet season data.

2. Analysis of variance of the wet season data led to the conclusion that the average EMCs of COD in the runoff from the three shoulder treatments were significantly different (P=0.003), but the BOD EMCs were not different.

The average wet season COD EMCs from the porous asphalt and gravel shoulders were 51 and 37 percent lower, respectively, than the average COD EMC from the conventional asphalt shoulder. Results of Tukey's Honestly Significant Difference Test (Table 2.12) showed that the average wet season EMCs of COD from the porous asphalt and gravel shoulders were not significantly different from one another, but they were significantly different from the EMCs of the conventional asphalt shoulder.

Table 2.12 Tukey's Honestly Significant Difference Test Results on Wet Season Chemical Oxygen Demand Concentrations

Shoulder:	Porous Asphalt	Gravel	Conventional Asphalt
Average EMC: (mg/L)	22.5	28.9	46.2

This table shows average wet season EMCs of COD for the three shoulder treatments. Underlines indicate those EMCs that were not significantly different (α= 0.05) using Tukey's HSD Test (Zar 1996). Double underlines indicates a Type II error has occurred.

3. The relative wet season COD loads from the gravel and porous asphalt shoulders were 56 and 94 percent lower, respectively, than the load from the conventional asphalt shoulder, whereas the BOD loads for the gravel and porous shoulders were 21 and 84 percent lower, respectively, than those of the conventional asphalt shoulders.

The relative COD and BOD loads from the shoulder treatments are shown in Figures 2.5 and 2.6. Despite the slightly higher BOD concentrations in the runoff from the gravel and porous asphalt shoulders in comparison to those of the conventional asphalt during the wet season, the gravel and porous asphalt loads were 79 and 16 percent, respectively, of the asphalt load because of the lower runoff coefficients associated with these shoulders.

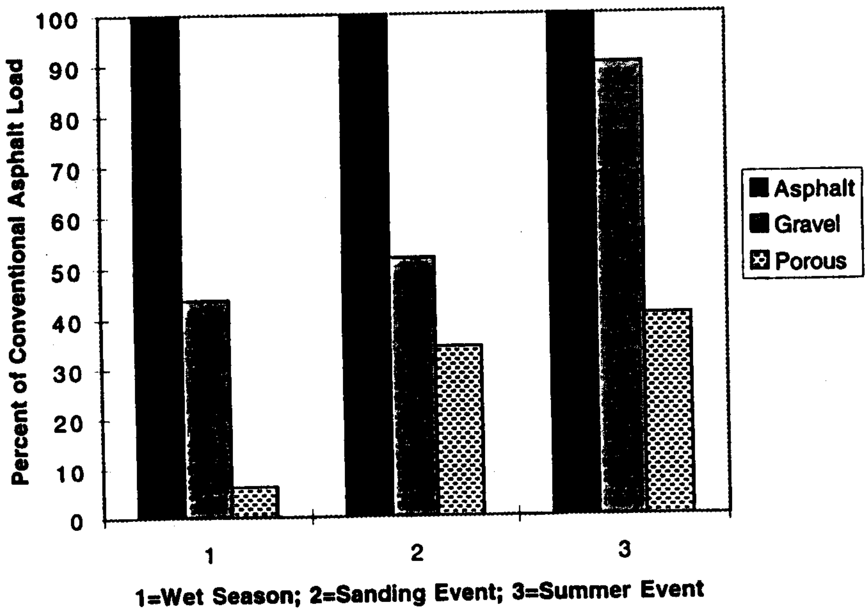

Figure 2.5 Comparison of Relative Chemical Oxygen Demand Loads for Various Seasons

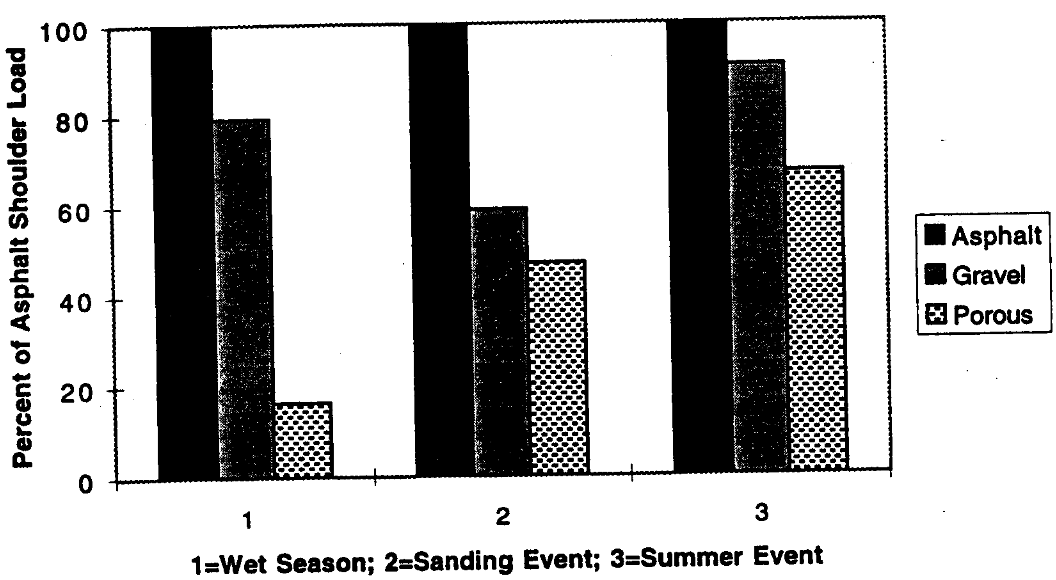

Figure 2.6 Comparison of Relative Biochemical Oxygen Demand Loads for Various Seasons

4. **The relative sanding event COD loads from the gravel and porous asphalt shoulders were 52 and 34 percent, respectively, of the load from the conventional asphalt shoulder, whereas the BOD loads from the gravel and porous shoulders were 59 and 47 percent, respectively, of the asphalt load** (Figures 2.5 and 2.6).

5. **The summer event BOD EMC from the porous asphalt shoulder was approximately 50 percent higher than the EMC from the conventional asphalt shoulder.**

Because there was only one data point from each test section for the summer event, definitive statements can not be made about differences in runoff concentrations. However, it is conceivable that soil bacteria or trapped organics present in the porous asphalt shoulders were flushed from the shoulder during the large summer event storm, resulting in higher BOD concentrations. Bacteriological tests would have to be conducted to test this hypothesis.

6. **Reductions in the relative loads of COD and BOD from the gravel and porous asphalt shoulders were smaller during the summer event than during the other seasons.**

The summer event COD loads from the gravel and porous asphalt shoulders were 10 and 60 percent lower, respectively, than the conventional asphalt loads (Figure 2.5). The BOD loads from the gravel and porous shoulders were 10 and 33 percent lower, respectively, than the conventional asphalt shoulder loads (Figure 2.6).

Total and Ortho Phosphorus

Total phosphorus (TP) and ortho-phosphorus (OP) seasonal summaries are provided in Tables 2.13 and 2.14. Total phosphorus includes all sorbed and complexed inorganic and organic phosphorus. Generally speaking, the ortho-phosphates include the dissolved inorganic forms of phosphorus. From a water quality standpoint the ortho-phosphates are most significant, as they are the forms available for uptake by algae and other aquatic plants. General observations of the seasonal data include the following:

Table 2.13 Total Phosphorus Summary

Site	# of Wet Season Samples	Wet Season Mean EMC +/- SE (mg/L)	Sanding Event EMC (mg/L)	Summer Event EMC (mg/L)
Road	15	0.358 +/- 0.035	2.345	0.408
Asphalt	16	0.229 +/- 0.025	1.385	0.388
Gravel	16	0.246 +/- 0.026	1.050	0.620
Porous	15	0.101 +/- 0.015	0.749	0.398

EMC = Event Mean Concentration.
1 SE of the mean presented for the wet season data.

Table 2.14 Ortho-Phosphorus Summary

Site	# of Wet Season Samples	Wet Season Mean EMC +/- SE (mg/L)	Sanding Event EMC (mg/L)	Summer Event EMC (mg/L)
Road	12	0.0191 +/- 0.0052	0.0765	0.1615
Asphalt	13	0.0084 +/- 0.0015	0.0345	0.0885
Gravel	13	0.0148 +/- 0.0018	0.0450	0.0580
Porous	12	0.0058 +/- 0.0010	0.0151	0.1010

EMC = Event Mean Concentration.
1 SE of the mean presented for the wet season data.

1. **Analysis of variance results on the wet season data showed that the average EMCs of both total and ortho-phosphorus in the runoff from the three shoulder treatments were significantly different (P<0.001).**

As depicted in Table 2.15, the average wet season TP EMC of the porous asphalt shoulder differed from both the conventional asphalt and gravel shoulder EMCs (at $\alpha=$

0.05). The gravel shoulder TP EMC did not differ from the conventional asphalt EMC. In fact, the TP EMC of the gravel shoulder was 7 percent higher than the conventional asphalt average EMC.

The porous asphalt average ortho-phosphorus EMC was not different from the conventional asphalt EMC, but it did differ from the gravel EMC (Table 2.16). In this case the gravel OP EMC was significantly higher than both the porous and conventional asphalt EMCs. Therefore, though there were significant differences among the shoulder treatments, the differences did not indicate reduced concentrations.

Table 2.15 Tukey's Honestly Significant Difference Test Results on Wet Season Total Phosphorus Concentrations

Shoulder:	Porous Asphalt	Conventional Asphalt	Gravel
Average EMC: (mg/L)	0.101	0.229	0.246

This table shows average wet season EMCs of TP for the three shoulder treatments. Underlines indicate those EMCs that were not significantly different ($\alpha = 0.05$) using Tukey's HSD Test (Zar 1996).

Table 2.16 Tukey's Honestly Significant Difference Test Results on Wet Season Ortho-Phosphorus Concentrations

Shoulder:	Porous Asphalt	Conventional Asphalt	Gravel
Average EMC: (mg/L)	0.0058	0.0084	0.0148

This table shows average wet season EMCs of OP for the three shoulder treatments. Underlines indicate those EMCs that were not significantly different ($\alpha = 0.05$) using Tukey's HSD Test (Zar 1996).

2. **The relative wet season TP loads for the gravel and porous asphalt shoulders were 81 and 6 percent, respectively, of the load from the conventional asphalt shoulder. The relative wet season OP load from the gravel shoulder was nearly 30 percent higher than the**

conventional asphalt load, whereas the porous asphalt load was 90 percent lower than the conventional asphalt load.

The fact that the total and ortho-phosphorus EMCs were higher in the gravel runoff than in the runoff from the porous and conventional asphalt shoulders had considerable effects on the loadings. The porous asphalt shoulders, on the other hand, demonstrated 90 to 94 percent removal in comparison to the conventional asphalt load (Figures 2.7 and 2.8).

3. **The relative sanding event TP loads for the gravel and porous asphalt shoulders were 33 and 76 percent lower, respectively, than the load from the conventional asphalt shoulder** (Figure 2.7). **The OP load from the gravel shoulder was 16 percent higher than the conventional asphalt load, whereas the porous OP load was 81 percent lower than the conventional asphalt load** (Figure 2.8).

4. **The summer event ortho phosphorus EMC in the road runoff was 8 times higher than the average wet season EMC from this site.**

The EMCs of the majority of the pollutants in the road runoff from the summer event were within the range of EMCs generated during the wet season. Ortho- phosphorus was an exception. Four days before the summer event storm Woodinville-Duvall NE was resurfaced with new asphalt. It is possible that newly applied asphalt contains ortho-phosphorus that is flushed out during the first storms following resurfacing. This hypothesis has not been substantiated.

5. **The relative summer event TP load for the gravel shoulder was 42 percent higher than the conventional asphalt load, whereas the porous asphalt load was 54 percent lower than the conventional asphalt load. The OP loads from the gravel and porous shoulders were 42 and 49 percent lower, respectively, than the conventional asphalt loads during the summer event** (Figure 2.8).

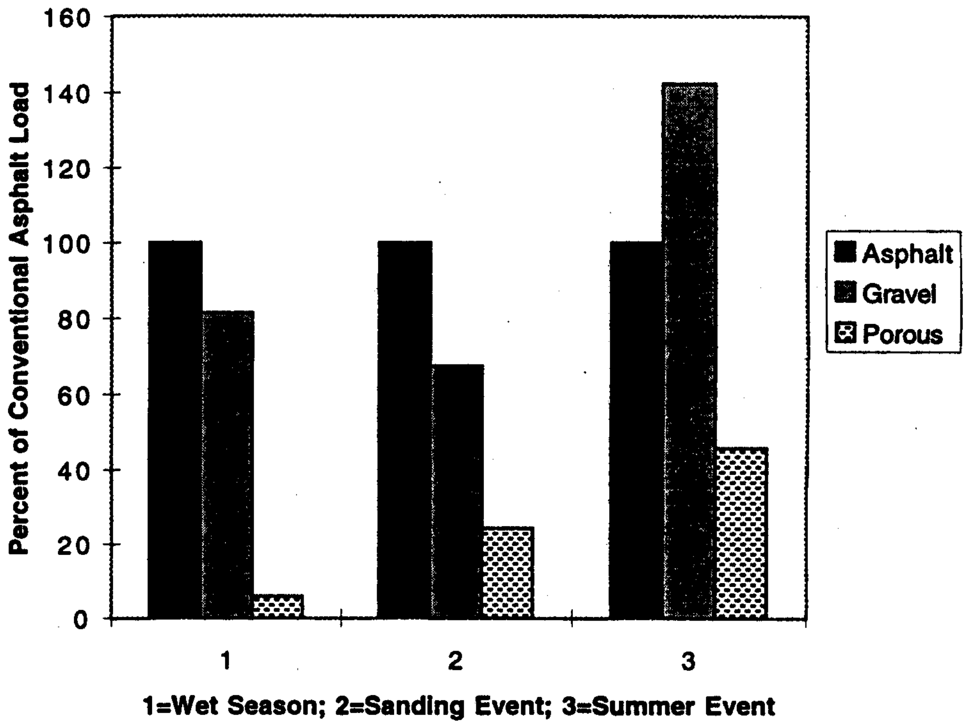

Figure 2.7 Comparison of Relative Total Phosphorus Loads for Various Seasons

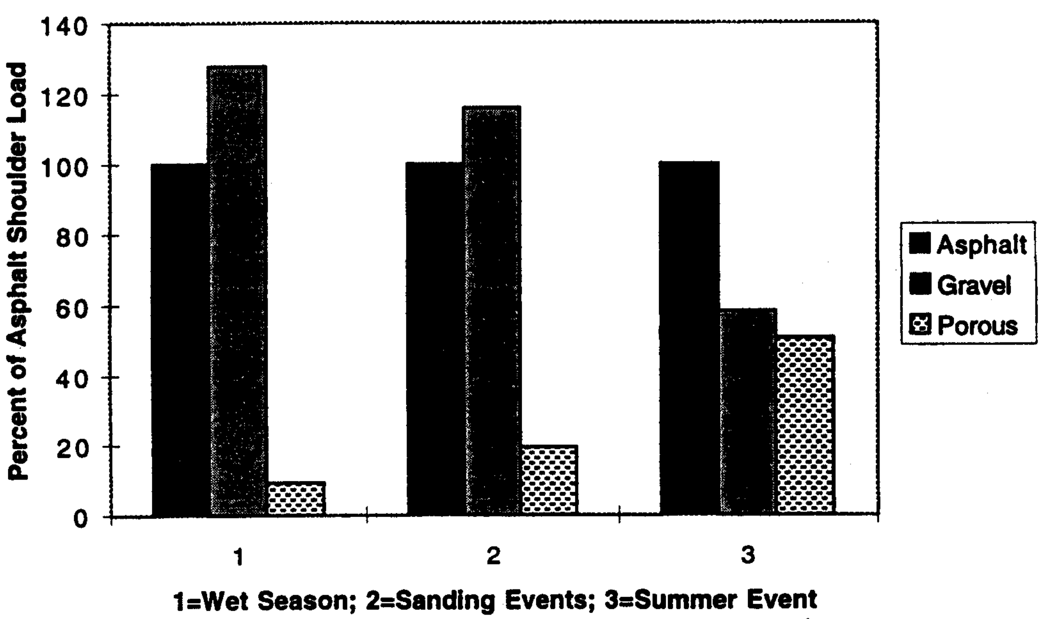

Figure 2.8 Comparison of Relative Ortho-Phosphorus Loads for Various Seasons

Metals—Lead, Zinc, and Copper

Seasonal summaries of lead, zinc, and copper are presented in Tables 2.17, 2.18, and 2.19. Only lead, zinc, and copper are reviewed in this section because they are the most frequently detected priority pollutant metals in urban runoff (US EPA 1983). The data for cadmium, chromium, nickel, and arsenic are presented in Appendix B. Several general observations follow:

Table 2.17 Lead Summary

Site	# of Wet Season Samples	Wet Season Mean EMC +/- SE (mg/L)	Sanding Event EMC (mg/L)	Summer Event EMC (mg/L)
Road	15	0.0397 +/- 0.0064	0.2685	0.0116
Asphalt	16	0.0216 +/- 0.0037	0.1235	0.0303
Gravel	16	0.0087 +/- 0.0008	0.0598	0.0212
Porous	15	0.0047 +/- 0.0008	0.0688	0.0143

EMC = Event Mean Concentration.
1 SE of the mean presented for the wet season data.

Table 2.18 Zinc Summary

Site	# of Wet Season Samples	Wet Season Mean EMC +/- SE (mg/L)	Sanding Event EMC (mg/L)	Summer Event EMC (mg/L)
Road	15	0.1052 +/- 0.0152	0.6065	0.0796
Asphalt	16	0.0.0530 +/- 0.0067	0.3035	0.0869
Gravel	16	0.0396 +/- 0.0044	0.1530	0.0791
Porous	15	0.0387 +/- 0.0108	0.1705	0.0988

EMC = Event Mean Concentration.
1 SE of the mean presented for the wet season data.

Table 2.19 Copper Summary

Site	# of Wet Season Samples	Wet Season Mean EMC +/- SE (mg/L)	Sanding Event EMC (mg/L)	Summer Event EMC (mg/L)
Road	15	0.0162 +/- 0.0024	0.0801	0.0180
Asphalt	16	0.0085 +/- 0.0009	0.0445	0.0171
Gravel	16	0.0112 +/- 0.0014	0.0279	0.0221
Porous	15	0.0048 +/- 0.0010	0.0252	0.0235

EMC = Event Mean Concentration.
1 SE of the mean presented for the wet season data.

1. **The EMCs of the runoff from the three shoulder treatments differed during the wet season for lead and copper (P<0.001) but not for zinc.**

Tukey's Honestly Significant Difference test results revealed that the average wet season EMCs of lead in the runoff from both the porous asphalt and gravel shoulders differed from the runoff EMC from the conventional asphalt shoulder ($\alpha = 0.01$), and they differed from one another (Table 2.20).

Table 2.20 Tukey's Honestly Significant Difference Test Results for Wet Season Lead Concentrations

Shoulder:	Porous Asphalt	Gravel	Conventional Asphalt
Average EMC: (mg/L)	0.0047	0.0087	0.0216

This table shows average wet season EMCs of lead for the three shoulder treatments. Underlines indicate those EMCs that were not significantly different ($\alpha = 0.05$) using Tukey's HSD Test (Zar 1996). Lack of underlines indicates all means are different.

Test results for the copper EMCs showed that the copper concentrations in the porous asphalt runoff differed from those in both the conventional asphalt and gravel shoulders (Table 2.21). The EMC of copper in the runoff from the gravel shoulder was 30 percent higher than the copper concentration in the conventional asphalt runoff, but the concentrations were not significantly different. The EMCs of zinc in the runoff from the three shoulder treatments did not differ from one another.

Table 2.21 Tukey's Honestly Significant Difference Test Results on Wet Season Copper Concentrations

Shoulder:	Porous Asphalt	Conventional Asphalt	Gravel
Average EMC: (mg/L)	0.0048	0.0085	0.0112

This table shows average wet season EMCs of copper for the three shoulder treatments. Underlines indicate those EMCs that were not significantly different ($\alpha = 0.05$) using Tukey's HSD Test (Zar 1996).

2. **The wet season lead, zinc, and copper loads from the porous asphalt shoulders are all at least 90 percent lower than the loads from the conventional asphalt shoulders. These loads from the gravel shoulder range from 7 to 70 percent lower than the conventional asphalt loads.**

The porous asphalt shoulder consistently demonstrated large reductions in metal loads in comparison to the loads in the runoff from the conventional asphalt shoulder. The performance of the gravel shoulder was less uniform. The loads for lead, zinc, and copper from the gravel shoulder during the wet season were 72, 47, and 7 percent lower, respectively, than those of the conventional asphalt (Figures 2.9, 2.10, and 2.11)

3. **The EMCs of lead, zinc, and copper in the runoff from the gravel and porous asphalt shoulders were all between 40 and 50 percent lower than the EMCs in the runoff from the conventional asphalt shoulder during the sanding event storm.**

While the porous asphalt shoulder was consistently better than the gravel shoulder at reducing the metal concentrations in the runoff during the wet season storms, the porous

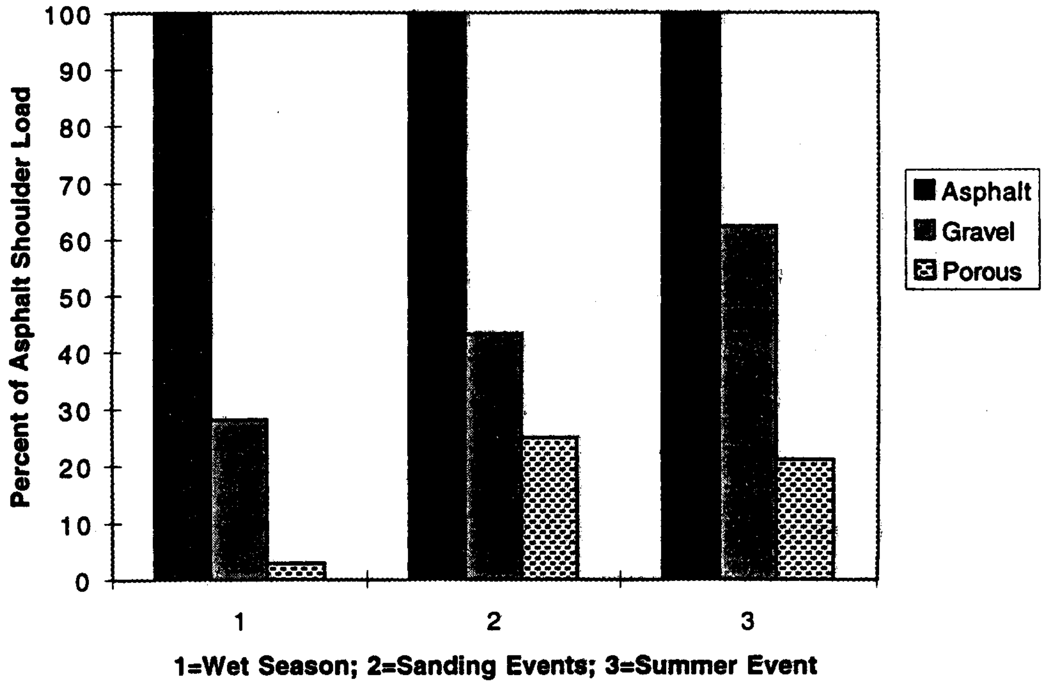

Figure 2.9 Comparison of Relative Lead Loads for Various Seasons

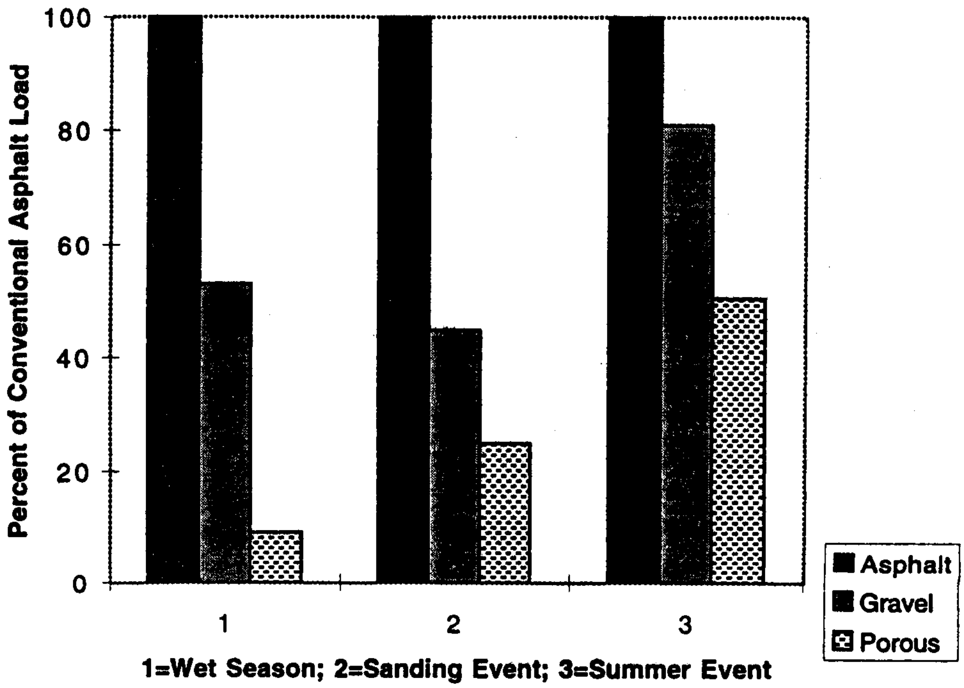

Figure 2.10 Comparison of Relative Zinc Loads for Various Seasons

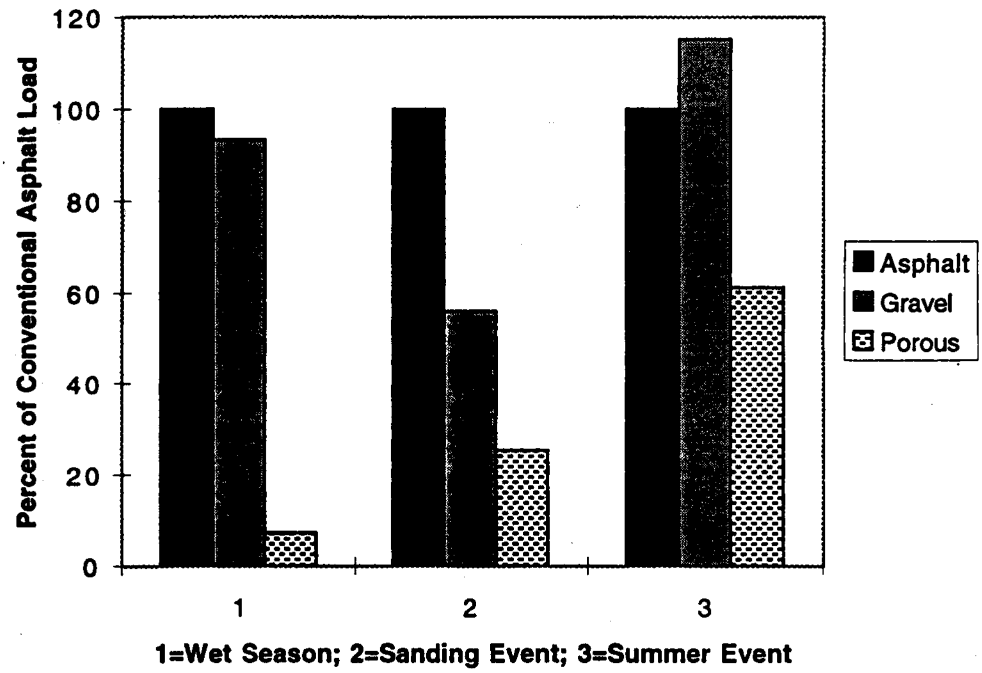

Figure 2.11 Comparison of Relative Copper Loads for Various Seasons

asphalt performance was only marginally better than that of the gravel shoulder during the sanding event storm (Tables 2.17, 2.18, 2.19).

4. **During the summer event the average EMCs of zinc and copper in the runoff from the gravel and porous asphalt shoulders were higher, or only slightly lower, than the EMCs in the runoff from the conventional asphalt shoulder.**

Petroleum Fractions—Oil and Grease, Heavy Oil Range, and Diesel Range

Summaries of Oil and Grease (O&G), Heavy Oil Range (HOR), and Diesel Range (DR) are presented in Tables 2.22, 2.23, 2.24. All three parameters are measures of petroleum products. Several general observations can be made:

Table 2.22 Oil and Grease Summary

Site	# of Wet Season Samples	Wet Season Mean EMC +/- SE (mg/L)	Sanding Event EMC (mg/L)	Summer Event EMC (mg/L)
Road	15	12.99 +/- 2.57	8.0	6.65
Asphalt	16	11.87 +/- 2.25	10.8	12.15
Gravel	14	10.86 +/- 2.69	74.5	6.90
Porous	13	7.82 +/- 0.59	4.2	15.10

EMC = Event Mean Concentration.
1 SE of the mean presented for the wet season data.

Table 2.23 Heavy Oil Range Summary

Site	# of Wet Season Samples	Wet Season Mean EMC +/- SE (mg/L)	Sanding Event EMC (mg/L)	Summer Event EMC (mg/L)
Road	15	2.50 +/- 0.30	4.31	1.74
Asphalt	16	1.99 +/- 0.23	1.44	1.91
Gravel	16	1.13 +/- 0.22	2.71	1.35
Porous	13	0.88 +/- 0.11	3.72	1.37

EMC = Event Mean Concentration.
1 SE of the mean presented for the wet season data.

Table 2.24 Diesel Range Summary

Site	# of Wet Season Samples	Wet Season Mean EMC +/- SE (mg/L)	Sanding Event EMC (mg/L)	Summer Event EMC (mg/L)
Road	11	1.03 +/- 0.18	NA	1.35
Asphalt	12	0.83 +/- 0.12	NA	1.14
Gravel	11	0.61 +/- 0.11	NA	0.85
Porous	10	0.64 +/- 0.12	NA	2.0

EMC = Event Mean Concentration.
1 SE of the mean presented for the wet season data.
NA = Not Available

1. **Analysis of Variance of the wet season data for the three parameters led to the conclusion that the HOR EMCs from the three shoulder treatments were significantly different (P=0.001), but the O&G and DR EMCs were not significantly different.**

Though the average EMCs of O&G in the runoff from the gravel and porous asphalt shoulders were 8 and 44 percent lower than the average EMC from the conventional asphalt shoulder during the wet season, the concentrations were not significantly different. Similarly, the average DR EMCs from the gravel and porous asphalt shoulders were both approximately 25 percent lower than the conventional asphalt shoulder DR EMC; however, these wet season concentrations were not significantly different. Results of Tukey's HSD Test for the HOR wet season data, on the other hand, showed that both the gravel and porous shoulders differed from the conventional asphalt shoulder but did not differ from one another (Table 2.25).

Table 2.25 Tukey's Honestly Significant Difference Test Results for Wet Season Heavy Oil Range Concentrations

Shoulder:	Porous Asphalt	Gravel	Conventional Asphalt
Average EMC: (mg/L)	<u>0.88</u>	<u>1.13</u>	1.99

This table shows average wet season EMCs of heavy oil range for the three shoulder treatments.
Underlines indicate those EMCs that were <u>not</u> significantly different ($\alpha = 0.05$) using Tukey's HSD Test (Zar 1996).

2. **The relative wet season loads of the three parameters O&G, HOR, and DR from the gravel shoulders were all between 40 and 60 percent of the loads from the conventional asphalt loads. The wet season loads from the porous asphalt shoulders were all about 10 percent of those of the conventional asphalt loads** (Figure 2.12).

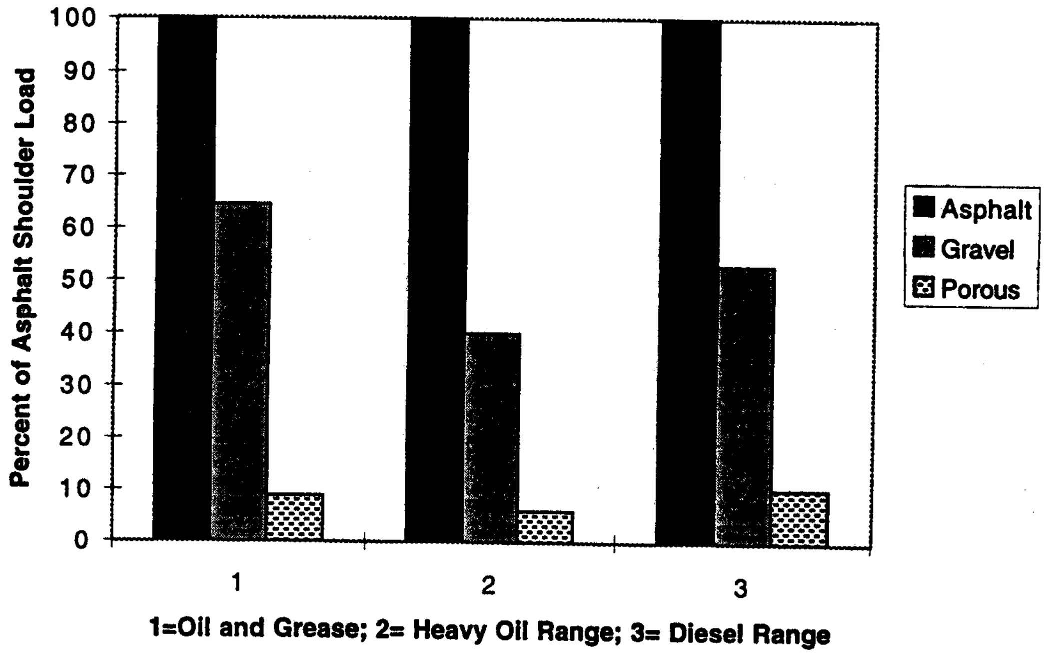

Figure 2.12 Relative Wet Season Loads: Oil and Grease, Heavy Oil Range, and Diesel Range

3. **There was considerable variation in the EMCs of the three parameters from the shoulder treatments during the sanding event and summer event storms.**

No consistent trends were identified for the shoulder treatments during the sanding event and summer event storms for the three parameters O&G, HOR, and DR (Tables 2.22, 2.23, 2.24). In some cases there was considerable variation within the treatment duplicates (Appendix B). The variations within and between the treatments, perhaps caused by petroleum spills, made it difficult to reach definitive conclusions on any possible shoulder treatment effects during these storms.

BIOASSAY RESULTS

Standardized toxicity bioassays were conducted on the runoff from each test section from two storms on February 5 and April 1, 1996. A preliminary bioassay test had been run to evaluate the testing procedures best suited for the runoff quality conditions associated with the road shoulder treatments. The February 5th storm occurred after a lengthy cold period during which the King County Road Maintenance Division had applied sand to the roads. Consequently, the total suspended solids and pollutant concentrations in the runoff from this storm were higher than those of the other wet season storms. The April 1st storm had water quality conditions representative of the wet season data.

Acute and Chronic Toxic Effects

Results of the 48-hour *Daphnia pulex* acute toxicity tests for both storms revealed a non-toxic effect. Survival was not significantly ($P>0.05$) reduced in any concentration of any treatment. In fact, survival was 100 percent for nearly all treatments at full-strength concentrations (no dilution).

Results of the 96-hour *Selenastrum capriocornutum* chronic toxicity tests on the April 1st storm showed minimal effect. Table 2.26 summarizes the data for three Lake Washington water (LWW) controls and the eight test section treatments. The Lake Washington water control samples are obtained monthly from Lake Washington at a site midway between the I-90 and 520 bridges and filtered to 0.45 µm before use. A modified version of the t-test which assumes unequal variance between samples (the Behrens-Fisher method [Zar 1996]), was used to compare the mean LWW control to each treatment mean. Variance ratio tests confirmed the unequal variance assumption. Only Asphalt 1 and Porous 2 were significantly different from the control mean ($P>0.05$). Analysis of variance and Tukey's Test for multiple comparisons determined minimal differences among the treatment means.

Results of the 96-hour *Selenastrum capriocornutum* chronic toxicity tests on the February 5th storm showed effects for most of the treatments. Table 2.27 summarizes the results. Again, a modified version of the t-test was used to compare the mean LWW control associated with each test section to the mean for each individual treatment (undiluted samples). In this case, the treatment means differed from the controls for all sites except

Table 2.26 Summary of 96-Hour *Selenastrum capriocornutum* Chronic Toxicity Test Results for April 1, 1996, Storm

Cells/mL ($x10^4$) for Lake Washington Water Controls
Mean +/- (SD) shown

Control 1	Control 2	Control 3
305.8	302.5	262.5
(4.87)	(46.16)	(13.40)

Cells/mL ($x10^4$) for 100% (no dilution) Samples
Mean +/- (SD) shown

Road 1	Road 2	Asphalt 1	Asphalt 2	Gravel 1	Gravel 2	Porous 1	Porous 2
291.3	303.2	330.1	249.9	317.3	315.5	311.1	330.8
(31.79)	(11.31)	(16.62)	(77.2)	(24.74)	(24.09)	(18.45)	(26.47)

Table 2.27 Summary of 96-Hour *Selenastrum capriocornutum* Chronic Toxicity Test Results for February 5, 1996, Storm

Cells/mL ($x10^4$) for Lake Washington Water Controls and 100% (no dilution) Samples
Mean +/- (SD) shown

	Road 1	Road 2	Asphalt 1	Asphalt 2	Gravel 2	Porous 1	Porous 2
Control Mean +/- (SD)	145.1+/- (62.44)	145.1 +/- (62.44)	259.5 +/- (9.66)	259.5 +/- (9.66)	228.2+/- (28.30)	270.2 +/- (15.49)	270.2+/- (15.49)
Site Mean +/- (SD)	250.0+/- (20.42)	14.9 +/- (2.54)	78.6 +/- (10.55)	221.8 +/- (2.75)	94.6 +/- (15.03)	218.7 +/- (14.25)	197.3+/- (14.46)

Note: For the February 5th storm, Lake Washington Water Controls were performed separately for each site.

Road 1 and 2. However, the sample variance associated with the controls for Road 1 and 2 were quite high (3898) in comparison to the average variance of the controls associated with the other sites (294). The high variance in the road controls restricted the determination of significant differences between these controls and the road treatments.

The road controls were the first samples analyzed (that is, they were the first samples for which cell counts were made), and analysis error is presumed. The Road 2 control had a mean cell count of 145.1 cells/mL (x10^4), while the Road 2 runoff had a mean cell count of 14.9 cells/mL (x10^4), suggesting toxic inhibition.

Analysis of variance and Tukey's Test for multiple comparisons determined significant difference between many of the treatments for the February 5 storm, as depicted in Table 2.28. There was significantly less growth ($P<0.05$) associated with Road 2 compared to all other treatments.

Table 2.28 Tukey's Honestly Significant Difference Test Results for 96-Hour *Selenastrum capriocornutum* Chronic Toxicity Data from February 5, 1996, Storm

Mean cells/mL (x10^4) for 100% (no dilution) samples shown.

Road 2	Asphalt 1	Gravel 2	Porous 2	Porous 1	Asphalt 2	Road 1
14.9	78.6	94.6	197.3	218.7	221.8	250.0

This table shows mean cell counts for treatment samples.
Underlines indicate those means that were not significantly different (α= 0.05) using Tukey's HSD Test (Zar 1996). Double underlines indicates a Type II error has occurred.

Biostimulatory Response

Results of the Algal Growth Potential tests on *Selenastrum capricornutum* revealed that the February 5th storm was biostimulatory, whereas the April 1st storm was not. The results for both storms are summarized in Table 2.29. All runoff samples from the February 5th storm supported higher algal growth than the LWW control, indicating that the runoff may be biostimulatory in typical receiving waters. The Road 2 runoff sample from the February 5th storm appeared quite toxic until Day 4 of the test, with essentially no cell multiplication observed (Figure 2.13). From Day 5 on, growth proceeded in a manner similar to that of the other samples. However, many abnormal cells were noted. The cells were broken, granular and enlarged with ragged edges. The personnel at the King County

Environmental Laboratory who conducted the bioassays indicated that although the observed cell morphology cannot be attributed to any specific toxic mechanism, it does indicate a general alteration of cell metabolism that may cause improper cell wall formation and cell division. After Day 5, the proportion of abnormal cells decreased in the Road 2 sample, and the new growth observed after time was generally normal. The inoculum for both storms equaled 12 fronds per treatment. For the February 5th storm the inoculum equaled 2.1 mg. The inoculum for the April 1st storm equaled 1.4 mg.

None of the April 1st samples supported significantly higher algal growth than the LWW reference in the Algal Growth Potential test, indicating that these runoff conditions are most likely not biostimulatory in typical receiving waters. Cell appearance and condition were normal for all treatments.

Table 2.29 *Selenastrum capricornutum* (Algal Growth Potential) Test Results for February 5 and April 1, 1996, Storms

The average maximum standing crop (mg/L) is shown.

Sample	February 5th Storm	April 1st Storm
Lake Water Control	6.41[a]	2.54[e,f]
Road 1	12.71[b]	3.27[e,f]
Road 2	10.77[a,b]	11.93[e]
Asphalt 1	28.38[d]	4.20[e,f]
Asphalt 2	26.15[c,d]	4.75[e,f]
Gravel 1	NA	1.64[f]
Gravel 2	22.56[c]	9.44[e]
Porous 1	8.53[a,b]	1.24[f]
Porous 2	10.60[a,b]	2.53[e,f]

Means sharing a common letter are not significantly different (P>0.05) based on Tukey Test results (Zar 1996).
NA = Not Available

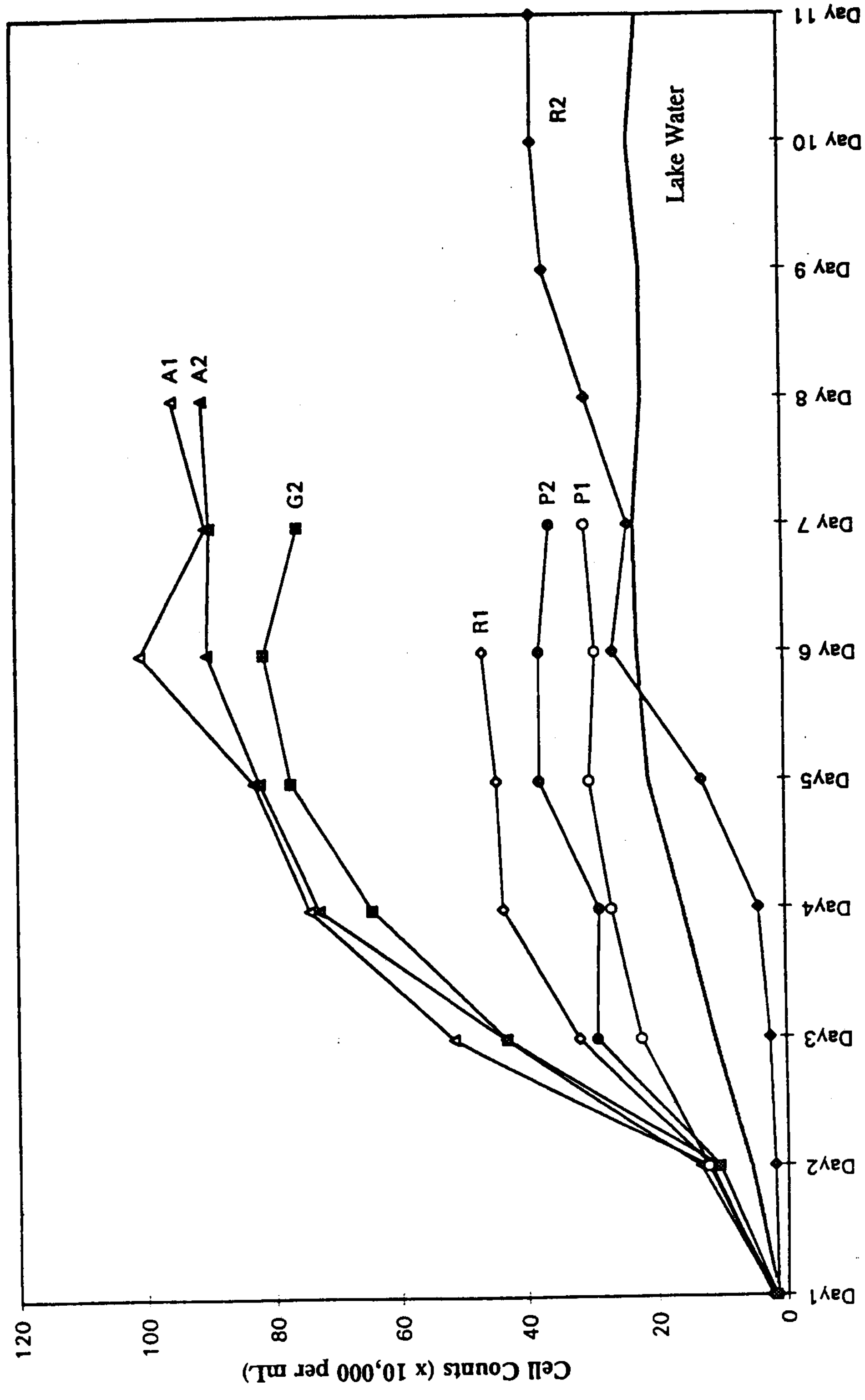

Figure 2.13 Daily Algal Growth Potential Test Results: *Selenastrum capricornutum* exposed to Shoulder Runoff from February 5, 1996, Storm.

Results of the 7-day *Lemna minor* growth potential tests for both the February 5th and April 1st storms revealed that the plants increased in number of fronds and weight approximately equally well in all treatments. Table 2.30 summarizes these results for both storms. In several cases, for both storms the within treatment differences were greater than the between treatment differences, which precluded the possibility of making conclusions about the different effects associated with the shoulder types.

Table 2.30 Results of the 7-Day *Lemna minor* Growth Potential Tests on the February 5 and April 1, 1996, Storms

February 5, 1996, Storm

	R 1	R 2	A1	A2	G1	G2	P1	P2
# of Fronds	65	67	68	77	NA	72	65	64
Dry Weight (mg)	14.0	12.4	12.8	15.5	NA	14.1	14.1	13.6

NA = Not Available

April 1, 1996, Storm

	R 1	R 2	A1	A2	G1	G2	P1	P2
# of Fronds	70	80	68	71	70	72	60	62
Dry Weight (mg)	13.1	14.7	11.6	13.7	14.0	14.0	11.9	11.3

Reasons for Toxic and Biostimulatory Effect

The predominant toxic and biostimulatory effects occurred during the February 5th storm. The total suspended solids and pollutant concentrations were most highly elevated in the runoff from all of the test sections during this storm than in the other wet season storms, apparently because of road sanding operations. Furthermore, the solids and pollutant concentrations in the runoff from the Road 2 test section were considerably higher than those of the other sites during the February 5th storm. The total suspended solids concentration in the Road 2 runoff was only 4 percent higher than the concentration in the Road 1 runoff, but it was 235 percent higher than the average concentrations from the other test sections. Similarly, on average the metals (particularly lead, zinc, copper, and cadmium) concentrations in the Road 2 runoff were 27 percent higher than the Road 1 concentrations, but were nearly 210 percent higher than the average concentrations from the other sites. Although direct effects can not be identified, it is possible that the metals produced a toxic inhibitory effect in the Road 2 runoff, as seen in the 96-hour *Selenastrum capriocornutum* chronic toxicity test (Table 2.27) and the Algal Growth Potential tests on *Selenastrum capricornutum* (Table 2.29 and Figure 2.13).

Table 2.31 compares metals concentrations in the runoff from the February 5th storm with freshwater acute and chronic water quality criteria. The metals concentrations in the runoff from Road 2, as well as the other sites, exceeded the water quality criteria. However, the Road 2 runoff concentrations were typically an order of magnitude higher than the other sites. Given these conditions, toxic inhibition due to high metals concentrations is conceivable.

Table 2.31 Comparison of February 5, 1996, Metal Concentrations to Water Quality Criteria

	February 5 EMCs from Road 2	February 5 EMCs from Other Sites[b]	Freshwater Acute[a]	Freshwater Chronic[a]
Lead	0.29	0.0886	0.0105	0.00041
Copper	0.0903	0.0334	0.0039	0.003
Zinc	0.641	0.2202	0.0300	0.027
Cadmium	0.0035	0.001	0.0006	0.00032

All concentrations are in mg/L.
[a] WDOE/EPA Standards at hardness = 20 mg/L; as cited in Washington Department of Ecology (1992).
[b] "Other sites" include Asphalt 1, Asphalt 2, Gravel 2, Porous 1, and Porous 2.

Contaminants such as poly-nuclear aromatic hydrocarbons were not measured. Therefore, the possibility of toxic inhibition due to the presence of toxicants such as these can not be considered. The concentrations of the petroleum fractions during the February 5th storm were within the range consistent with the wet season storms. Though diesel range was not analyzed for this storm, the O&G and HOR concentrations from the Road 2 site were <u>lower</u> than the concentrations from the Road 1 site, and in fact the Road 2 O&G concentration was lower than all of the other sites. Therefore, it does not appear that petroleum fractions were inhibitory.

Total phosphorus concentrations in the runoff from the test sections ranged from 1.05 to 2.88 mg/L during the February 5th storm. All samples supported higher algal growth during this storm than did the lake water controls. Mean summer TP concentrations greater than 0.025 mg/L were attributed to eutrophic lake conditions (Welch 1992), typically characterized by blooms of phytoplankton. Given this trophic state threshold, it is not unexpected that the TP concentrations in the runoff from the February 5th storm yielded increased algal growth. The total phosphorus concentrations in the runoff during the April 1st storm were between 0.007 and 0.51 mg/L. Although some of these concentrations were above the eutrophic threshold, increased growth was not observed for the April 1st storm. The reason for this is not clear, although there may have been a balance of stimulation and inhibition.

ROADSIDE DITCH SURVEY RESULTS

A total of 48 roadside ditches were surveyed. As described in the previous chapter, attempts were made to randomly pick ditches to survey. The primary criterion used to "randomly" pick sites was ease and safety of accessing the ditches. In conducting the survey it became apparent that there are generally two distinct classifications of gravel shoulders: those that are greater than 4 feet wide and those that are less than 3 feet wide. Therefore, comparisons were made between roadside ditches adjacent to these two gravel shoulder classifications and those adjacent to paved shoulders of any width greater than 3 feet. Of the 48 total ditches surveyed, 13 were adjacent to gravel shoulders wider than 4 feet, 20 were adjacent to gravel shoulders narrower than 3 feet, and 15 were adjacent to paved shoulders wider than 3 feet.

The results were expressed as the relative frequency of cover in the different Braun-Blanquet cover classifications for each type of shoulder. For each given shoulder type, the relative frequencies added up to 1.0. The amount of vegetative cover was expressed in three ways: the percentage of cover on the entire surface area of the roadside ditch, and the percentage of cover on the roadside and on the bottoms of the ditches. In addition, the vegetative composition was expressed in terms of the relative frequency of grasses and herbs versus "other" vegetation in the Braun-Blanquet cover classifications for each shoulder type. In this case, the sum of the relative frequencies for both vegetation classification (grasses and herbs versus "other") equaled 1.0 for each shoulder type.

Vegetative Cover

The vegetative cover results from the three types of shoulders are presented in Figures 2.14, 2.15, and 2.16. Both types of gravel shoulders (> 4 ft and <3 ft) had a fairly uniform distribution of cover among the various percentage cover classifications (Figure 2.14). That is, of all the gravel shoulders surveyed, approximately 20 to 30 percent had vegetative cover corresponding to each of the following classifications: 6-25 percent, 26-50 percent, 51-75 percent, and 76-100 percent. On the other hand, 60 percent of the paved shoulders had 76-100 percent vegetative cover in the ditches (Figure 2.14).

The percentage of vegetative cover is also expressed for the roadside and bottoms of the ditches independently (Figures 2.15 and 2.16). The roadside and bottoms of ditches have the most contact with road runoff, and therefore the amount of cover on these parts of ditches provides some indication of the degree of biofiltration that may be occurring in the ditch. Figures 2.15 and 2.16 show that the percentage of vegetative cover on the roadside and bottoms of ditches is similar for the different shoulder types. On the basis of the ditches surveyed, it appears that shoulder type is not the predominant factor affecting percentage of vegetative cover in roadside ditches.

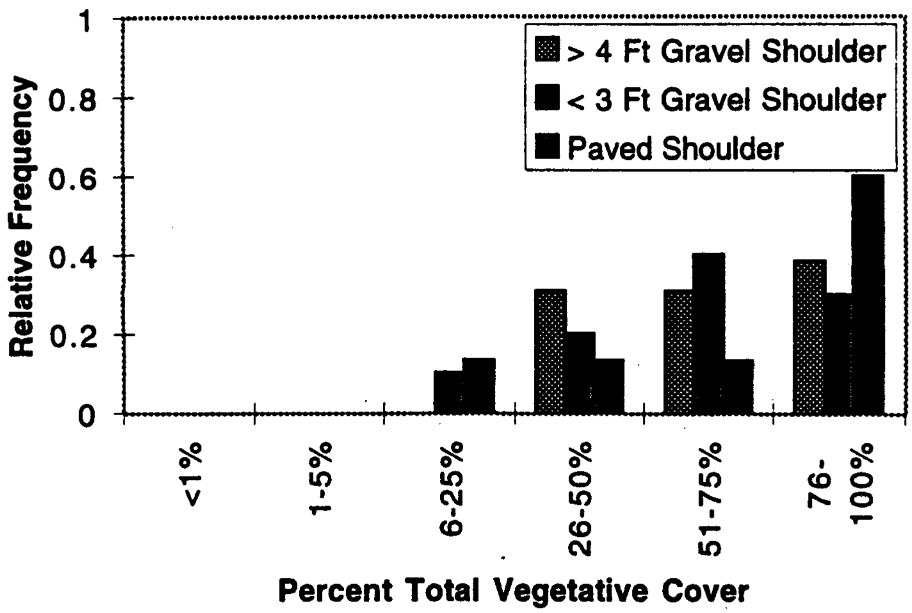

Figure 2.14 Comparison of Total Vegetative Cover in Roadside Ditches Adjacent to Different Roadside Shoulders

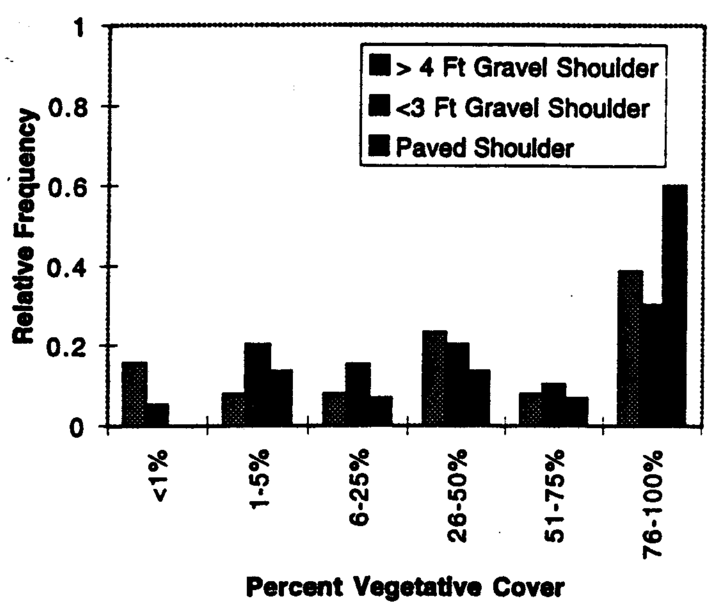

Figure 2.15 Vegetative Cover on the RoadSide of Ditches

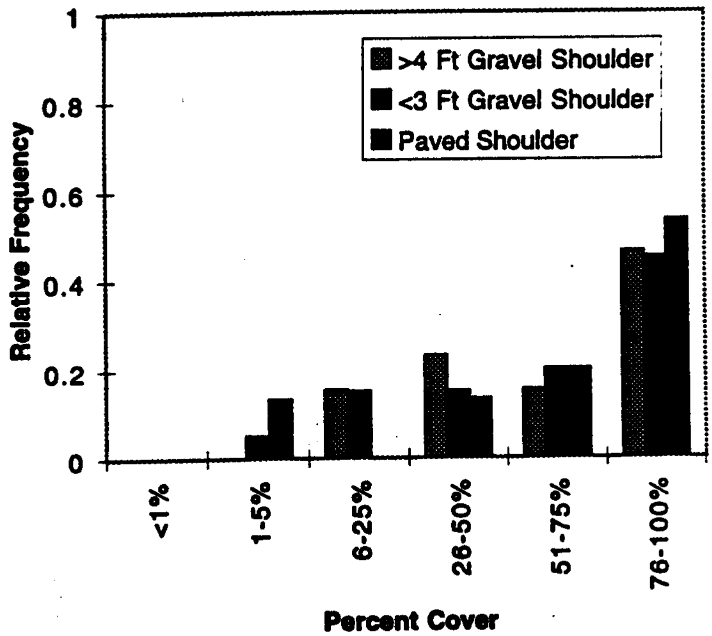

Figure 2.16 Vegetative Cover on the Bottoms of Roadside Ditches

Vegetative Composition

The vegetative composition results are presented in Figures 2.17, 2.18, and 2.19. In ditches adjacent to both types of gravel shoulders (>4 ft and <3 ft) approximately 70 percent of the vegetation comprised grasses and herbs, and approximately 30 percent comprised "other" vegetation (Figures 2.17 and 2.18). More grasses and herbs occurred in the 76-100 percent cover classification than other types of vegetation in ditches adjacent to gravel shoulders wider than 4 feet. In ditches adjacent to gravel shoulders narrower than 3 feet, grasses and herbs predominated in the 26-50 percent, 51-75 percent, and 76-100 percent cover classifications.

In ditches adjacent to paved shoulders vegetative composition comprised grasses and herbs and "other" vegetation equally (Figure 2.19). However, in ditches adjacent to paved shoulders grasses and herbs predominated in the 76-100 percent vegetative cover classification.

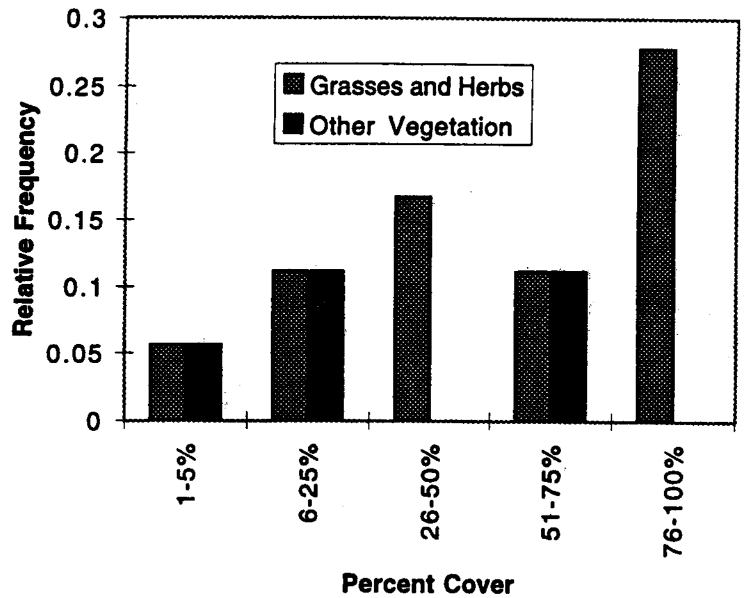

Figure 2.17 Percentage of Cover of Grasses and Herbs versus Other Vegetation in Ditches Adjacent to Gravel Shoulders Wider Than Four Feet

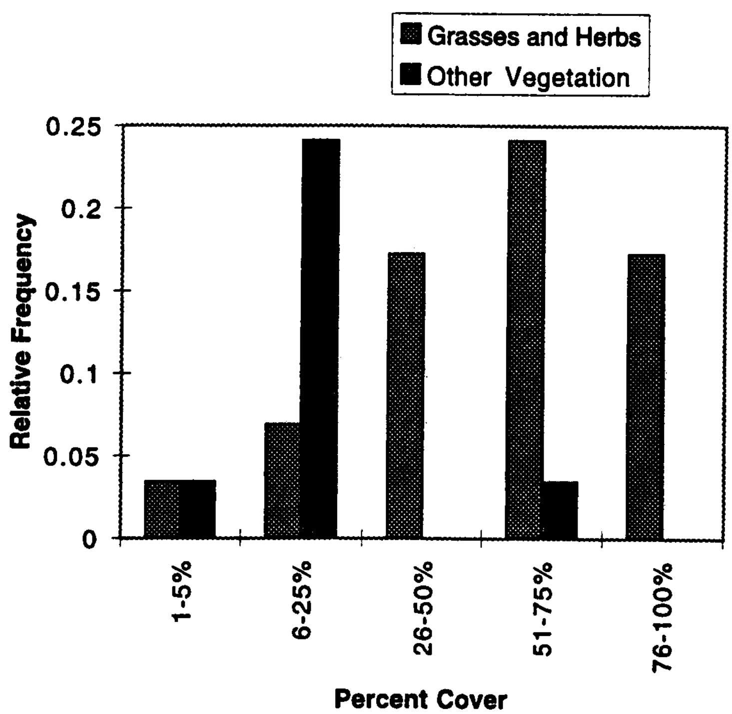

Figure 2.18 Percentage of Cover of Grasses and Herbs versus Other Vegetation in Ditches Adjacent to Gravel Shoulders Narrower Than Three Feet

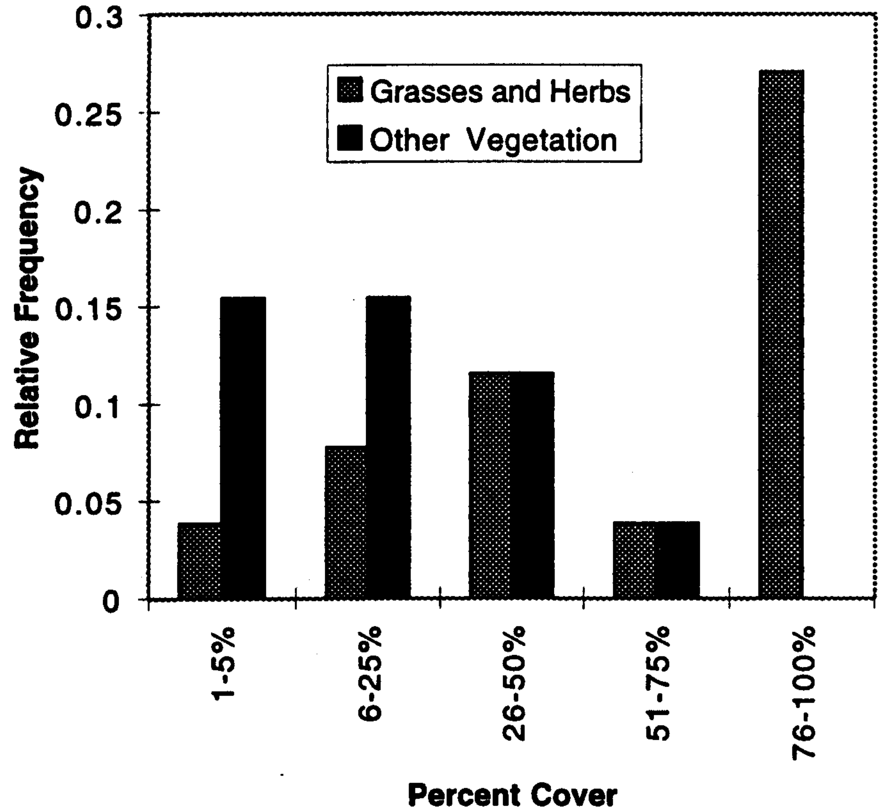

Figure 2.19 Percentage of Cover of Grasses and Herbs versus Other Vegetation in Ditches Adjacent to Paved Shoulders

Summary and Conclusions

There was considerable variation in the survey results. Although ditches adjacent to paved shoulders appeared to have higher total percentages of vegetative cover (Figure 2.14), the vegetative composition in these ditches was mixed. he survey results indicated no trends, suggesting that shoulder type does not definitively affect vegetative cover and composition in roadside ditches.

The only variable examined in this survey was the type of roadside shoulder. Clearly other variables influence the amount and types of vegetation existing in roadside ditches. For instance, aspect and surrounding vegetation affect the amount of sunlight reaching the ditch, which in turn affects moisture availability. Slope affects drainage patterns, which also affect moisture availability. In addition, slope affects erosion tendency in ditches, which can greatly change the amount of vegetative cover. Finally, the types of surrounding vegetation can act as a seed bank, affecting the vegetative composition in the ditches. Considerations of variables such as these was beyond the scope of this survey.

HIGHWAY POLLUTANT REMOVAL

Transport Pathways

To explore the mechanisms by which solids and pollutants may be removed by the shoulder treatments, a discussion of the general pathways by which pollutants are transported from highways is necessary. Pollutants are deposited on highways from vehicular traffic, road maintenance operations, atmospheric fallout, and runoff from surrounding land uses. After of solids and pollutants have been deposited on highways, the pathways by which they are transported depend on both highway and weather conditions.

Washington state highway runoff monitoring studies have concluded that pollutant loadings in highway runoff are related to traffic volumes during the storm (Asplund 1980, and Little, Horner, and Mar 1983). Chui (1981) confirmed that, in addition to depositing pollutants due to operation and frictional wear, vehicles actually "acquire" pollutants that are later deposited. The present study did not monitor vehicular traffic, but these relationships are interesting to consider.

Dry Period Transport Pathways

Whereas pollutants on highways may be transported by vehicles, weather conditions largely determine the removal pathways. During dry periods the primary mechanisms that affect pollutant transport from highways are prevailing winds, traffic-generated vortex winds, and mechanical scrubbing by tires (Asplund 1980). Studies have shown that during dry periods nearly 90 percent of the pollutants that are originally deposited on driving lanes are reentrained and blown onto the sides of highways (Asplund 1980).

In this study the presence of elevated pollutant concentrations in the runoff from all of the shoulder treatments during the summer storm supports these conclusions. Runoff concentrations from the shoulder treatments were typically two to four times higher during the summer event that concentrations during the wet season. Furthermore, the runoff concentrations from the road sections during the summer storm were generally lower than the concentrations during the wet season.

Wet Period Transport Pathways

Stormwater runoff is the primary removal pathway during wet periods. Pollutants become entrained in highway runoff through scrubbing action by rainfall or by mechanical scrubbing of vehicle tires during the storm. The intensity and duration of storms is known to affect the removal of pollutants from highways. According the Asplund (1980), a rainfall event of 1.0 inch or greater with a peak intensity of 0.5 inches/hour that lasts at least one hour is required before 90 percent of the pollutants on highways are removed. The predominant storms in the Pacific Northwest are of low intensity and long duration. A storm of the size and intensity required to remove 90 percent of highway pollutants has a return period of between 1 and 20 years, indicating that transport mechanisms other than storm intensity and size are significant.

Review of road runoff concentrations during wet season storms indicated that storm size may affect runoff concentrations. Runoff concentrations from "large" storms, characterized by generating at least 1.5 inches of rain with instantaneous maximum intensities of 0.5 inches/hour, were compared with runoff concentrations from "small" storms that generate less than 0.5 inches of rain. Though certainly not statistically significant, the road runoff concentrations of total suspended solids, total phosphorus, and lead and zinc were slightly higher in the "large" storm runoff. These results are not conclusive but support the trends identified in other studies (Bryant 1995).

Pollutant Removal Mechanisms by Shoulder Treatments

Generally speaking, pollutants can be removed from stormwater via physical, chemical, and/or biological means (Urban Water Resources Research Council of ASCE 1992). The principle physical mechanisms by which pollutants are removed are sedimentation/settling and filtration. Chemical mechanisms include precipitation, adsorption, and ion exchange. Chemical precipitation involves the formation of a precipitate from two chemical species existing in solution, and the subsequent settling of this precipitate. Adsorption involves the attraction of certain compounds to solid surfaces and removal via settling. Ion exchange involves the transfer of cations in solution to bonding sites on soil particles. Finally, biological pollutant removal mechanisms involve the reduction of organic substances by microbes and nutrient assimilation by microbes and plants.

The pollutant removal mechanisms of greatest importance in infiltration systems are settling, filtration, adsorption, ion exchange, and biological microbial decomposition. The removal of pollutants by the gravel and porous asphalt shoulder treatments is associated with these infiltration mechanisms.

Settling/Sedimentation

Settling is perhaps the most significant pollutant removal mechanism in all wastewater treatment systems. The degree of removal by settling is dependent on whether a given pollutant is in a particulate or soluble form. Pollutant removal from stormwater is typically higher for particulate forms of pollutants (Schueler 1987). Pollutants affected by sedimentation include suspended solids, BOD, particulate COD, and particulate forms of metals (Horner et al. 1994). Settling of pollutants is promoted by low turbulence and a long residence time for the runoff in the treatment system (Horner et al. 1994).

The removal of particulate pollutants and solids from highway runoff can be characterized by sediment transport processes. Factors such as runoff volume, rate of flow, and duration of the runoff event affect the "opportunity" for settling to occur. In addition, the length of the runoff path affects settling. Longer runoff paths result in decrease runoff velocity, causing solids to settle. Road shoulders extend the runoff path and therefore facilitate settling. In addition, existing deposited solids on the roadway or shoulder will impede the flow of runoff and facilitate settling.

The fact that typical runoff concentrations from all the shoulder treatments, including the conventional asphalt shoulder, were lower than runoff concentrations from the road can be explained in part by settling. The conventional asphalt shoulder was identical in physical characteristics to the road itself. Therefore, removal of pollutants from the conventional asphalt shoulders was likely due in part to settling as runoff flowed over the shoulder.

Filtration and Soil Incorporation

The same pollutants that are affected by settling are affected by filtration. In this discussion filtration includes incorporation of pollutants in soils. Soil incorporation can affect all pollutants and is enhanced by the presence of medium-fine textured soils (Horner et al. 1994). Fine-grained particles present in runoff can become trapped in the void spaces between soil particles as they percolate through the soil. However, physical filtration is not limited to simple straining but may involve adhesion and surface electrostatic attraction (Horner and Horner 1995).

The soil underlying the gravel and porous asphalt shoulders consisted of roughly 60 percent sand, 30 percent gravel, and less than 10 percent fines. These soil conditions are preferred for purposes of runoff infiltration and percolation, but they are not as beneficial for pollutant removal by soil incorporation. However, removal of solids and particulate pollutants as runoff infiltrated the gravel and porous asphalt shoulders was likely. The porous asphalt itself had a void volume of about 15 percent, indicating that particulates could be trapped within the asphalt.

Adsorption and Ion Exchange

Dissolved pollutants are affected by adsorption (dissolved phosphorus and dissolved metals) and ion exchange (dissolved metals). These mechanisms are promoted by high soil cation exchange capacity and high soil organic content (Horner et al. 1994). When these mechanisms are operating, soluble forms of pollutants become attached to binding sites on soil particles as they pass through the soil. Most sorption of soluble pollutants occurs within the first foot of soil, and pollutants can be bound for a long time (Schueler 1987).

The cation exchange capacity and the amount of soil organics in the subsoils underlying the gravel and porous asphalt shoulders was not known. However, removal of soluble pollutants via adsorption and ion exchange was possible at these sites.

Correlations Between Specific Pollutants and Removal Mechanisms

Reductions in pollutant concentrations in the runoff from the shoulder treatments can generally be attributed to particular removal mechanisms. While it is not possible to conclude specifically which mechanisms acted to remove which pollutants, trends in the data indicated that certain mechanisms were at work.

Association Between Solids and Pollutants

Most pollutants in highway runoff are characteristically associated with solids found on the highway (Asplund 1980, Hamilton et al. 1984, Colandini et al. 1995). Results of Washington state highway runoff monitoring studies found a high correlation between total suspended solids and pollutant concentrations in highway runoff, with r^2 values typically between 0.7 and 0.95 (Little 1982). Results of soluble fraction studies have shown that a major fraction of runoff loads of metals, nutrients, and COD are associated with the particulate fraction (Asplund 1980). These results point to an important relationship: as total suspended solids are removed from runoff, pollutant loads are decreased. Further, because a majority of pollutants are associated with the particulate fraction, removal of TSS will lead to low specific pollutant loads.

Scatter plots of various pollutants versus TSS concentrations in the runoff from all of the test sections during all of the storms monitored during this study revealed a high correlation between some pollutants and solids, whereas the correlation was quite low for other pollutants. A linear regression of these plots produced r^2 values, as shown in Table 2.32. Regressions with the y-intercept forced to zero were conducted on correlations for which it was assumed that the line passed through the origin. This coincided with those pollutants that were highly correlated with TSS. For other pollutants, regressions were done without the y-intercept forced to zero.

The close association between some pollutants (TP, Pb, Cu, Zn, and to a lesser extent COD) and solids indicated that the concentrations of these pollutants in the runoff were due in part to the solids concentrations. Adsorption of pollutants to solids is the mechanism that best describes this association. Further, this association indicated that the major fraction of metals, total phosphorus, and chemical oxygen demand were in the particulate form.

Table 2.32 Correlation Between Total Suspended Solids and Various Pollutants

R^2 values of linear regression lines from scatter plots of pollutants versus TSS are shown.

Parameter	R^2 Value
Turbidity	0.785[a]
Total Phosphorus	0.831[a]
Ortho-Phosphorus	0.056
Chemical Oxygen Demand	0.588[a]
Biochemical Oxygen Demand	0.074
Lead	0.953[a]
Copper	0.809[a]
Zinc	0.889[a]
Oil and Grease	0.003

[a] These r^2 values are from linear regression lines with the y-intercept forced to zero.

Studies that have analyzed dirt and dust deposited on highways reveal that these solids can represent an important source of toxic metals (Hamilton et al. 1984, Harrison et al. 1981, and Colandini et al. 1995). Researchers in France have characterized the solids deposited in porous pavement installations (Colandini et al. 1995). The predominant fractions of the solids deposited in the pores of the porous asphalt are fines (20-200 μm) and coarse sands (200-2000 μm), which represent 33 and 49 percent of the sample mass, respectively. Clays account for less than 2 percent, but the silt content (2-20 μm) accounts for 4 to 17 percent. These researchers found that heavy metals are associated with all particle size fractions, but heavy metals are primarily associated with fine fractions. Whereas the fine fractions (<40 μm) account for approximately 25 percent of the particles, between 40 to 50 percent of the metals by weight are associated with these particle sizes.

These results are important in several respects. During runoff events the finer particles are more efficiently transported by flowing water. Therefore, when solids are present, metals will be adsorbed, and the finer particles will be transported by the runoff. Road shoulders that have the capacity to trap these particles will yield lower pollutant loads. These relationships likely explain the large reductions of metal loads from the porous asphalt shoulders and indicate that settling, filtration, and soil incorporation were probably the dominant removal mechanisms at work.

Removal of Soluble Pollutants

The exceptionally low r^2 values for the correlation between ortho-phosphorus, biochemical oxygen demand, and oil and grease to TSS (Table 2.32) can be explained, at least in part, by the large soluble fraction of these pollutants. Removal rates of pollutants known to exist largely in the soluble fractions were lower during this study than the rates associated with particulates. For instance, during the wet season the porous asphalt shoulders reduced the total phosphorus concentrations by nearly 60 percent while only reducing the ortho-phosphorus concentrations by 30 percent. Similarly, the concentrations of zinc in the runoff from the porous asphalt and gravel shoulders were not significantly different from the concentrations in the conventional asphalt runoff. In urban stormwater, as much as 70 percent of zinc can exist in the dissolved form (Schueler 1987). By contrast, lead is known to be closely affiliated with suspended sediments, and lead concentrations in the porous asphalt runoff were nearly 80 percent lower than those concentrations in the conventional asphalt runoff. These statistics further indicate the importance of settling and filtration in removing pollutants from the road shoulder runoff. However, the fact that ortho-phosphorus loads were reduced by as much as 90 percent during the wet season indicates that mechanisms such as adsorption and soil incorporation were also involved.

Pollutants such as oil and grease and biochemical oxygen demand can be adsorbed to plastic materials. It is possible that these pollutants were removed from the runoff in the stormwater conveyance and collection system, which was plastic. However, all of the shoulder treatments had the same conveyance system. Therefore, the relative reductions of these pollutants can be attributed to the different shoulder treatments, but the absolute reductions may be influenced in part by pollutant removal in the conveyance system.

IMPLICATIONS OF RESULTS FOR FIRST FLUSH CAPTURE BY POROUS ASPHALT SHOULDER

Pollutant concentrations in runoff vary during the course of a storm event (Horner *et al.* 1995). Typically, pollutant concentrations in runoff are highest at the onset of the storm and decrease as the storm proceeds. This phenomenon is called the "first flush," and may be more or less pronounced depending on storm intensity.

The results of the rain simulation/overland flow experiments indicated that porous asphalt shoulders have the capacity to store runoff in the voids of the pavement. Theory predicts, and the results of the experiments indicated, that when this storage capacity is filled surface runoff will occur. The implication of this is that the porous asphalt shoulders appear to capture the first flush of runoff during a storm. If the porous asphalt shoulders do capture the first flush, which contain the highest pollutant concentrations during the storm event, then they are serving an important water quality function. The relative load reduction served by capturing the first flush is large.

COMPARISON OF POLLUTANT REMOVAL RATES TO PREVIOUS STUDIES

The pollutant removal rates from the porous asphalt shoulders during the wet season were typically between 90 and 95 percent in comparison to the pollutant loads from the conventional asphalt shoulders. The removal rates from the gravel shoulders were typically 20 to 50 percent in comparison to the conventional asphalt loads. Two important factors produced these loading reductions: pollutant removal mechanisms and reductions in the total volume of runoff. The efficiency of the porous asphalt in removing pollutants from the runoff was compounded by the ability of the porous asphalt to reduce runoff volumes. The gravel shoulders, on the other hand, seemed to be less efficient at removing pollutants and did not reduce runoff volumes as much as the porous asphalt. The removal rates associated with the porous asphalt were impressive and were compared to removal rates found in previous studies.

Schueler (1987) estimated the long-term pollutant removal rates of infiltration basins designed to store and infiltrate the 2-year frequency runoff volume. The author estimated removal rates of total suspended solids of 99 percent, total phosphorus removal rates of between 65 and 75 percent, metals removal of between 95 and 99 percent, and biochemical oxygen demand removal rates of 90 percent. For the most part this study's removal rates for the porous asphalt shoulder during the wet season were close to those rates for all parameters except BOD.

Schueler also estimated the projected long-term removal rates for constructed wetlands (cited in Horner et al. 1994). Projected removal rates of total suspended solids by constructed wetlands were 75 percent; total phosphorus was 45 percent; BOD and COD were 15 percent; lead was 75 percent; and zinc was 50 percent. The removal rates of the current porous asphalt during the first year of operation exceeded all of these rates.

Few studies have monitored the pollutant removal capabilities of porous pavement installations and none have done so on road shoulders. Schueler (1987) reported on the performance of two "partial exfiltration" porous asphalt systems. Partial exfiltration systems consist of a porous asphalt surface course on top of a filter course and stone reservoir. These systems are designed for runoff volume storage and pollutant removal and involve a collection system to drain surface runoff that cannot be infiltrated. The author reported removal rates of sediment approaching 95 percent, total phosphorus removal rates of 65 percent, COD removal of 82 percent, and lead and zinc removal rates of 98 and 99 percent.

Researchers in France monitored the pollutant removal capabilities of porous asphalt surfacing on roadways (Balades et al. 1995). Measurements over a three-year period demonstrated reductions of COD by 89 percent, TSS by 50 percent, and lead by 93 percent. These authors concluded that permeable surfacing of roadways could reduce pollutants by 50 to 60 percent. The performance of the porous asphalt shoulders during the first year of monitoring in this study equaled or exceeded the removal rates of other systems presented above.

CLOGGING OF POROUS PAVEMENTS

Clogging has been cited as the leading cause of failure of infiltration systems (Schueler et al. 1992, Washington Department of Ecology 1992). Clogging of porous asphalt systems is no exception. In fact, Schueler (1987) specifically cautioned against use of porous pavement systems that are expected to receive particulate pollutants.

Despite the considerable concern regarding porous pavement systems, few studies have actually monitored their long-term performance in relation to clogging. Though many studies have documented initial permeability results at the time of installation, few have evaluated infiltration performance over time.

The results of several studies that examined the performance of porous pavement systems are discussed below. These studies were conducted under a variety of conditions.

A brief description of the application is described, but the specifics of the systems are not provided. A study of porous pavement systems in parking lots and other low-traffic applications in Austin, Texas (Goforth et al. 1983), reported an average initial in-situ infiltration rate of 4486 cm/hr (1766 in/hr), strikingly similar to the infiltration rate determined for the porous asphalt shoulders in this study of 4445 cm/hr (1750 in/hr). However, no infiltration rates were reported after several years of use.

In 1986, the Arizona Department of Transportation constructed a 1067-m (3500-ft) long porous pavement experimental test section located on Arizona State Route 87 (Hossain and Scofield 1991). After construction, the porous pavement test section had an infiltration rate (reported as a coefficient of permeability) of 254 cm/hr (100 in/hr). After four years of service the test section had an average infiltration rate of 102 cm/hr (40 in/hr), representing a 60 percent decrease in infiltration capacity.

Since 1982, the Institute of Transportation, Traffic, Highway and Railway Engineering of the Swiss Federal Institute of Technology in Zurich has monitored the performance of 17 porous asphalt test sections located on motorways, interurban, and urban roads (Isenring et al. 1991). On average, the infiltration rates following construction were approximately 851 cm/hr (335 in/hr). After four years of operation the infiltration rates had decreased to 533 cm/hr (210 in/hr), a 63 percent decrease.

Researchers at Nottingham Trent University in the United Kingdom observed the performance of a concrete block-surface permeable pavement in a parking lot (Pratt et al. 1995). No initial infiltration rates were reported. However, after nine years of operation the infiltration rate was 100 cm/hr (39.4 in/hr), despite the pavement having received no maintenance during that period.

Researchers in France evaluated the performance of permeable pavement surfacings on 27 sites, including roadways, in residential and industrial areas and car parks (Balades et al. 1995). The average initial infiltration rates were 4681 cm/hr (1843 in/hr) following installation. After four years of operation, the average infiltration rate was 2159 cm/hr (850 in/hr). The authors reported that on roads with heavy traffic, clogging developed rapidly during the first year, with decreasing infiltration rates between 60 and 90 percent in heavily polluted areas. At these sites the infiltration rates seemed to stabilize after the first year, however.

These studies evaluated a variety of porous pavement systems used for a variety of applications. The large difference in initial infiltration rates is due to these differences. Therefore, direct comparisons can not be made, but general trends can be identified. Regardless of the specific initial infiltration rates, after four years of use all of the systems had experienced reductions of approximately 50 to 60 percent in infiltration rates. Despite the reductions, all of these systems had fairly remarkable post-use infiltration rates, ranging from 102 to 2160 cm/hr (40 to 850 in/hr).

In the present study the porous asphalt shoulders had average infiltration rates of 4445 cm/hr (1750 in/hr) after the first year of use. During this year of operation a total load of approximately 4.2 ft^3 of sand was applied per 50-lane-feet of roadway (the length of each test section) during routine sanding operations. No signs of clogging were observed throughout the monitoring period. Further study will be necessary to determine the potential for the porous asphalt shoulders to clog and to monitor the water quality effects clogging may incur.

CHAPTER THREE: CONCLUSIONS

From the analysis of the data, and observations of trends and their implications, the following has been concluded:

1. Porous asphalt shoulders have a greater potential to reduce runoff volumes than gravel and conventional asphalt shoulders. Results from rain simulation/ overland flow experiments indicated that during typical wet season storms (0.76 cm [0.3 in]), the porous asphalt shoulder test sections can reduce runoff volumes by approximately 85 percent in comparison to the runoff volumes from the conventional asphalt test sections. The gravel test sections can reduce runoff volumes by nearly 30 percent in comparison to the conventional asphalt shoulders during wet season storms. During "larger" storms (>1.27 cm [0.5 in]), the porous asphalt shoulders can reduce runoff volumes by nearly 60 percent, whereas gravel shoulders reduce volumes by only 10 percent.

2. Given the operational characteristics of porous asphalt, it seems that the porous asphalt shoulders have a greater potential to reduce peak runoff discharge rates than gravel and conventional asphalt shoulders. Porous asphalt acts as a storage reservoir, containing runoff volumes within the void spaces in the asphalt. Consequently, there is a lag in the discharge of runoff from the porous asphalt shoulders, which likely reduces peak discharge rates in drainage catchments. Discharge rates were not measured during this study; therefore, this conclusion is based on theory rather than observation.

3. During the wet season the runoff from all three of the shoulder treatments, conventional asphalt, gravel, and porous asphalt, had lower average concentrations of solids and pollutants (BOD and COD, TP and OP, metals, and petroleum fractions) than the runoff directly from the road.

4. The porous asphalt shoulders demonstrated a greater ability to reduce solids and pollutant concentrations than the gravel and conventional asphalt shoulders. On average, the pollutant concentrations in the runoff from the porous asphalt shoulders during the wet

season were 30 to 60 percent lower than the concentrations from the conventional asphalt shoulders. By contrast, the average wet season concentrations of total suspended solids and total ortho-phosphorus from the gravel shoulders were higher than the concentrations from the conventional asphalt shoulders.

During storms that follow the application of sand to roads, porous asphalt shoulders seem to be more efficient at reducing solids and pollutant concentrations than gravel and conventional asphalt shoulders. Data from a single storm following sanding operations showed that concentrations of solids and pollutants in the porous asphalt shoulder runoff were, on average, 40 to 50 percent lower than the concentrations from the conventional asphalt shoulder. During this storm the runoff concentrations from the gravel shoulders were, on average, 25 to 50 percent lower than the conventional asphalt runoff concentrations, though ortho-phosphorus was 30 percent higher.

5. The ability of the porous asphalt shoulders to reduced pollutant loads far exceeded that of the gravel and conventional asphalt shoulders. During typical wet season storms the solids and pollutant loads from the porous asphalt shoulders were more than 90 percent lower than the loads from the conventional asphalt shoulders. The gravel shoulders yielded load reductions ranging from 10 to 70 percent lower than the conventional asphalt, though ortho-phosphorus loads exceeded those from the conventional asphalt shoulder by nearly 30 percent.

The loads from the porous asphalt shoulders during the storm that followed road sanding operations were typically 75 percent lower than the loads from the conventional asphalt shoulder. During this storm the loads from the gravel shoulders were on average 50 percent lower than the conventional asphalt loads, though the ortho-phosphorus loads again were higher.

The load reduction trends observed during the wet season also occurred during the summer storm event. The porous asphalt shoulders yielded 40 to 80 percent load reductions in comparison to the performance of the conventional asphalt shoulders during the summer storm. The gravel shoulders had load reductions ranging from 15 to 50 percent for some pollutants, but had TSS and TP loads that exceeded those of the conventional asphalt shoulders.

6. The pollutant removal rates of the porous asphalt shoulders equaled or exceeded the removal rates reported in other studies on porous pavement installations (Schueler 1987), infiltration basins (Schueler 1987), and constructed wetlands (Horner et al. 1994).

7. Removal rates were highest for those pollutants that are correlated with total suspended solids ($0.70<r^2<0.95$), indicating that physical mechanisms of settling and filtration were critical in removing pollutants from the runoff of both the porous asphalt and gravel shoulders. This association between solids and many pollutants suggests that as total suspended solids are removed from runoff, pollutant loads will be decreased.

8. The porous asphalt shoulders were more efficient at removing soluble pollutants, particularly ortho-phosphorus, than the conventional asphalt and gravel shoulders.

9. The removal of both particulate and soluble pollutants by the porous asphalt shoulder can be attributed to infiltration of runoff in the soils beneath the porous asphalt. Physical and chemical mechanisms are known to occur as water infiltrates soil. In addition to the removal mechanisms known to exist through infiltration, it is possible, though not measured during this study, that the porous asphalt directly removed pollutants from the runoff either by filtration or adsorption.

10. After one year of use the porous asphalt shoulders showed no signs of clogging, maintaining infiltration rates of 4445 cm/hr (1750 in/hr).

11. The gravel shoulders, on the other hand, were beginning to erode by the fall of 1996. The proximity of the gravel shoulder test sections to the entrance of Cottage Lake Park may have accelerated the erosion process.

12. Bioassays were conducted to evaluate the toxic or biostimulatory effect of the road shoulder runoff on aquatic organisms. The runoff from the shoulders was not toxic

but was somewhat biostimulatory. However, there was no significant difference between the shoulder treatments with regard to toxic inhibition and biostimulation.

13. Vegetative cover and composition in roadside ditches are not clearly affected by shoulder type. Though roadside ditches adjacent to paved shoulders appeared to have slightly higher total vegetative cover, the vegetative composition was mixed, indicating that any advantages associated with biofiltration may not be realized.

14. Two low-flow sampling devices were designed to consistently provide flow-weighted composite samples for flow rates between 2 to 15 L/min (0.53 to 4 gal/min). At flow rates of less than 2 L/min (0.53 gal/min), however, the samplers performed inconsistently, typically producing elevated sampling coefficients (ratio of the volume of sample collected to the volume applied).

CHAPTER FOUR: RECOMMENDATIONS/IMPLEMENTATION

The conclusions demonstrate that road shoulders do affect the quality and quantity of runoff from highways. However, there are distinct differences in the degree to which the three shoulder treatments reduce runoff volumes and pollutant concentrations. The study results indicated that there is considerable promise in the use of porous asphalt on road shoulders. Porous asphalt shoulders appear to provide both the environmental and road operations benefits desired by environmental and transportation agencies. Several recommendations are suggested to help facilitate the implementation of the study results.

The potential for porous asphalt shoulders to clog should be quantitatively evaluatied. If clogging occurs, the water quality benefits of the material will diminish. Controlled experiments could be conducted to determine the length of time before clogging occurs in porous asphalt shoulders when they are exposed to typical annual sanding and highway runoff conditions. Several considerations should be made before such an experiment is conducted.

1. The particle size distribution of total suspended solids from highways during typical wet season storms and storms following road sanding operations should be evaluated.
2. Before future experiments using the Dura Channel System slot drains are conducted, the plastic channel sections should be sealed restrict the inflow of subsurface flow. In addition, a baffle should be installed to divert subsurface flow beneath the slot drain.
3. Composite flow splitters should only be used at sites that produce adequate runoff volumes necessary to distribute the runoff evenly across the width of the flow splitter channel. A large mesh screen should be installed to prevent the introduction of debris into the flow splitter which may impede the uniform flow of the runoff down the channel.

Assuming that the results of clogging experiments do not suggest that the porous asphalt shoulders will become completely clogged within five years, it is recommended that a program to install porous asphalt shoulders be implemented. The runoff reduction and water quality benefits associated with porous asphalt shoulders are impressive. Even if the pollutant removal capacity of porous asphalt shoulders decreases over time, there are still benefits that exceed those of conventional asphalt and gravel shoulders.

The study results indicated that gravel shoulders are quite inadequate with regard to several important pollutants. *Ortho-phosphorus* is environmentally significant, as it is typically the limiting nutrient that causes algal blooms in receiving waters. The ortho-phosphorus loads from the gravel shoulders were consistently higher than the loads from both the porous and conventional asphalt shoulders. Furthermore, most storms during the wet season yielded *total suspended solids* concentrations that were higher in the runoff from the gravel shoulders than the concentrations for the porous and conventional asphalt shoulders. Given these factors, porous asphalt shoulders are favored over gravel shoulders.

If gravel shoulders are to be used, it is recommended that extractions be conducted on the gravel mix to determine whether the gravel is a source of phosphorus. If something in the gravel mix contains high concentrations of phosphorus, it is possible that this can be excluded from the mix, thereby reducing phosphorus loading from gravel shoulders.

To further test the water quality conditions associated with gravel shoulders, as well as those of porous and conventional asphalt shoulders, it is recommended that water quality tests be run on runoff samples following rain simulation experiments. This analysis may assist in understanding whether the shoulder treatments are contributing to specific pollutant loadings.

Finally, the ortho-phosphorus concentrations from the road during the summer event storm were nearly ten times higher than those concentrations during the wet season. Four days before the summer event storm the Woodinville-Duvall NE Road has been resurfaced with new asphalt. It is recommended that extractions be conducted on the asphalt mix as well to determine whether it is a source of phosphorus.

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APPENDIX A -- Data Sets for Individual Water Quality Parameters and Bioassay Summaries

The non-transformed data for individual water quality parameters are tabulated below. In addition, summaries of the bioassay tests are presented.

Total Suspended Solids Summary -- Concentrations in mg/L								
Date	Site	SS conc	Site	SS conc	Site	SS conc	Site	SS conc
7-Nov	Road 1		Road 2	92.50	Gravel 1	62.50	Gravel 2	
8-Nov	Road 1		Road 2	105.00	Gravel 1	207.00	Gravel 2	
18-Nov	Road 1		Road 2	172.00	Gravel 1	131.00	Gravel 2	130.00
27-Nov	Road 1	14.00	Road 2	53.50	Gravel 1	33.50	Gravel 2	40.50
16-Jan	Road 1	112.00	Road 2	219.00	Gravel 1	65.20	Gravel 2	51.30
21-Jan	Road 1	158.00	Road 2	118.00	Gravel 1	43.20	Gravel 2	37.30
5-Feb	Road 1	944.00	Road 2	980.00	Gravel 1		Gravel 2	229.00
21-Feb	Road 1	105.00	Road 2	129.00	Gravel 1	65.30	Gravel 2	48.00
1-Apr	Road 1	160.00	Road 2	269.00	Gravel 1	47.50	Gravel 2	54.00
16-Apr	Road 1	52.60	Road 2	347.00	Gravel 1	71.40	Gravel 2	53.00
2-Aug	R1	43.70	R2	37.20	G1		G2	112.00
Date	Site	SS conc	Site	SS conc	Site	SS conc	Site	SS conc
7-Nov	Asphalt 1		Asphalt 2	21.80	Porous 1	5.30	Porous 2	
8-Nov	Asphalt 1		Asphalt 2	22.00	Porous 1	5.30	Porous 2	
18-Nov	Asphalt 1	36.00	Asphalt 2	54.70	Porous 1	24.00	Porous 2	22.00
27-Nov	Asphalt 1	8.50	Asphalt 2	18.50	Porous 1	4.20	Porous 2	7.00
16-Jan	Asphalt 1	73.40	Asphalt 2	46.00	Porous 1	10.80	Porous 2	22.00
21-Jan	Asphalt 1	75.10	Asphalt 2	96.00	Porous 1	12.90	Porous 2	19.00
5-Feb	Asphalt 1	370.00	Asphalt 2	444.00	Porous 1	264.00	Porous 2	159.00
21-Feb	Asphalt 1	49.00	Asphalt 2	52.00	Porous 1	13.60	Porous 2	
1-Apr	Asphalt 1	118.00	Asphalt 2	107.00	Porous 1	10.30	Porous 2	24.70
16-Apr	Asphalt 1	124.00	Asphalt 2	124.00	Porous 1	63.00	Porous 2	5.00
2-Aug	A1	108.00	A2	80.00	P1	19.40	P2	125.00

Turbidity Summary -- Nephelometric Turbidity Units								
Date	Site	Turbidity	Site	Turbidity	Site	Turbidity	Site	Turbidity
7-Nov	Road 1		Road 2	26	Gravel 1	44	Gravel 2	
8-Nov	Road 1		Road 2	31	Gravel 1	140	Gravel 2	
18-Nov	Road 1		Road 2	42	Gravel 1	58	Gravel 2	89
27-Nov	Road 1	8.8	Road 2	26	Gravel 1	32	Gravel 2	51
16-Jan	Road 1	24	Road 2	31	Gravel 1	32	Gravel 2	29
21-Jan	Road 1	34	Road 2	29	Gravel 1	27	Gravel 2	27
5-Feb	Road 1	500	Road 2	540	Gravel 1		Gravel 2	190
21-Feb	Road 1	38	Road 2	36	Gravel 1	40	Gravel 2	42
1-Apr	Road 1	36	Road 2	28	Gravel 1	21	Gravel 2	29
16-Apr	Road 1	14	Road 2	31	Gravel 1	23	Gravel 2	21
Date	Site	Turbidity	Site	Turbidity	Site	Turbidity	Site	Turbidity
7-Nov	Asphalt 1		Asphalt 2	16.0	Porous 1	3.7	Porous 2	
8-Nov	Asphalt 1		Asphalt 2	23.0	Porous 1	5.0	Porous 2	
18-Nov	Asphalt 1	19.0	Asphalt 2	26.0	Porous 1	23.0	Porous 2	20.0
27-Nov	Asphalt 1	5.7	Asphalt 2	9.7	Porous 1	5.1	Porous 2	5.2
16-Jan	Asphalt 1	19.0	Asphalt 2	1[illegible].0	Porous 1	9.1	Porous 2	14.0
21-Jan	Asphalt 1	22.0	Asphalt 2	25.0	Porous 1	13.0	Porous 2	12.0
5-Feb	Asphalt 1	300.0	Asphalt 2	380.0	Porous 1	260.0	Porous 2	140.0
21-Feb	Asphalt 1	29.0	Asphalt 2	28.0	Porous 1	18.0	Porous 2	
1-Apr	Asphalt 1	22.0	Asphalt 2	23.0	Porous 1	7.0	Porous 2	14.0
16-Apr	Asphalt 1	20.0	Asphalt 2	21.0	Porous 1	16.0	Porous 2	4.0

Alkalinity Summary -- Concentrations in mg/L								
Date	Site		Site		Site		Site	
7-Nov	Road 1		Road 2		Gravel 1	40.1	Gravel 2	
8-Nov	Road 1		Road 2		Gravel 1		Gravel 2	
18-Nov	Road 1		Road 2	30.2	Gravel 1	21.4	Gravel 2	14.8
27-Nov	Road 1	11.3	Road 2	16.5	Gravel 1	11.6	Gravel 2	11.1
16-Jan	Road 1		Road 2		Gravel 1		Gravel 2	
21-Jan	Road 1		Road 2		Gravel 1		Gravel 2	
5-Feb	Road 1		Road 2		Gravel 1		Gravel 2	
21-Feb	Road 1		Road 2		Gravel 1		Gravel 2	
1-Apr	Road 1		Road 2		Gravel 1		Gravel 2	
16-Apr	Road 1		Road 2		Gravel 1		Gravel 2	
2-Aug	Road 1		Road 2		Gravel 1		Gravel 2	
Date	Site		Site		Site		Site	
7-Nov	Asphalt 1		Asphalt 2		Porous 1	9.3	Porous 2	
8-Nov	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
18-Nov	Asphalt 1	13.9	Asphalt 2	8.8	Porous 1	14.4	Porous 2	10.4
27-Nov	Asphalt 1	8	Asphalt 2	6.4	Porous 1	7.2	Porous 2	6.6
16-Jan	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
21-Jan	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
5-Feb	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
21-Feb	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
1-Apr	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
16-Apr	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
2-Aug	Asphalt 1		Asphalt 2		Porous 1		Porous 2	

Total Phosphorus Summary -- Concentrations in mg/L								
Date	Site	TP conc	Site	TP conc	Site	TP conc	Site	TP conc
7-Nov	Road 1		Road 2	0.315	Gravel 1	0.115	Gravel 2	
8-Nov	Road 1		Road 2	0.337	Gravel 1	0.242	Gravel 2	
18-Nov	Road 1		Road 2	0.464	Gravel 1	0.443	Gravel 2	0.509
27-Nov	Road 1	0.118	Road 2	0.216	Gravel 1	0.129	Gravel 2	0.188
16-Jan	Road 1	0.357	Road 2	0.485	Gravel 1	0.292	Gravel 2	0.262
21-Jan	Road 1	0.472	Road 2	0.381	Gravel 1	0.230	Gravel 2	0.216
5-Feb	Road 1	1.810	Road 2	2.880	Gravel 1		Gravel 2	1.050
21-Feb	Road 1	0.289	Road 2	0.255	Gravel 1	0.288	Gravel 2	0.185
1-Apr	Road 1	0.509	Road 2	0.505	Gravel 1	0.211	Gravel 2	0.241
16-Apr	Road 1	0.142	Road 2	0.524	Gravel 1	0.208	Gravel 2	0.176
2-Aug	R1	0.380	R2	0.435	G1		G2	0.620
Date	Site	TP conc	Site	TP conc	Site	TP conc	Site	TP conc
7-Nov	Asphalt 1		Asphalt 2	0.083	Porous 1	0.030	Porous 2	
8-Nov	Asphalt 1		Asphalt 2	0.073	Porous 1	0.053	Porous 2	
18-Nov	Asphalt 1	0.220	Asphalt 2	0.303	Porous 1	0.230	Porous 2	0.180
27-Nov	Asphalt 1	0.065	Asphalt 2	0.103	Porous 1	0.046	Porous 2	0.047
16-Jan	Asphalt 1	0.273	Asphalt 2	0.221	Porous 1	0.085	Porous 2	0.137
21-Jan	Asphalt 1	0.282	Asphalt 2	0.380	Porous 1	0.081	Porous 2	0.104
5-Feb	Asphalt 1	1.540	Asphalt 2	1.230	Porous 1	1.150	Porous 2	0.348
21-Feb	Asphalt 1	0.216	Asphalt 2	0.188	Porous 1	0.105	Porous 2	
1-Apr	Asphalt 1	0.321	Asphalt 2	0.310	Porous 1	0.074	Porous 2	0.130
16-Apr	Asphalt 1	0.279	Asphalt 2	0.341	Porous 1	0.164	Porous 2	0.050
2-Aug	A1	0.390	A2	0.385	P1	0.295	P2	0.500

Ortho Phosphorus Summary -- Concentrations in mg/L								
Date	Site	OP conc	Site	OP cond	Site	OP conc	Site	OP conc
7-Nov	Road 1		Road 2		Gravel 1		Gravel 2	
8-Nov	Road 1		Road 2	0.027	Gravel 1	0.012	Gravel 2	
18-Nov	Road 1		Road 2		Gravel 1		Gravel 2	
27-Nov	Road 1	0.012	Road 2	0.026	Gravel 1	0.005	Gravel 2	0.017
16-Jan	Road 1	0.002	Road 2	0.002	Gravel 1	0.005	Gravel 2	0.013
21-Jan	Road 1	0.069	Road 2	0.024	Gravel 1	0.021	Gravel 2	0.025
5-Feb	Road 1	0.078	Road 2	0.075	Gravel 1		Gravel 2	0.045
21-Feb	Road 1	0.006	Road 2		Gravel 1	0.016	Gravel 2	0.019
1-Apr	Road 1	0.014	Road 2	0.021	Gravel 1	0.017	Gravel 2	0.024
16-Apr	Road 1	0.012	Road 2	0.014	Gravel 1	0.008	Gravel 2	0.010
2-Aug	R1	0.137	R2	0.186	G1		G2	0.058
Date	Site	OP conc	Site	OP conc	Site	OP conc	Site	OP conc
7-Nov	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
8-Nov	Asphalt 1		Asphalt 2	0.012	Porous 1	0.007	Porous 2	
18-Nov	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
27-Nov	Asphalt 1	0.012	Asphalt 2	0.021	Porous 1	0.010	Porous 2	0.008
16-Jan	Asphalt 1	0.005	Asphalt 2	0.002	Porous 1	0.002	Porous 2	0.004
21-Jan	Asphalt 1	0.006	Asphalt 2	0.005	Porous 1	0.006	Porous 2	0.013
5-Feb	Asphalt 1	0.041	Asphalt 2	0.028	Porous 1	0.015	Porous 2	0.015
21-Feb	Asphalt 1	0.017	Asphalt 2	0.008	Porous 1	0.004	Porous 2	
1-Apr	Asphalt 1	0.007	Asphalt 2	0.006	Porous 1	0.002	Porous 2	0.006
16-Apr	Asphalt 1	0.004	Asphalt 2	0.005	Porous 1	0.004	Porous 2	0.004
2-Aug	A1	0.082	A2	0.095	P1	0.090	P2	0.112

Biochemical Oxygen Demand Summary -- Concentrations in mg/L

Date	Site	BOD conc	Site	BOD conc	Site	BOD conc	Site	BOD conc
7-Nov	Road 1		Road 2	6.400	Gravel 1	4.000	Gravel 2	
8-Nov	Road 1		Road 2	8.600	Gravel 1	13.100	Gravel 2	
18-Nov	Road 1		Road 2	14.400	Gravel 1	13.000	Gravel 2	8.900
27-Nov	Road 1	3.400	Road 2	3.400	Gravel 1	3.000	Gravel 2	
16-Jan	Road 1	4.200	Road 2	2.200	Gravel 1		Gravel 2	2.100
21-Jan	Road 1	2.500	Road 2	2.100	Gravel 1		Gravel 2	
5-Feb	Road 1	24.600	Road 2	19.700	Gravel 1		Gravel 2	7.000
21-Feb	Road 1	9.700	Road 2	5.600	Gravel 1	5.900	Gravel 2	5.500
1-Apr	Road 1	7.300	Road 2	5.100	Gravel 1	6.100	Gravel 2	3.400
16-Apr	Road 1	5.400	Road 2	7.500	Gravel 1	3.600	Gravel 2	4.300
2-Aug	R1	21.800	R2	27.300	G1		G2	22.100

Date	Site	BOD conc	Site	BOD conc	Site	BOD conc	Site	BOD conc
7-Nov	Asphalt 1		Asphalt 2	3.500	Porous 1	3.700	Porous 2	
8-Nov	Asphalt 1		Asphalt 2	4.900	Porous 1		Porous 2	
18-Nov	Asphalt 1	8.600	Asphalt 2	12.500	Porous 1	15.400	Porous 2	11.000
27-Nov	Asphalt 1		Asphalt 2	2.400	Porous 1		Porous 2	
16-Jan	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
21-Jan	Asphalt 1	2.000	Asphalt 2	2.900	Porous 1		Porous 2	
5-Feb	Asphalt 1	10.300	Asphalt 2	10.800	Porous 1	12.800	Porous 2	9.500
21-Feb	Asphalt 1	4.900	Asphalt 2	3.900	Porous 1		Porous 2	
1-Apr	Asphalt 1	5.100	Asphalt 2	7.100	Porous 1	3.500	Porous 2	3.000
16-Apr	Asphalt 1	6.200	Asphalt 2	7.600	Porous 1	3.700	Porous 2	
2-Aug	A1	21.300	A2	22.100	P1	28.300	P2	37.200

COD Summary -- Concentrations in mg/L

Date	Site	COD conc	Site	COD conc	Site	COD conc	Site	COD conc
7-Nov	Road 1		Road 2	35	Gravel 1	12	Gravel 2	
8-Nov	Road 1		Road 2	48	Gravel 1	50	Gravel 2	
18-Nov	Road 1		Road 2	86	Gravel 1	52	Gravel 2	42
27-Nov	Road 1	29	Road 2	24	Gravel 1	20	Gravel 2	10
16-Jan	Road 1	67	Road 2	103	Gravel 1	26	Gravel 2	15
21-Jan	Road 1	69	Road 2	59	Gravel 1	18	Gravel 2	19
5-Feb	Road 1	265	Road 2	235	Gravel 1		Gravel 2	71
21-Feb	Road 1	70	Road 2	78	Gravel 1	35	Gravel 2	41
1-Apr	Road 1	61	Road 2	75	Gravel 1	45	Gravel 2	25
16-Apr	Road 1	39	Road 2	138	Gravel 1	30	Gravel 2	22
2-Aug	R1	98	R2	72	G1		G2	72

Date	Site	COD conc	Site	COD conc	Site	COD conc	Site	COD conc
7-Nov	Asphalt 1		Asphalt 2	10	Porous 1	10	Porous 2	
8-Nov	Asphalt 1		Asphalt 2	32	Porous 1	10	Porous 2	
18-Nov	Asphalt 1	44	Asphalt 2	65	Porous 1	67	Porous 2	48
27-Nov	Asphalt 1	19	Asphalt 2	12	Porous 1	12	Porous 2	12
16-Jan	Asphalt 1	43	Asphalt 2	32	Porous 1	12	Porous 2	17
21-Jan	Asphalt 1	53	Asphalt 2	58	Porous 1	9	Porous 2	9
5-Feb	Asphalt 1	110	Asphalt 2	134	Porous 1	110	Porous 2	77
21-Feb	Asphalt 1	49	Asphalt 2	35	Porous 1	32	Porous 2	
1-Apr	Asphalt 1	68	Asphalt 2	62	Porous 1	30	Porous 2	25
16-Apr	Asphalt 1	68	Asphalt 2	89	Porous 1	30	Porous 2	15
2-Aug	A1	90	A2	52	P1	74	P2	55

Oil and Grease Summary -- Concentrations in mg/L

Date	Site	O&G conc	Site	O&G conc	Site	O&G conc	Site	O&G conc
7-Nov	Road 1		Road 2	7.2	Gravel 1	7.1	Gravel 2	
8-Nov	Road 1		Road 2	13.9	Gravel 1		Gravel 2	
18-Nov	Road 1		Road 2	8.3	Gravel 1	3.8	Gravel 2	18.6
27-Nov	Road 1	6.1	Road 2	2	Gravel 1	6.3	Gravel 2	
16-Jan	Road 1	11.7	Road 2	16.1	Gravel 1	6.9	Gravel 2	11.6
21-Jan	Road 1	36.2	Road 2	35.4	Gravel 1	22.6	Gravel 2	39.9
5-Feb	Road 1	11.3	Road 2	4.7	Gravel 1		Gravel 2	74.5
21-Feb	Road 1	12.2	Road 2	12.9	Gravel 1	7.8	Gravel 2	8.7
1-Apr	Road 1	9.8	Road 2	7.4	Gravel 1	5.4	Gravel 2	5.6
16-Apr	Road 1	5.4	Road 2	10.2	Gravel 1	3.5	Gravel 2	4.2
2-Aug	R1	6.4	R2	6.9	G1		G2	6.9
Date	Site	O&G conc	Site	O&G conc	Site	O&G conc	Site	O&G conc
7-Nov	Asphalt 1		Asphalt 2	3.6	Porous 1	11	Porous 2	
8-Nov	Asphalt 1		Asphalt 2	10.7	Porous 1	10.3	Porous 2	
18-Nov	Asphalt 1	11.2	Asphalt 2	4.3	Porous 1		Porous 2	6.9
27-Nov	Asphalt 1	6.3	Asphalt 2	8.8	Porous 1	8.9	Porous 2	6.7
16-Jan	Asphalt 1	13.9	Asphalt 2	18.9	Porous 1	6.8	Porous 2	5.1
21-Jan	Asphalt 1	36.4	Asphalt 2	27.8	Porous 1	7.8	Porous 2	9
5-Feb	Asphalt 1	13.7	Asphalt 2	7.9	Porous 1	8.4	Porous 2	
21-Feb	Asphalt 1	9.3	Asphalt 2	10.4	Porous 1		Porous 2	
1-Apr	Asphalt 1	4.2	Asphalt 2	4.7	Porous 1	4.3	Porous 2	5.5
16-Apr	Asphalt 1	8	Asphalt 2	11.4	Porous 1	10	Porous 2	9.3
2-Aug	A1	10.5	A2	13.8	P1	14.2	P2	16

Diesel Range Summary -- Concentrations in mg/L

Date	Site	DR	Site	DR	Site	DR	Site	DR
7-Nov	Road 1		Road 2	0.686	Gravel 1	0.315	Gravel 2	
8-Nov	Road 1		Road 2	0.47	Gravel 1	0.648	Gravel 2	
18-Nov	Road 1		Road 2	1.62	Gravel 1	1.09	Gravel 2	1.16
27-Nov	Road 1	1.21	Road 2	1.49	Gravel 1	0.964	Gravel 2	0.763
16-Jan	Road 1		Road 2		Gravel 1		Gravel 2	
21-Jan	Road 1		Road 2		Gravel 1		Gravel 2	
5-Feb	Road 1		Road 2		Gravel 1		Gravel 2	
21-Feb	Road 1	1.19	Road 2	0.663	Gravel 1	0.581	Gravel 2	0.389
1-Apr	Road 1	0.635	Road 2	0.627	Gravel 1	0.265	Gravel 2	0.258
16-Apr	Road 1	0.404	Road 2	2.28	Gravel 1	0.237	Gravel 2	
2-Aug	R1	1.02	R2	1.68	G1		G2	0.852
Date	Site	DR	Site	DR	Site	DR	Site	DR
7-Nov	Asphalt 1		Asphalt 2	0.467	Porous 1	0.322	Porous 2	
8-Nov	Asphalt 1		Asphalt 2	0.506	Porous 1	0.29	Porous 2	
18-Nov	Asphalt 1	0.986	Asphalt 2	1.44	Porous 1	1.25	Porous 2	1.2
27-Nov	Asphalt 1	0.899	Asphalt 2	0.959	Porous 1	0.928	Porous 2	0.863
16-Jan	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
21-Jan	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
5-Feb	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
21-Feb	Asphalt 1	0.585	Asphalt 2	0.565	Porous 1		Porous 2	
1-Apr	Asphalt 1	0.54	Asphalt 2	0.6	Porous 1	0.429	Porous 2	0.401
16-Apr	Asphalt 1	0.682	Asphalt 2	1.77	Porous 1	0.528	Porous 2	0.228
2-Aug	A1	0.882	A2	1.39	P1	2.15	P2	1.84

Heavy Oil Range Summary -- Concentrations in mg/L								
Date	Site	HOR	Site	HOR	Site	HOR	Site	HOR
7-Nov	Road 1		Road 2	1.62	Gravel 1	0.52	Gravel 2	
8-Nov	Road 1		Road 2	1.30	Gravel 1	1.39	Gravel 2	
18-Nov	Road 1		Road 2	4.70	Gravel 1	1.71	Gravel 2	4.10
27-Nov	Road 1	1.26	Road 2	2.26	Gravel 1	1.03	Gravel 2	0.79
16-Jan	Road 1	2.55	Road 2	4.57	Gravel 1	0.98	Gravel 2	0.93
21-Jan	Road 1	2.84	Road 2	2.76	Gravel 1	1.01	Gravel 2	1.01
5-Feb	Road 1	4.39	Road 2	4.22	Gravel 1		Gravel 2	2.71
21-Feb	Road 1	3.95	Road 2	2.37	Gravel 1	1.38	Gravel 2	1.02
1-Apr	Road 1	2.05	Road 2	1.96	Gravel 1	0.63	Gravel 2	0.51
16-Apr	Road 1	0.89	Road 2	2.38	Gravel 1	0.71	Gravel 2	0.41
2-Aug	R1	1.85	R2	1.62	G1		G2	1.35
Date	Site	HOR	Site	HOR	Site	HOR	Site	HOR
7-Nov	Asphalt 1		Asphalt 2	0.75	Porous 1		Porous 2	
8-Nov	Asphalt 1		Asphalt 2	1.11	Porous 1	0.29	Porous 2	
18-Nov	Asphalt 1	2.57	Asphalt 2	4.54	Porous 1	1.51	Porous 2	1.82
27-Nov	Asphalt 1	0.95	Asphalt 2	1.08	Porous 1	0.87	Porous 2	0.88
16-Jan	Asphalt 1	2.60	Asphalt 2	1.71	Porous 1	0.79	Porous 2	0.88
21-Jan	Asphalt 1	2.58	Asphalt 2	2.35	Porous 1	0.67	Porous 2	0.71
5-Feb	Asphalt 1	1.55	Asphalt 2	1.32	Porous 1	4.76	Porous 2	2.68
21-Feb	Asphalt 1	1.86	Asphalt 2	1.64	Porous 1		Porous 2	
1-Apr	Asphalt 1	1.77	Asphalt 2	1.77	Porous 1	0.70	Porous 2	0.74
16-Apr	Asphalt 1	1.82	Asphalt 2	2.77	Porous 1	1.12	Porous 2	0.45
2-Aug	A1	1.88	A2	1.93	P1	1.33	P2	1.40

Lead Summary -- Concentrations in	mg/L							
Date	Site	Lead conc	Site	Lead conc	Site	Lead conc	Site	Lead conc
7-Nov	Road 1		Road 2	0.0373	Gravel 1	0.0043	Gravel 2	
8-Nov	Road 1		Road 2	0.0207	Gravel 1	0.0133	Gravel 2	
18-Nov	Road 1		Road 2	0.0304	Gravel 1	0.0095	Gravel 2	0.0075
27-Nov	Road 1	0.0081	Road 2	0.0145	Gravel 1	0.0039	Gravel 2	0.0035
16-Jan	Road 1	0.0275	Road 2	0.0469	Gravel 1	0.0091	Gravel 2	0.0063
21-Jan	Road 1	0.0564	Road 2	0.0451	Gravel 1	0.0121	Gravel 2	0.0118
5-Feb	Road 1	0.2470	Road 2	0.2900	Gravel 1		Gravel 2	0.0598
21-Feb	Road 1	0.0357	Road 2	0.0517	Gravel 1	0.0126	Gravel 2	0.0081
1-Apr	Road 1	0.0433	Road 2	0.0622	Gravel 1	0.0102	Gravel 2	0.0070
16-Apr	Road 1	0.0102	Road 2	0.1060	Gravel 1	0.0125	Gravel 2	0.0072
2-Aug	R1	0.0117	R2	0.0114	G1		G2	0.0212
Date	Site	Lead conc	Site	Lead conc	Site	Lead conc	Site	Lead conc
7-Nov	Asphalt 1		Asphalt 2	0.0075	Porous 1	0.0013	Porous 2	
8-Nov	Asphalt 1		Asphalt 2	0.0093	Porous 1	0.0016	Porous 2	
18-Nov	Asphalt 1	0.0068	Asphalt 2	0.0122	Porous 1	0.0053	Porous 2	0.0050
27-Nov	Asphalt 1	0.0036	Asphalt 2	0.0069	Porous 1	0.0019	Porous 2	0.0022
16-Jan	Asphalt 1	0.0220	Asphalt 2	0.0134	Porous 1	0.0035	Porous 2	0.0067
21-Jan	Asphalt 1	0.0372	Asphalt 2	0.0408	Porous 1	0.0054	Porous 2	0.0072
5-Feb	Asphalt 1	0.1140	Asphalt 2	0.1330	Porous 1	0.0904	Porous 2	0.0471
21-Feb	Asphalt 1	0.0160	Asphalt 2	0.0158	Porous 1	0.0048	Porous 2	
1-Apr	Asphalt 1	0.0352	Asphalt 2	0.0348	Porous 1	0.0034	Porous 2	0.0080
16-Apr	Asphalt 1	0.0331	Asphalt 2	0.0505	Porous 1	0.0121	Porous 2	0.0015
2-Aug	A1	0.0347	A2	0.0258	P1	0.0048	P2	0.0238

Copper Summary -- Concentrations	in mg/L							
Date	Site	Copper con	Site	Copper con	Site	Copper con	Site	Copper con
7-Nov	Road 1		Road 2	0.0147	Gravel 1	0.0131	Gravel 2	
8-Nov	Road 1		Road 2	0.0167	Gravel 1	0.0277	Gravel 2	
18-Nov	Road 1		Road 2	0.0220	Gravel 1	0.0189	Gravel 2	0.0185
27-Nov	Road 1	0.0063	Road 2	0.0086	Gravel 1	0.0073	Gravel 2	0.0083
16-Jan	Road 1	0.0119	Road 2	0.0181	Gravel 1	0.0086	Gravel 2	0.0083
21-Jan	Road 1	0.0167	Road 2	0.0113	Gravel 1	0.0075	Gravel 2	0.0067
5-Feb	Road 1	0.0699	Road 2	0.0903	Gravel 1		Gravel 2	0.0279
21-Feb	Road 1	0.0120	Road 2	0.0129	Gravel 1	0.0107	Gravel 2	0.0085
1-Apr	Road 1	0.0172	Road 2	0.0223	Gravel 1	0.0078	Gravel 2	0.0084
16-Apr	Road 1	0.0074	Road 2	0.0454	Gravel 1	0.0100	Gravel 2	0.0096
2-Aug	R1	0.0147	R2	0.0212	G1		G2	0.0221
Date	Site	Copper con	Site	Copper con	Site	Copper con	Site	Copper con
7-Nov	Asphalt 1		Asphalt 2	0.0067	Porous 1	0.0028	Porous 2	
8-Nov	Asphalt 1		Asphalt 2	0.0075	Porous 1	0.0032	Porous 2	
18-Nov	Asphalt 1	0.0058	Asphalt 2	0.0096	Porous 1	0.0181	Porous 2	0.0066
27-Nov	Asphalt 1	0.0026	Asphalt 2	0.0039	Porous 1	0.0020	Porous 2	0.0025
16-Jan	Asphalt 1	0.0088	Asphalt 2	0.0068	Porous 1	0.0039	Porous 2	0.0047
21-Jan	Asphalt 1	0.0086	Asphalt 2	0.0092	Porous 1	0.0020	Porous 2	0.0029
5-Feb	Asphalt 1	0.0419	Asphalt 2	0.0470	Porous 1	0.0317	Porous 2	0.0187
21-Feb	Asphalt 1	0.0063	Asphalt 2	0.0063	Porous 1	0.0047	Porous 2	
1-Apr	Asphalt 1	0.0114	Asphalt 2	0.0129	Porous 1	0.0036	Porous 2	0.0051
16-Apr	Asphalt 1	0.0117	Asphalt 2	0.0181	Porous 1	0.0071	Porous 2	0.0024
2-Aug	A1	0.0176	A2	0.0165	P1	0.0235	P2	0.0234

Zinc Summary -- Concentrations in mg/L								
Date	Site	Zinc conc	Site	Zinc conc	Site	Zinc conc	Site	Zinc conc
7-Nov	Road 1		Road 2	0.0543	Gravel 1	0.0195	Gravel 2	
8-Nov	Road 1		Road 2	0.0694	Gravel 1	0.0694	Gravel 2	
18-Nov	Road 1		Road 2	0.1180	Gravel 1	0.0652	Gravel 2	0.0395
27-Nov	Road 1	0.0379	Road 2	0.0453	Gravel 1	0.0190	Gravel 2	0.0236
16-Jan	Road 1	0.0768	Road 2	0.1140	Gravel 1	0.0260	Gravel 2	0.0227
21-Jan	Road 1	0.0993	Road 2	0.0754	Gravel 1	0.0277	Gravel 2	0.0264
5-Feb	Road 1	0.5720	Road 2	0.6410	Gravel 1		Gravel 2	0.1530
21-Feb	Road 1	0.1020	Road 2	0.0901	Gravel 1	0.0385	Gravel 2	0.0357
1-Apr	Road 1	0.1780	Road 2	0.1370	Gravel 1	0.0555	Gravel 2	0.0545
16-Apr	Road 1	0.1080	Road 2	0.2720	Gravel 1	0.0419	Gravel 2	0.0686
2-Aug	R1	0.0562	R2	0.1030	G1		G2	0.0791
Date	Site	Zinc conc	Site	Zinc conc	Site	Zinc conc	Site	Zinc conc
7-Nov	Asphalt 1		Asphalt 2	0.0220	Porous 1	0.0072	Porous 2	
8-Nov	Asphalt 1		Asphalt 2	0.0982	Porous 1	0.0289	Porous 2	
18-Nov	Asphalt 1	0.0287	Asphalt 2	0.0546	Porous 1	0.0842	Porous 2	0.0340
27-Nov	Asphalt 1	0.0135	Asphalt 2	0.0250	Porous 1	0.0146	Porous 2	0.0106
16-Jan	Asphalt 1	0.0570	Asphalt 2	0.0402	Porous 1	0.0164	Porous 2	0.0186
21-Jan	Asphalt 1	0.0608	Asphalt 2	0.0604	Porous 1	0.0153	Porous 2	0.0176
5-Feb	Asphalt 1	0.2740	Asphalt 2	0.3330	Porous 1	0.2190	Porous 2	0.1220
21-Feb	Asphalt 1	0.0364	Asphalt 2	0.0352	Porous 1	0.1700	Porous 2	
1-Apr	Asphalt 1	0.0677	Asphalt 2	0.0732	Porous 1	0.0449	Porous 2	0.0633
16-Apr	Asphalt 1	0.0673	Asphalt 2	0.1080	Porous 1	0.0347	Porous 2	0.0198
2-Aug	A1	0.0933	A2	0.0804	P1	0.0746	P2	0.1230

Antimony Summary -- Concentrations in mg/L								
Date	Site	Ant. conc	Site	Ant. conc	Site	Ant. conc	Site	Ant. conc
7-Nov	Road 1		Road 2	0.00087	Gravel 1	0.00062	Gravel 2	
8-Nov	Road 1		Road 2	0.00100	Gravel 1	0.00091	Gravel 2	
18-Nov	Road 1		Road 2	0.00140	Gravel 1	0.00087	Gravel 2	0.00078
27-Nov	Road 1	0.00058	Road 2	0.00078	Gravel 1		Gravel 2	
16-Jan	Road 1	0.00092	Road 2	0.00110	Gravel 1		Gravel 2	
21-Jan	Road 1	0.00110	Road 2	0.00091	Gravel 1		Gravel 2	
5-Feb	Road 1	0.00240	Road 2	0.00190	Gravel 1		Gravel 2	0.00110
21-Feb	Road 1	0.00091	Road 2	0.00110	Gravel 1	0.00069	Gravel 2	0.00054
1-Apr	Road 1	0.00120	Road 2		Gravel 1		Gravel 2	
16-Apr	Road 1	0.00072	Road 2	0.00150	Gravel 1	0.00056	Gravel 2	0.00055
2-Aug	Road 1	0.00110	Road 2	0.00140	Gravel 1		Gravel 2	0.00091
Date	Site	Ant. conc	Site	Ant. conc	Site	Ant conc	Site	Ant. conc
7-Nov	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
8-Nov	Asphalt 1		Asphalt 2	0.00050	Porous 1		Porous 2	
18-Nov	Asphalt 1	0.00064	Asphalt 2	0.00075	Porous 1	0.00072	Porous 2	0.00063
27-Nov	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
16-Jan	Asphalt 1	0.00055	Asphalt 2	0.00058	Porous 1		Porous 2	
21-Jan	Asphalt 1	0.00061	Asphalt 2	0.00067	Porous 1		Porous 2	
5-Feb	Asphalt 1	0.00160	Asphalt 2	0.00160	Porous 1	0.00150	Porous 2	0.00100
21-Feb	Asphalt 1	0.00060	Asphalt 2	0.00069	Porous 1	0.00065	Porous 2	
1-Apr	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
16-Apr	Asphalt 1	0.00078	Asphalt 2	0.00092	Porous 1	0.00056	Porous 2	
2-Aug	Asphalt 1	0.00092	Asphalt 2	0.00100	Porous 1	0.00100	Porous 2	0.00110

Arsenic Summary -- Concentrations in mg/L									
Date	Site	Ar conc	Site	Ar conc	Site	Ar conc	Site	Ar conc	
7-Nov	Road 1		Road 2	0.00332	Gravel 1	0.00312	Gravel 2		
8-Nov	Road 1		Road 2	0.00219	Gravel 1	0.00493	Gravel 2		
18-Nov	Road 1		Road 2		Gravel 1		Gravel 2		
27-Nov	Road 1	0.00087	Road 2	0.00098	Gravel 1	0.00120	Gravel 2	0.00160	
16-Jan	Road 1	0.00130	Road 2	0.00200	Gravel 1	0.00130	Gravel 2	0.00130	
21-Jan	Road 1	0.00170	Road 2	0.00130	Gravel 1	0.00110	Gravel 2	0.00097	
5-Feb	Road 1	0.00713	Road 2	0.01100	Gravel 1		Gravel 2	0.00442	
21-Feb	Road 1	0.00081	Road 2	0.00160	Gravel 1	0.00150	Gravel 2	0.00100	
1-Apr	Road 1	0.00229	Road 2	0.00250	Gravel 1	0.00120	Gravel 2	0.00120	
16-Apr	Road 1	0.00110	Road 2		Gravel 1		Gravel 2		
2-Aug	R1	0.00170	R2	0.00190	G1		G2	0.00227	
Date	Site	Ar conc	Site	Ar conc	Site	Ar conc	Site	Ar conc	
7-Nov	Asphalt 1		Asphalt 2	0.00099	Porous 1	0.00070	Porous 2		
8-Nov	Asphalt 1		Asphalt 2	0.00110	Porous 1	0.00064	Porous 2		
18-Nov	Asphalt 1		Asphalt 2		Porous 1		Porous 2		
27-Nov	Asphalt 1	0.00061	Asphalt 2		Porous 1		Porous 2		
16-Jan	Asphalt 1	0.00087	Asphalt 2	0.0C074	Porous 1		Porous 2	0.00061	
21-Jan	Asphalt 1	0.00095	Asphalt 2	0.00100	Porous 1		Porous 2		
5-Feb	Asphalt 1	0.00580	Asphalt 2	0.00666	Porous 1	0.00507	Porous 2	0.00286	
21-Feb	Asphalt 1		Asphalt 2	0.00077	Porous 1		Porous 2		
1-Apr	Asphalt 1	0.00093	Asphalt 2	0.00110	Porous 1		Porous 2		
16-Apr	Asphalt 1		Asphalt 2		Porous 1		Porous 2		
2-Aug	A1	0.00140	A2	0.00110	P1	0.00110	P2	0.00243	

Barium Summary -- Concentrations in mg/L									
Date	Site	Br conc	Site	Br conc	Site	Br conc	Site	Br conc	
7-Nov	Road 1		Road 2	0.0365	Gravel 1	0.0281	Gravel 2		
8-Nov	Road 1		Road 2	0.0500	Gravel 1	0.0732	Gravel 2		
18-Nov	Road 1		Road 2	0.0674	Gravel 1	0.0450	Gravel 2	0.0557	
27-Nov	Road 1	0.0215	Road 2	0.0289	Gravel 1	0.0154	Gravel 2	0.0258	
16-Jan	Road 1	0.0414	Road 2	0.0587	Gravel 1	0.0223	Gravel 2	0.0206	
21-Jan	Road 1	0.0656	Road 2	0.0432	Gravel 1	0.0211	Gravel 2	0.0205	
5-Feb	Road 1	0.2840	Road 2	0.3780	Gravel 1		Gravel 2	0.0999	
21-Feb	Road 1	0.0354	Road 2	0.0455	Gravel 1	0.0249	Gravel 2	0.0197	
1-Apr	Road 1	0.0579	Road 2	0.0881	Gravel 1	0.0204	Gravel 2	0.0237	
16-Apr	Road 1		Road 2		Gravel 1		Gravel 2		
2-Aug	R1	0.0349	R2	0.0371	G1		G2	0.0612	
Date	Site	Br conc	Site	Br conc	Site	Br conc	Site	Br conc	
7-Nov	Asphalt 1		Asphalt 2	0.0101	Porous 1	0.0038	Porous 2		
8-Nov	Asphalt 1		Asphalt 2	0.0136	Porous 1	0.0045	Porous 2		
18-Nov	Asphalt 1	0.0162	Asphalt 2	0.0229	Porous 1	0.0141	Porous 2	0.0134	
27-Nov	Asphalt 1	0.0079	Asphalt 2	0.0113	Porous 1	0.0044	Porous 2	0.0061	
16-Jan	Asphalt 1	0.0250	Asphalt 2	0.0183	Porous 1	0.0070	Porous 2	0.0128	
21-Jan	Asphalt 1	0.0283	Asphalt 2	0.0309	Porous 1	0.0070	Porous 2	0.0098	
5-Feb	Asphalt 1	0.1460	Asphalt 2	0.1840	Porous 1	0.1300	Porous 2	0.0767	
21-Feb	Asphalt 1	0.0178	Asphalt 2	0.0177	Porous 1	0.0100	Porous 2		
1-Apr	Asphalt 1	0.0346	Asphalt 2	0.0306	Porous 1	0.0073	Porous 2	0.0128	
16-Apr	Asphalt 1		Asphalt 2		Porous 1		Porous 2		
2-Aug	A1	0.0403	A2	0.0322	P1	0.0226	P2	0.0508	

Cadmium Summary -- Concentrations in mg/L								
Date	Site	Cd conc	Site	Cd conc	Site	Cd conc	Site	Cd conc
7-Nov	Road 1		Road 2	0.00036	Gravel 1		Gravel 2	
8-Nov	Road 1		Road 2	0.00046	Gravel 1	0.00036	Gravel 2	
18-Nov	Road 1		Road 2	0.00068	Gravel 1	0.00030	Gravel 2	0.00025
27-Nov	Road 1		Road 2	0.00030	Gravel 1	0.00042	Gravel 2	
16-Jan	Road 1	0.00052	Road 2		Gravel 1		Gravel 2	
21-Jan	Road 1	0.00056	Road 2	0.00043	Gravel 1		Gravel 2	
5-Feb	Road 1	0.00272	Road 2	0.00350	Gravel 1		Gravel 2	0.00077
21-Feb	Road 1	0.00043	Road 2	0.00042	Gravel 1		Gravel 2	
1-Apr	Road 1	0.00054	Road 2	0.00075	Gravel 1		Gravel 2	
16-Apr	Road 1	0.00023	Road 2	0.00160	Gravel 1		Gravel 2	
2-Aug	Road1		Road 2		Gravel 1		Gravel 2	
Date	Site	Cd conc	Site	Cd conc	Site	Cd conc	Site	Cd conc
7-Nov	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
8-Nov	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
18-Nov	Asphalt 1		Asphalt 2	0.00050	Porous 1		Porous 2	
27-Nov	Asphalt 1		Asphalt 2	0.00048	Porous 1		Porous 2	
16-Jan	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
21-Jan	Asphalt 1	0.00029	Asphalt 2	0.00032	Porous 1		Porous 2	
5-Feb	Asphalt 1	0.00120	Asphalt 2	0.00160	Porous 1	0.00100	Porous 2	0.00049
21-Feb	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
1-Apr	Asphalt 1	0.00039	Asphalt 2	0.00042	Porous 1		Porous 2	
16-Apr	Asphalt 1	0.00045	Asphalt 2	0.00071	Porous 1		Porous2	
2-Aug	Asphalt 1		Asphalt 2		Porous 1		Porous 2	

Chromium Summary -- Concentration in mg/L								
Date	Site	Cr conc	Site	Cr conc	Site	Cr conc	Site	Cr conc
7-Nov	Road 1		Road 2	0.00543	Gravel 1	0.00808	Gravel 2	
8-Nov	Road 1		Road 2	0.00755	Gravel 1	0.01390	Gravel 2	
18-Nov	Road 1		Road 2	0.01210	Gravel 1	0.00828	Gravel 2	0.01000
27-Nov	Road 1	0.00332	Road 2	0.00472	Gravel 1	0.00294	Gravel 2	0.00471
16-Jan	Road 1	0.00892	Road 2		Gravel 1		Gravel 2	
21-Jan	Road 1	0.01600	Road 2	0.01270	Gravel 1	0.00571	Gravel 2	0.00525
5-Feb	Road 1	0.06500	Road 2	0.07810	Gravel 1		Gravel 2	0.02490
21-Feb	Road 1	0.01080	Road 2	0.01690	Gravel 1	0.00671	Gravel 2	0.00448
1-Apr	Road 1	0.01450	Road 2	0.01870	Gravel 1	0.00409	Gravel 2	0.00425
16-Apr	Road 1	0.00379	Road 2	0.03040	Gravel 1	0.00555	Gravel 2	0.00432
2-Aug	R1	0.00565	R2	0.00760	G1		G2	0.00965
Date	Site	Cr conc	Site	Cr conc	Site	Cr conc	Site	Cr conc
7-Nov	Asphalt 1		Asphalt 2	0.00190	Porous 1	0.00075	Porous 2	
8-Nov	Asphalt 1		Asphalt 2	0.00250	Porous 1	0.00078	Porous 2	
18-Nov	Asphalt 1	0.00266	Asphalt 2	0.00414	Porous 1	0.00260	Porous 2	0.00246
27-Nov	Asphalt 1	0.00130	Asphalt 2	0.00204	Porous 1	0.00100	Porous 2	0.00100
16-Jan	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
21-Jan	Asphalt 1	0.01020	Asphalt 2	0.01080	Porous 1	0.00252	Porous 2	0.00265
5-Feb	Asphalt 1	0.03800	Asphalt 2	0.04370	Porous 1	0.03230	Porous 2	0.01790
21-Feb	Asphalt 1	0.00564	Asphalt 2	0.00593	Porous 1	0.00289	Porous 2	
1-Apr	Asphalt 1	0.00877	Asphalt 2	0.01010	Porous 1	0.00140	Porous 2	0.00243
16-Apr	Asphalt 1	0.00915	Asphalt 2	0.01320	Porous 1	0.00387	Porous 2	0.00085
2-Aug	A1	0.00979	A2	0.00698	P1	0.00268	P2	0.00859

Cobalt Summary -- Concentrations in mg/L								
Date	Site		Site		Site		Site	
7-Nov	Road 1		Road 2	0.00140	Gravel 1	0.00252	Gravel 2	
8-Nov	Road 1		Road 2	0.00200	Gravel 1	0.00629	Gravel 2	
18-Nov	Road 1		Road 2	0.00291	Gravel 1	0.00351	Gravel 2	0.00373
27-Nov	Road 1	0.00064	Road 2	0.00090	Gravel 1	0.00120	Gravel 2	0.00150
16-Jan	Road 1		Road 2		Gravel 1		Gravel 2	
21-Jan	Road 1	0.00273	Road 2	0.00190	Gravel 1	0.00130	Gravel 2	0.00130
5-Feb	Road 1	0.01740	Road 2	0.02100	Gravel 1		Gravel 2	0.00647
21-Feb	Road 1	0.00170	Road 2	0.00232	Gravel 1	0.00207	Gravel 2	0.00120
1-Apr	Road 1		Road 2		Gravel 1		Gravel 2	
16-Apr	Road 1	0.00081	Road 2	0.00747	Gravel 1	0.00180	Gravel 2	0.00130
2-Aug	R1	0.00120	R2	0.00160	G1		G2	0.00306
Date	Site		Site		Site		Site	
7-Nov	Asphalt 1		Asphalt 2	0.00056	Porous 1		Porous 2	
8-Nov	Asphalt 1		Asphalt 2	0.00065	Porous 1		Porous 2	
18-Nov	Asphalt 1	0.00059	Asphalt 2	0.00097	Porous 1	0.00063	Porous 2	0.00056
27-Nov	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
16-Jan	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
21-Jan	Asphalt 1	0.00140	Asphalt 2	0.00150	Porous 1		Porous 2	
5-Feb	Asphalt 1	0.01000	Asphalt 2	0.01190	Porous 1	0.00831	Porous 2	0.00464
21-Feb	Asphalt 1	0.00089	Asphalt 2	0.00087	Porous 1		Porous 2	
1-Apr	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
16-Apr	Asphalt 1	0.00170	Asphalt 2	0.00247	Porous 1	0.00093	Porous 2	
2-Aug	A1	0.00203	A2	0.00160	P1	0.00100	P2	0.00288

Molybdenum Summary -- Concentrations in mg/L								
Date	Site		Site		Site		Site	
7-Nov	Road 1		Road 2	0.0015	Gravel 1	0.00497	Gravel 2	
8-Nov	Road 1		Road 2	0.0014	Gravel 1	0.00263	Gravel 2	
18-Nov	Road 1		Road 2	0.00302	Gravel 1	0.0015	Gravel 2	0.00099
27-Nov	Road 1	0.00065	Road 2	0.00088	Gravel 1	0.00057	Gravel 2	
16-Jan	Road 1	0.0011	Road 2	0.0011	Gravel 1		Gravel 2	0.00055
21-Jan	Road 1	0.0013	Road 2	0.00081	Gravel 1		Gravel 2	
5-Feb	Road 1	0.00424	Road 2	0.00227	Gravel 1		Gravel 2	0.00533
21-Feb	Road 1	0.001	Road 2	0.0011	Gravel 1	0.00086	Gravel 2	0.00063
1-Apr	Road 1	0.0014	Road 2	0.0013	Gravel 1	0.00055	Gravel 2	0.00064
16-Apr	Road 1		Road 2		Gravel 1		Gravel 2	
2-Aug	Road 1		Road 2		Gravel 1		Gravel 2	
Date	Site		Site		Site		Site	
7-Nov	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
8-Nov	Asphalt 1		Asphalt 2	0.00057	Porous 1		Porous 2	
18-Nov	Asphalt 1	0.00075	Asphalt 2	0.00084	Porous 1	0.0011	Porous 2	0.00073
27-Nov	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
16-Jan	Asphalt 1	0.00051	Asphalt 2		Porous 1		Porous 2	
21-Jan	Asphalt 1	0.0006	Asphalt 2	0.00055	Porous 1		Porous 2	
5-Feb	Asphalt 1	0.0021	Asphalt 2	0.0019	Porous 1	0.0017	Porous 2	0.0019
21-Feb	Asphalt 1	0.00057	Asphalt 2	0.00058	Porous 1	0.0006	Porous 2	
1-Apr	Asphalt 1	0.00077	Asphalt 2	0.00076	Porous 1		Porous 2	0.00052
16-Apr	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
2-Aug	Asphalt 1		Asphalt 2		Porous 1		Porous 2	

Nickel Summary -- Concentrations in mg/L								
Date	Site		Site		Site		Site	
7-Nov	Road 1		Road 2	0.00591	Gravel 1	0.00753	Gravel 2	
8-Nov	Road 1		Road 2	0.00695	Gravel 1	0.0207	Gravel 2	
18-Nov	Road 1		Road 2	0.00992	Gravel 1	0.0107	Gravel 2	0.0141
27-Nov	Road 1	0.00259	Road 2	0.00329	Gravel 1	0.00369	Gravel 2	0.00643
16-Jan	Road 1	0.00562	Road 2	0.00811	Gravel 1	0.00465	Gravel 2	0.00434
21-Jan	Road 1	0.0083	Road 2	0.00615	Gravel 1	0.00443	Gravel 2	0.00414
5-Feb	Road 1	0.0514	Road 2	0.0653	Gravel 1		Gravel 2	0.0214
21-Feb	Road 1	0.0061	Road 2	0.00767	Gravel 1	0.00569	Gravel 2	0.00434
1-Apr	Road 1	0.0101	Road 2	0.0109	Gravel 1	0.0036	Gravel 2	0.00478
16-Apr	Road 1	0.00294	Road 2	0.0215	Gravel 1	0.00483	Gravel 2	0.0049
2-Aug	R1	0.0047	R2	0.0069	G1		G2	0.0107
Date	Site		Site		Site		Site	
7-Nov	Asphalt 1		Asphalt 2	0.0024	Porous 1	0.00095	Porous 2	
8-Nov	Asphalt 1		Asphalt 2	0.00283	Porous 1	0.0016	Porous 2	
18-Nov	Asphalt 1	0.00258	Asphalt 2	0.00406	Porous 1	0.00398	Porous 2	0.00281
27-Nov	Asphalt 1	0.001	Asphalt 2	0.0018	Porous 1	0.00095	Porous 2	0.00088
16-Jan	Asphalt 1	0.00359	Asphalt 2	0.00295	Porous 1	0.00097	Porous 2	0.0017
21-Jan	Asphalt 1	0.00458	Asphalt 2	0.00476	Porous 1	0.001	Porous 2	0.0015
5-Feb	Asphalt 1	0.0343	Asphalt 2	0.0405	Porous 1	0.0293	Porous 2	0.0158
21-Feb	Asphalt 1	0.00313	Asphalt 2	0.00334	Porous 1	0.0019	Porous 2	
1-Apr	Asphalt 1	0.00502	Asphalt 2	0.00642	Porous 1	0.0011	Porous 2	0.0019
16-Apr	Asphalt 1	0.00559	Asphalt 2	0.00829	Porous 1	0.00293	Porous 2	0.00075
2-Aug	A1	0.0065	A2	0.0067	P1	0.0041	P2	0.0083

Vanadium Summary -- Concentrations in mg/L								
Date	Site		Site		Site		Site	
7-Nov	Road 1		Road 2	0.00929	Gravel 1	0.0258	Gravel 2	
8-Nov	Road 1		Road 2	0.0123	Gravel 1	0.0314	Gravel 2	
18-Nov	Road 1		Road 2	0.0153	Gravel 1	0.0167	Gravel 2	0.0179
27-Nov	Road 1		Road 2		Gravel 1		Gravel 2	
16-Jan	Road 1		Road 2		Gravel 1		Gravel 2	
21-Jan	Road 1	0.0156	Road 2	0.00987	Gravel 1	0.00762	Gravel 2	0.00713
5-Feb	Road 1		Road 2		Gravel 1		Gravel 2	
21-Feb	Road 1	0.00638	Road 2	0.0111	Gravel 1	0.00994	Gravel 2	0.00609
1-Apr	Road 1		Road 2		Gravel 1		Gravel 2	
16-Apr	Road 1	0.00543	Road 2	0.0479	Gravel 1	0.00897	Gravel 2	0.00797
2-Aug	Road 1		Road 2		Gravel 1		Gravel 2	
Date	Site		Site		Site		Site	
7-Nov	Asphalt 1		Asphalt 2	0.00228	Porous 1	0.00252	Porous 2	
8-Nov	Asphalt 1		Asphalt 2	0.00244	Porous 1	0.0019	Porous 2	
18-Nov	Asphalt 1	0.00298	Asphalt 2	0.00423	Porous 1	0.00423	Porous 2	0.00395
27-Nov	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
16-Jan	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
21-Jan	Asphalt 1	0.00725	Asphalt 2	0.00692	Porous 1	0.00217	Porous 2	0.0029
5-Feb	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
21-Feb	Asphalt 1	0.00384	Asphalt 2	0.00422	Porous 1	0.00279	Porous 2	
1-Apr	Asphalt 1		Asphalt 2		Porous 1		Porous 2	
16-Apr	Asphalt 1	0.00826	Asphalt 2	0.00923	Porous 1	0.00553	Porous 2	0.0018
2-Aug	Asphalt 1		Asphalt 2		Porous 1		Porous 2	

Conductivity Summary -- Concentrations in mg/L								
Date	Site		Site		Site		Site	
7-Nov	Road 1		Road 2	61.8	Gravel 1	101.0	Gravel 2	
8-Nov	Road 1		Road 2	47.4	Gravel 1	64.6	Gravel 2	
18-Nov	Road 1		Road 2	71.3	Gravel 1	64.2	Gravel 2	51.9
27-Nov	Road 1	27.3	Road 2	40.4	Gravel 1	29.2	Gravel 2	29.5
16-Jan	Road 1	28.2	Road 2	26.1	Gravel 1	25.6	Gravel 2	27.5
21-Jan	Road 1	32.2	Road 2	21.4	Gravel 1	17.0	Gravel 2	17.0
5-Feb	Road 1	285.0	Road 2	228.0	Gravel 1		Gravel 2	103.0
21-Feb	Road 1	45.7	Road 2	61.8	Gravel 1	59.9	Gravel 2	44.8
1-Apr	Road 1	38.3	Road 2	43.8	Gravel 1	31.6	Gravel 2	36.1
16-Apr	Road 1	64.2	Road 2	72.0	Gravel 1	37.7	Gravel 2	68.0
2-Aug	R1	58.7	R2	108.0	G1		G2	59.1
Date	Site		Site		Site		Site	
7-Nov	Asphalt 1		Asphalt 2	27.3	Porous 1	22.9	Porous 2	
8-Nov	Asphalt 1		Asphalt 2	23.3	Porous 1	19.4	Porous 2	
18-Nov	Asphalt 1	40.8	Asphalt 2	31.9	Porous 1	50.7	Porous 2	34.3
27-Nov	Asphalt 1	19.5	Asphalt 2	17.4	Porous 1	19.1	Porous 2	40.5
16-Jan	Asphalt 1	19.4	Asphalt 2	21.8	Porous 1	19.8	Porous 2	19.9
21-Jan	Asphalt 1	13.9	Asphalt 2	12.0	Porous 1	14.7	Porous 2	14.8
5-Feb	Asphalt 1	128.0	Asphalt 2	156.0	Porous 1	179.0	Porous 2	143.0
21-Feb	Asphalt 1	40.0	Asphalt 2	39.2	Porous 1	38.8	Porous 2	
1-Apr	Asphalt 1	27.4	Asphalt 2	24.1	Porous 1	24.3	Porous 2	25.7
16-Apr	Asphalt 1	32.6	Asphalt 2	29.1	Porous 1	27.4	Porous 2	21.3
2-Aug	A1	34.4	A2	45.9	P1	98.4	P2	82.4

Hardness Summary -- Concentrations in mg CaCO3/L								
Date	Site	Hardness	Site	Hardness	Site	Hardness	Site	Hardness
7-Nov	Road 1		Road 2	28.4	Gravel 1	31.2	Gravel 2	
8-Nov	Road 1		Road 2	26.6	Gravel 1	39.6	Gravel 2	
18-Nov	Road 1		Road 2	40.5	Gravel 1	31.9	Gravel 2	36.1
27-Nov	Road 1	12.7	Road 2	15.9	Gravel 1	13.9	Gravel 2	15.8
16-Jan	Road 1	20.6	Road 2	24.5	Gravel 1	17.7	Gravel 2	17.4
21-Jan	Road 1	30.3	Road 2	20.5	Gravel 1	12.9	Gravel 2	12.8
5-Feb	Road 1	113.0	Road 2	160.0	Gravel 1		Gravel 2	58.3
21-Feb	Road 1	19.1	Road 2	29.1	Gravel 1	25.5	Gravel 2	18.2
1-Apr	Road 1	26.3	Road 2	41.8	Gravel 1	14.8	Gravel 2	18.0
16-Apr	Road 1	29.4	Road 2	89.6	Gravel 1	20.7	Gravel 2	19.5
2-Aug	R1	23.4	R2	40.0	G1		G2	36.2
Date	Site	hardness	Site	Hardness	Site	Hardness	Site	Hardness
7-Nov	Asphalt 1		Asphalt 2	9.6	Porous 1	6.3	Porous 2	
8-Nov	Asphalt 1		Asphalt 2	9.2	Porous 1	7.3	Porous 2	
18-Nov	Asphalt 1	13.8	Asphalt 2	13.1	Porous 1	17.3	Porous 2	14.0
27-Nov	Asphalt 1	6.6	Asphalt 2	6.1	Porous 1	6.3	Porous 2	6.2
16-Jan	Asphalt 1	13.2	Asphalt 2	11.3	Porous 1	8.4	Porous 2	9.8
21-Jan	Asphalt 1	13.0	Asphalt 2	12.5	Porous 1	6.3	Porous 2	7.3
5-Feb	Asphalt 1	59.4	Asphalt 2	63.6	Porous 1	46.5	Porous 2	34.2
21-Feb	Asphalt 1	16.9	Asphalt 2	15.2	Porous 1	11.4	Porous 2	
1-Apr	Asphalt 1	19.7	Asphalt 2	14.7	Porous 1	8.3	Porous 2	10.8
16-Apr	Asphalt 1	22.8	Asphalt 2	23.2	Porous 1	13.6	Porous 2	7.3
2-Aug	A1	18.4	A2	17.8	P1	38.7	P2	38.3

The **semi-volatile organic pollutants** were analyzed for several storms. The raw data from these storms are presented below.

	Locator	2,4-Dimethylphenol ug/L	Diethyl Phthalate ug/L	Pentachlorophenol ug/L	Bis(2-Ethylhexyl)Phthalate ug/L	Benzyl Alcohol ug/L	2-Methylphenol ug/L	4-Methylphenol ug/L	Benzoic Acid ug/L
	ROAD2				3.36				
Nov. 7	GRAVEL1								
	ASPHALT2				1.36				
	POROUS1				1.66				3.3
	ROAD2	0.54			5.15				3.57
	GRAVEL1		0.7		2.39	4.27	0.61	0.54	4.56
Nov. 8	ASPHALT2			4.33	3.12				2.8
	POROUS1				1.65				
	ROAD2								
	GRAVEL1								
	GRAVEL2								
Nov. 18	ASPHALT1								
	ASPHALT2								
	POROUS1								
	POROUS2								

Nov. 27

Locator	Sample Depth	Lab ID	2-Methylphenol ug/L	Benzo(a)anthracene ug/L	Benzo(g,h,i)perylene ug/L	Benzoic Acid ug/L	Benzyl Alcohol ug/L	Benzyl Butyl Phthalate ug/L	Bis(2-Ethylhexyl)Phthalate ug/L	Chrysene ug/L	Di-N-Octyl Phthalate ug/L	Diesel Range (>C12-C24) mg/L	Fluoranthene ug/L	Heavy Oil Range (>C24) mg/L	Indeno(1,2,3-Cd)Pyrene ug/L	N-Nitrosodiphenylamine ug/L	Pentachlorophenol ug/L	Phenol ug/L	Pyrene ug/L
ROAD1		L7396-1										1.21		1.26					
ROAD2		L7396-2	0.963	0.45	0.81	8.15	0.72	0.718	5.47	0.682	0.69	1.49	0.33	2.26	0.76	0.62		2	0.39
GRAVEL1		L7396-3										0.964		1.03					
GRAVEL2		L7396-4										0.763		0.787					
ASPHALT1		L7396-5										0.899		0.954					
ASPHALT2		L7396-6							3.64			0.959		1.08			2.49		
POROUS1		L7396-7										0.928		0.868					
POROUS2		L7396-8										0.863		0.881					

Aug. 27

Locator	Sample Depth	Lab ID	2-Methylphenol ug/L	4-Methylphenol ug/L	Benzoic Acid ug/L	Benzyl Alcohol ug/L	Bis(2-Ethylhexyl)Phthalate ug/L	Chrysene ug/L	Di-N-Butyl Phthalate ug/L	Di-N-Octyl Phthalate ug/L	Diesel Range (>C12-C24) mg/L	Diethyl Phthalate ug/L	Heavy Oil Range (>C24) mg/L	Pentachlorophenol ug/L	Phenol ug/L
ROAD1		L9207-1	0.91	1.6	5.03	1.21	5.06		4.42	0.861	1.02		1.85		2.6
ROAD2		L9207-2	1.21	2.47	16.4	1.45	3.94		3.42		1.68		1.62		4.47
GRAVEL3		L9207-4			3.49		2.75		0.81		0.852	0.53	1.36		
ASPHALT1		L9207-5	0.67	1.38	11.3	0.88	4.2	0.36	1.89	0.635	0.882		1.88		2.3
ASPHALT2		L9207-6	0.52	0.948	3.65	0.7	4.15		0.82	0.8	1.39		1.93	2.31	
POROUS1		L9207-7		0.54	3.72	0.48	1.13		0.79	0.36	2.15		1.33		
POROUS2		L9207-8		0.71	3.01	0.61	2.15		0.88	0.975	1.84		1.4	0.49	
SHOULDERDUP		L9207-9					2.25			0.41	0.829	0.49	1.36		

February 5, 1996

SAMPLE (KCEL Sample #)	*Daphnia pulex* 48h Survival	*Selenastrum* 96h Chronic Toxicity		*Selenastrum* Growth Potential	*Lemna minor* Growth Potential
		*	EC50	*	*
Road 1 (7816-1)	100%	c	N/A	c	a,b
Road 2 (7816-2)	100%	d	71	d	a
Gravel 2 (7816-3)	100%	a	89	a	a,b
Asphalt 1 (7816-4)	100%	a	71	a	a
Asphalt 2 (7816-5)	100%	b,c	N/A	b,c	b
Porous 1 (7816-6)	100%	b,c	N/A	b,c	a,b
Porous 2 (7816-7)	100%	b	N/A	b	a,b

* Means sharing a common letter within each column are not significantly (p > 0.05) different

April 1, 1996.

SAMPLE (KCEL Sample #)	*Daphnia pulex* 48h Survival	*Selenastrum* 96h Chronic Toxicity		*Selenastrum* Growth Potential	*Lemna minor* Growth Potential
		*	EC50	*	*
Road 1 (8204-1)	100%	a,b	N/A	a,b	b
Road 2 (8204-2)	90%	a,b	N/A	a	a
Gravel 1 (8204-3)	100%	a,b	N/A	b	a
Gravel 2 (8204-4)	100%	a,b	N/A	a	a
Asphalt 1 (8204-5)	100%	b	N/A	a,b	b
Asphalt 2 (8204-6)	100%	a	N/A	a,b	a
Porous 1 (8204-7)	95%	a,b	N/A	b	b
Porous 2 (8204-8)	100%	b	N/A	a,b	b

* Means sharing a common letter within each column are not significantly (p > 0.05) different

APPENDIX B -- QA/QC DATA SUMMARIES

The QA/QC data summaries provided by the Municipality of Metropolitan Seattle Environmental Laboratory are presented below.

KCRM Shoulders Project (November 7, 1995) QA/QC Data Summary

Laboratory Method Blank

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Total Organic Carbon, mg/L	Total Oil, mg/L	Total Petroleum Hydrocarbons, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU	Conductivity, umhos/cm	Alkalinity, mg/L
Result											
Blank	<MDL	NA	<MDL	<MDL	<MDL	NA	<MDL	<MDL	NA	NA	NA

Laboratory Positive Control (80 - 120%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Total Organic Carbon, mg/L	Total Oil, mg/L	Total Petroleum Hydrocarbons, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU	Conductivity, umhos/cm	Alkalinity, mg/L
True Value	300	100	10.00	71.5	32.9		0.030		2.0	74.0	94.0
Det'd Value	296	108	8.88	72.3	28.9		0.032		2.0	71.5	91.1
% Recovery	99%	108%	89%	101%	88%	NA	108%	NA	100%	97%	97%

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Total Organic Carbon, mg/L	Total Oil, mg/L	Total Petroleum Hydrocarbons, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU	Conductivity, umhos/cm	Alkalinity, mg/L
True Value							0.180		16.0	718	94.0
Det'd Value							0.186		16.0	679	90.2
% Recovery	NA	NA	NA	NA	NA	NA	104%	NA	100%	95%	96%

Laboratory Duplicate Samples (25%RPD)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Total Organic Carbon, mg/L	Total Oil, mg/L	Total Petroleum Hydrocarbons, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU	Conductivity, umhos/cm	Alkalinity, mg/L
Sample			L7298-3				L7314-1	L7298-1	L7294-3	L7298-2	L7341-1
Result 1			2.96				0.337	92.5	4.5	100.6	25.6
Result 2			2.69				0.356	104.5	4.4	100.8	26.1
Rel. % Diff.	NA	NA	10%	NA	NA	NA	-5%	-12%	2%	0%	-2%

Laboratory Spiked Samples (70 - 130%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Total Organic Carbon, mg/L	Total Oil, mg/L	Total Petroleum Hydrocarbons, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU	Conductivity, umhos/cm	Alkalinity, mg/L
Sample			L7298-3				L7314-1				
Result 1			2.96				0.337				
Spike Amount			10.00				0.100				
Result 2			15.64				0.433				
% Recovery	NA	NA	127%	NA	NA	NA	96%	NA	NA	NA	NA

KCRM Shoulders Project (November 8, 1995) QA/QC Data Summary

Laboratory Method Blank

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Total Organic Carbon, mg/L	Total Oil, mg/L	Total Petroleum Hydrocarbons, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU	Conductivity, umhos/cm
Result										
Blank	<MDL	NA	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	NA	NA

Laboratory Positive Control (80 - 120%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Total Organic Carbon, mg/L	Total Oil, mg/L	Total Petroleum Hydrocarbons, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU	Conductivity, umhos/cm
True Value	300	100	10.00	53.1	32.9	0.030	0.030		2.0	74.0
Det'd Value	296	110	8.37	50.7	30.9	0.033	0.032		2.0	71.0
% Recovery	99%	110%	84%	95%	94%	110%	108%	NA	100%	96%

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Total Organic Carbon, mg/L	Total Oil, mg/L	Total Petroleum Hydrocarbons, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU	Conductivity, umhos/cm
True Value						0.180	0.180		16.0	74.0
Det'd Value						0.188	0.186		16.0	70.8
% Recovery	NA	NA	NA	NA	NA	104%	104%	NA	100%	96%

Laboratory Duplicate Samples (25%RPD)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Total Organic Carbon, mg/L	Total Oil, mg/L	Total Petroleum Hydrocarbons, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU	Conductivity, umhos/cm
Sample			L7314-2			L7314-4	L7314-1	L7341-2	L7314-1	L7314-1
Result 1			8.27			MDL	0.337	41.67	136	47.37
Result 2			8.07			MDL	0.356	39.5	136	47.26
Rel. % Diff.	NA	NA	2%	NA	NA	NA	-5%	5%	0%	0%

Laboratory Spiked Samples (70 - 130%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Total Organic Carbon, mg/L	Total Oil, mg/L	Total Petroleum Hydrocarbons, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU	Conductivity, umhos/cm
Sample			L7314-2			L7314-4	L7314-1			
Result 1			8.27			0.007	0.337			
Spike Amount			10.00			0.100	0.100			
Result 2			17.72			0.135	0.433			
% Recovery	NA	NA	94%	NA	NA	128%	96%	NA	NA	NA

KCRM Shoulders Project (November 18, 1995) QA/QC Data Summary

Laboratory Method Blank

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Total Organic Carbon, mg/L	Total Oil, mg/L	Total Petroleum Hydrocarbons, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU	Conductivity, umhos/cm	Alkalinity, mg/L
Result						0.003					
Blank	<MDL	NA	<MDL	<MDL	<MDL	<RDL	<MDL	<MDL	NA	NA	NA

Laboratory Positive Control (80 - 120%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Total Organic Carbon, mg/L	Total Oil, mg/L	Total Petroleum Hydrocarbons, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU	Conductivity, umhos/cm	Alkalinity, mg/L
True Value	300	100	10.00	45.2	23.0	0.030	0.030		16.0	74.0	94.0
Det'd Value	288	110	10.42	42.4	19.5	0.033	0.032		16.0	71.6	90.4
% Recovery	96%	110%	104%	94%	85%	110%	108%	NA	100%	97%	96%

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Total Organic Carbon, mg/L	Total Oil, mg/L	Total Petroleum Hydrocarbons, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU	Conductivity, umhos/cm	Alkalinity, mg/L
True Value						0.180	0.180				94.0
Det'd Value						0.178	0.173				90.5
% Recovery	NA	NA	NA	NA	NA	99%	96%	NA	NA	NA	96%

Laboratory Duplicate Samples (25%RPD)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Total Organic Carbon, mg/L	Total Oil, mg/L	Total Petroleum Hydrocarbons, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU	Conductivity, umhos/cm	Alkalinity, mg/L
Sample			L7372-5			L7372-5	L7372-4	L7372-2	L7372-5	L7372-3	L7372-4
Result 1			7.50			0.019	0.509	172	19	64.2	14.8
Result 2			7.57			0.017	0.504	169.0	18	64.1	14.9
Rel. % Diff.	NA	NA	-1%	NA	NA	11%	1%	2%	5%	0%	0%

Laboratory Spiked Samples (70 - 130%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Total Organic Carbon, mg/L	Total Oil, mg/L	Total Petroleum Hydrocarbons, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU	Conductivity, umhos/cm	Alkalinity, mg/L
Sample			L7372-5			L7372-5	L7372-4				
Result 1			7.50			0.019	0.509				
Spike Amount			10.00			0.100	0.100				
Result 2			17.94			0.117	0.630				
% Recovery	NA	NA	104%	NA	NA	98%	121%	NA	NA	NA	NA

KCRM Shoulders Project (November 28, 1995) QA/QC Data Summary

Laboratory Method Blank

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Total Organic Carbon, mg/L	Total Oil, mg/L	Total Petroleum Hydrocarbons, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU	Conductivity, umhos/cm	Alkalinity, mg/L
Result											
Blank	<MDL	NA	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	NA	NA	NA

Laboratory Positive Control (80 - 120%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Total Organic Carbon, mg/L	Total Oil, mg/L	Total Petroleum Hydrocarbons, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU	Conductivity, umhos/cm	Alkalinity, mg/L
True Value	300	100	10.00	48.5	23.4	0.030	0.020		2.0	74.0	94.0
Det'd Value	288	110	10.33	46.7	21.2	0.032	0.022		2.2	72.3	89.6
% Recovery	96%	110%	103%	96%	91%	107%	110%	NA	110%	98%	95%

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Total Organic Carbon, mg/L	Total Oil, mg/L	Total Petroleum Hydrocarbons, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU	Conductivity, umhos/cm	Alkalinity, mg/L
True Value						0.180	0.180		40.0		94.0
Det'd Value						0.174	0.182		39.0		90.0
% Recovery	NA	NA	NA	NA	NA	97%	101%	NA	98%	NA	96%

Laboratory Duplicate Samples (25%RPD)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Total Organic Carbon, mg/L	Total Oil, mg/L	Total Petroleum Hydrocarbons, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU	Conductivity, umhos/cm	Alkalinity, mg/L
Sample			L7396-3			L7439-3	L7181-3	L7396-3	L7372-5	L7396-6	L7396-1
Result 1			4.63			0.013	0.155	33.5	19	17.37	11.3
Result 2			4.60			0.012	0.150	38.5	18	17.44	11.3
Rel. % Diff.	NA	NA	1%	NA	NA	8%	3%	-14%	5%	0%	1%

Laboratory Spiked Samples (70 - 130%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Total Organic Carbon, mg/L	Total Oil, mg/L	Total Petroleum Hydrocarbons, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU	Conductivity, umhos/cm	Alkalinity, mg/L
Sample			L7396-3			L7439-3	L7181-3				
Result 1			4.63			0.013	0.155				
Spike Amount			10.00			0.100	0.100				
Result 2			14.82			0.112	0.226				
% Recovery	NA	NA	102%	NA	NA	99%	71%	NA	NA	NA	NA

KCRM Shoulders Project (January 16, 1996) QA/QC Data Summary

Laboratory Method Blank

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Total Oil, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Result								
Blank	<MDL	<MDL	NA	<MDL	<MDL	<MDL	<MDL	NA

Laboratory Positive Control (80 - 120%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Total Oil, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
True Value	300	100	73.9	294	0.030	0.030		5.0
Det'd Value	233	112	66.6	281	0.031	0.036		5.4
% Recovery	78%	112%	90%	96%	103%	120%	NA	108%

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Total Oil, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
True Value			717.8		0.180	0.180		40
Det'd Value			648.6		0.184	0.181		41
% Recovery	NA	NA	90%	NA	102%	101%	NA	103%

Laboratory Duplicate Samples (25%RPD)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Total Oil, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Sample		L7690-5	L7690-2		L7690-8	L7690-8	L7690-6	L7690-5
Result 1		43	26.1		<RDL	0.137	46	19
Result 2		46	26.1		<RDL	0.134	47.4	20
Rel. % Diff.	NA	-7%	0%	NA	NA	2%	-3%	-5%

Laboratory Spiked Samples (70 - 130%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Total Oil, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Sample					L7690-8	L7690-8		
Result 1					0.004	0.137		
Spike Amount					0.100	0.100		
Result 2					0.107	0.237		
% Recovery	NA	NA	NA	NA	103%	100%	NA	NA

KCRM Shoulders Project (January 21, 1996) QA/QC Data Summary

Laboratory Method Blank

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Total Oil, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Result								
Blank	<MDL	<MDL	NA	<MDL	<MDL	<MDL	<MDL	NA

Laboratory Positive Control (80 - 120%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Total Oil, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
True Value	300	100	73.9	253	0.030	0.030		40.0
Det'd Value	226	113	66.6	236	0.027	0.031		42.0
% Recovery	75%	113%	90%	93%	90%	103%	NA	105%

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Total Oil, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
True Value			717.8		0.180	0.180		
Det'd Value			648.6		0.183	0.173		
% Recovery	NA	NA	90%	NA	102%	96%	NA	NA

Laboratory Duplicate Samples (25%RPD)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Total Oil, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Sample		L7690-5	L7721-3		L7721-9	L7722-2	L7721-4	L7721-3
Result 1		43	17.0		0.0105	0.069	37.33	27
Result 2		46	17.0		0.01	0.058	40.0	28
Rel. % Diff.	NA	-7%	0%	NA	5%	17%	-7%	-4%

Laboratory Spiked Samples (70 - 130%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Total Oil, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Sample					L7721-9	L7722-2		
Result 1					0.0105	0.069		
Spike Amount					0.100	0.100		
Result 2					0.116	0.167		
% Recovery	NA	NA	NA	NA	105%	98%	NA	NA

KCRM Shoulders Project (February 5, 1996) QA/QC Data Summary

Laboratory Method Blank

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Total Oil, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Result								
Blank	NA	NA	NA	<MDL	<MDL	<MDL	<MDL	NA

Laboratory Positive Control (80 - 120%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Total Oil, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
True Value	300	100	73.9	289.9	0.030	0.030		40.0
Det'd Value	206	117	69.0	272.8	0.030	0.027		42.0
% Recovery	69%	117%	93%	94%	100%	90%	NA	105%

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Total Oil, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
True Value	300	100.00	717.8		0.180	0.180		
Det'd Value	245	117	637.6		0.181	0.176		
% Recovery	82%	117%	89%	NA	101%	98%	NA	NA

Laboratory Duplicate Samples (25%RPD)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Total Oil, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Sample	L7816-7	L7816-7	L7824-1		L7816-7	L7816-3	L7823-2	L7816-2
Result 1	9.5	77	116.8		0.015	1.045	68	540
Result 2	9.3	74	116.9		0.016	1.085	67.0	580
Rel. % Diff.	2%	4%	0%	NA	-6%	-4%	1%	-7%

Laboratory Spiked Samples (70 - 130%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Total Oil, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Sample					L7816-7	L7825-7		
Result 1					0.015	0.181		
Spike Amount					0.100	0.100		
Result 2					0.129	0.283		
% Recovery	NA	NA	NA	NA	114%	103%	NA	NA

KCRM Shoulders Project (February 21, 1996) QA/QC Data Summary

Laboratory Method Blank

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Oil and Grease, Total, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Result								
Blank	<MDL	<MDL	NA	<MDL	<MDL	<MDL	<MDL	<MDL

Laboratory Positive Control (80 - 120%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Oil and Grease, Total, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
True Value	300.0	100	73.90	249.00	0.03	0.030		5
Det'd Value	290.2	120	77.53	234.10	0.03	0.035		5
% Recovery	97%	120%	105%	94%	110%	117%	NA	100%

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Oil and Grease, Total, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
True Value			717.8		0.180	0.180		
Det'd Value			731.6		0.173	0.188		
% Recovery	NA	NA	102%	NA	96%	104%	NA	NA

Laboratory Duplicate Samples (25%RPD)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Oil and Grease, Total, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Sample	L7962-2	L7962-6	L7962-4		L7962-7	L7962-6	L7968-1	L7962-4
Result 1	3.9	35	44.82		<RDL	0.188	36.20	42
Result 2	4.3	36	44.87		0.006	0.208	32.44	41
Rel. % Diff.	-10%	-3%	0%	NA	NA	-10%	11%	2%

Laboratory Spiked Samples (70 - 130%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Oil and Grease, Total, mg/L	Ortho Phosphorus, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Sample					L7962-7	L7962-6		
Result 1					0.004	0.188		
Spike Amount					0.100	0.100		
Result 2					0.115	0.297		
% Recovery	NA	NA	NA	NA	111%	109%	NA	NA

KCRM Shoulders Project (April 1, 1996) QA/QC Data Summary

Laboratory Method Blank

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Ortho Phosphorus, mg/L	Total Oil and Grease, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Result								
Blank	NA	NA	NA	<MDL	<MDL	<MDL	<MDL	NA

Laboratory Positive Control (80 - 120%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Ortho Phosphorus, mg/L	Total Oil and Grease, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
True Value	300	100	73.9	0.03	245.9	0.03		40
Det'd Value	287	102	75.1	0.03	226.0	0.03		44
% Recovery	96%	102%	102%	90%	92%	93%	NA	110%

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Ortho Phosphorus, mg/L	Total Oil and Grease, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
True Value		100	717.8	0.180		0.180		40
Det'd Value		115	703.7	0.177		0.186		40
% Recovery	NA	115%	98%	98%	NA	103%	NA	100%

Laboratory Duplicate Samples (25%RPD)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Ortho Phosphorus, mg/L	Total Oil and Grease, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Sample	L8204-9	L8204-9	L8204-9	L8204-9		L8204-5	L8204-1	L8204-1
Result 1	3.276	22	24.43	0.006		0.321	160.00	36
Result 2	3.324	25	24.27	0.007		0.336	164.00	34
Rel. % Diff.	-1%	-13%	1%	-15%	NA	-5%	-2%	6%

Laboratory Spiked Samples (70 - 130%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Ortho Phosphorus, mg/L	Total Oil and Grease, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Sample				L8204-9		L8204-5		
Result 1				0.006		0.321		
Spike Amount				0.100		0.100		
Result 2				0.114		0.429		
% Recovery	NA	NA	NA	108%	NA	108%	NA	NA

KCRM Shoulders Project (April 17, 1996) QA/QC Data Summary

Laboratory Method Blank

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Ortho Phosphorus, mg/L	Total Oil and Grease, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Result								
Blank	NA	NA	NA	<MDL	<MDL	<MDL	<MDL	NA

Laboratory Positive Control (80 - 120%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Ortho Phosphorus, mg/L	Total Oil and Grease, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
True Value	300	100	73.9	0.03	252.7	0.028		40
Det'd Value	243	115	73.3	0.03	237.5	0.03		41
% Recovery	81%	115%	99%	100%	94%	100%	NA	103%

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Ortho Phosphorus, mg/L	Total Oil and Grease, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
True Value		100	717.8	0.180		0.180		5.0
Det'd Value		110	699.3	0.181		0.180		5.6
% Recovery	NA	110%	97%	101%	NA	100%	NA	112%

Laboratory Duplicate Samples (25%RPD)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Ortho Phosphorus, mg/L	Total Oil and Grease, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Sample	L8290-7	L8290-7	L8290-6	L8290-9		L8290-6	L8290-2	L8290-1
Result 1	3.56	30	29.07	0.004		0.341	346.5	14
Result 2	3.92	30	29.16	0.004		0.321	344.5	14
Rel. % Diff.	-10%	0%	0%	0%	NA	6%	1%	0%

Laboratory Spiked Samples (70 - 130%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, umhos/cm	Ortho Phosphorus, mg/L	Total Oil and Grease, mg/L	Total Phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Sample				L8290-9		L8290-6		
Result 1				0.004		0.341		
Spike Amount				0.100		0.100		
Result 2				0.124		0.445		
% Recovery	NA	NA	NA	120%	NA	104%	NA	NA

KCRM - Shoulders (August 2, 1996) QA/QC Data Summary

Laboratory Method Blank

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, uS/cm	Total Oil and Grease, mg/L	Ortho phosphorus, mg/L	Total phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Result				<MDL	0.002	<MDL	<MDL	<MDL
Blank	NA	NA	NA	<MDL	=MDL	<MDL	<MDL	<MDL

Laboratory Positive Control (80-120%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, uS/cm	Total Oil and Grease, mg/L	Ortho phosphorus, mg/L	Total phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
True Value	300	100	73.9	271	0.180	0.180		40
Det'd Value	312	111	72.9	254	0.182	0.181		45
% Recovery	104%	111%	99%	94%	101%	101%	NA	113%

Laboratory Duplicate Samples (25%RPD)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, uS/cm	Total Oil and Grease, mg/L	Ortho phosphorus, mg/L	Total phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Sample		L9226-8	L9207-4		L9207-5	L9207-7	L9207-7	L9207-2
Result 1		40	59.1		0.082	0.295	19.40	28
Result 2		35	59.2		0.081	0.290	24.30	27
Rel. % Diff.	NA	13%	0%	NA	1%	2%	22%	4%

Laboratory Spiked Samples (70 - 130%)

Parameter	Biochemical Oxygen Demand, mg/L	Chemical Oxygen Demand, mg/L	Conductivity, uS/cm	Total Oil and Grease, mg/L	Ortho phosphorus, mg/L	Total phosphorus, mg/L	Total Suspended Solids, mg/L	Turbidity, NTU
Sample					L9207-5	L9234-11		L9116-3
Result 1					0.082	0.095		84.3
Spike Amount					0.100	0.100		250
Result 2					0.195	0.186		317
% Recovery	NA	NA	NA	NA	113%	91%	NA	93%

APPENDIX C -- Absolute Loads

Absolute loads were calculated based on the probabilistic method described by Marsalek (1990) and discussed in Chapter 2. Absolute loads have been caluculated for the following conditions:

- A "typical" wet season storm of 0.5 inches;
- The entire wet season from November to April, based on rain gauge data from Cottage Lake Park for the 1995 water year. The load estimate for this period excludes storms which follow sanding operations.
- A "typical" sanding event storm, based on conditions from the February 5, 1996 storm.
- A "typical" summer event storm, based on conditions from the August 2, 1996 storm.

The runoff coefficients used to calculate the loads are presented in Table 4.5. The load estimations for the wet season storm and entire wet season include 95% confidence intervals.

Table C.1 Wet Season Storm (0.5") Loads

Loads are reported in mass/area/time. The mass is reported in grams. The area is that of an individual shoulder test section (400 ft^2), and is reported as (site). The time is the duration of a 0.5" storm, and is reported as (storm). Thus the units are: g/site/ wet season storm.

The 95% Confidence Intervals are reported.

Parameter	Conventional Asphalt	Gravel	Porous
TSS	47.76<68.76<98.98	45.48<50.74<56.65	1.57<2.23<3.16
TP	0.202<0.237<0.279	0.178<0.193<0.209	0.012<0.014<0.016
OP	0.007<0.009<0.011	0.009<0.011<0.013	0.0006<0.0008<0.0009
BOD	4.83<5.57<6.43	3.68<4.42<5.30	0.56<0.91<1.48
COD	39.76<48.35<58.79	18.64<21.14<23.98	2.40<2.99<3.77
Cu	0.0078<0.0086<0.0095	0.0075<0.0080<0.0086	0.0005<0.0006<0.0007
Pb	0.0157<0.0226<0.0327	0.0059<0.0063<0.0069	0.0005<0.0006<0.0008
Zn	0.0467<0.0543<0.0630	0.0264<0.0287<0.0313	0.0032<0.0050<0.0079
O&G	9.48<11.87<14.86	5.71<7.66<10.26	0.99<1.04<1.10
HOR	1.83<2.01<2.20	0.70<0.80<0.92	0.11<0.12<0.13
DR	0.77<0.83<0.90	0.37<0.45<0.54	0.07<0.09<0.11

Table C.2 Wet Season (November to April) Loads

Loads are reported in mass/area/time. The mass is reported in grams, with the exception of TSS and COD which are reported in kilograms. The area is that of an individual shoulder test section (400 ft^2), and is reported as (site). The time is the duration of the wet season (November to April), and is reported as (season). Thus the units are: g/site/season for all parameters except TSS and COD which are: kg/site/wet season.

The 95% Confidence Intervals are reported.

Parameter	Conventional Asphalt	Gravel	Porous Asphalt
TSS	2.67<3.85<5.54	2.54<2.84<3.17	0.09<0.12<0.18
TP	11.31<13.28<15.60	9.98<10.80<11.69	0.65<0.77<0.91
OP	0.38<0.48<0.61	0.53<0.61<0.71	0.037<0.044<0.053
BOD	270.10<311.74<359.79	205.89<247.15<296.69	31.40<51.10<83.16
COD	2.226<2.706<3.291	1.043<1.183<1.342	0.135<0.167<0.208
Cu	0.44<0.48<0.53	0.42<0.45<0.58	0.03<0.03<0.04
Pb	0.88<1.27<1.83	0.33<0.36<0.38	0.03<0.04<0.05
Zn	2.62<3.04<3.53	1.48<1.61<1.75	0.18<0.28<0.44
O&G	530.64<664.41<831.90	319.78<428.44<574.02	55.67<58.52<61.52
HOR	102.49<112.28<123.00	39.14<44.94<51.60	5.93<6.63<7.41
DR	43.06<46.56<50.34	20.65<25.04<30.36	3.98<4.90<6.04

Table C.3 Sanding Event Storm (0.8") Loads

Loads are reported in mass/area/time. The mass is reported in grams. The area is that of an individual shoulder test section (400 ft^2), and is reported as (site). The time is the duration of the sanding event storm, and is reported as (storm). Thus the units are: g/site/sanding event storm.

Parameter	Conventional Asphalt	Gravel	Porous Asphlat
TSS	649.98	324.95	150.17
TP	2.21	1.49	0.53
OP	0.055	0.064	0.011
BOD	16.85	9.93	7.92
COD	194.83	100.75	66.39
Cu	0.071	0.040	0.018
Pb	0.197	0.085	0.049
Zn	0.485	0.217	0.121
O&G	17.25	105.72	2.98
HOR	2.29	3.85	2.64
DR	NA	NA	NA

Table C.4 Summer Event Storm (1.5") Loads

Loads are reported in mass/area/time. The mass is reported in grams. The area is that of an individual shoulder test section (400 ft^2), and is reported as (site). The time is the duration of the sanding event storm, and is reported as (storm). Thus the units are: g/site/summer event storm.

Parameter	Conventional Asphalt	Gravel	Porous Asphlat
TSS	305.22	323.23	104.18
TP	1.26	1.79	0.59
OP	0.287	0.167	0.146
BOD	70.46	63.78	47.26
COD	230.54	207.79	93.07
Cu	0.055	0.064	0.034
Pb	0.098	0.061	0.021
Zn	0.282	0.228	0.143
O&G	39.45	19.91	21.79
HOR	6.19	3.90	1.97
DR	3.69	2.46	2.88

Appendix D -- Porous Asphalt Road Shoulder Hydraulics Model

The prediction of the hydraulic characteristics of porous asphalt road shoulders, and the simulation of their response under varying storm conditions is a necessary task if porous asphalt road shoulders are to be used for stormwater detention. A two-dimentional dynamic water budget model was developed in Stella™ by Doell (1995) for analysis of flow and storage of runoff in porous asphalt road shoulders.

The model developed by Doell (1995) incorporates a mass balance approach applied to the porous asphalt pavement and the underlying soil base course. For a complete discussion of the model development and operation see the discussion by Doell (1995). Inflow to the porous asphalt pavement was expressed as the sum of runoff from the adjacent road and direct precipitation onto the porous pavement. Outflow from the porous asphalt pavement was a function of both vertical movement to the underlying soil layer and surface runoff. The vertical movement to the underlying soil layer is determined by the limiting permeability of the two layers. Surface runoff from the pavement is a function of the storage capacity of the porous asphalt pavement and the underlying soil. Horizontal discharge from the porous pavement or soil base course was expressed as a function of Darcy's Law.

Modifications to Porous Pavement Hydraulics Model

Several modifications have been made to the Stella™ model developed by Doell (1995). For purposes of calibrating the modified model, simulations were made based on data from the rain simulation/overland flow experiments (presented in Chapters 3 and 4). The original model incorporated a horizontal drainage component for the soil base course and porous pavement layer based on Darcy's Law. Horizontal drainage from the porous asphalt layer at the Cottage Lake site was not possible, however, due to the positioning of slot drains which were installed on the downslope side of the shoulders, and acted as a barrier to horizontal discharge from the porous pavement. Therefore, for purposes of calibrating the model using data from the site, this component of the model was eliminated.

The most significant modification to the model involved the storage capacity of the porous pavement. The original model did not account for the slope of the shoulder, and therefore predicted a larger storage capacity of the pavement. By considering the slope of the shoulder the storage capacity was decreased by almost half.

A diagram of the modified model is presented in Figure D.1. The calculations and variables used in the model, and comments about these calculations and variables, are presented in Table D.1.

Model Calibration

Data from the rain simulation/overland flow experiments were used in order to calibrate the modified model. The "rain intensity" and "storm size" used in the rain simulation experiments were used as inputs to the model. The amount of runoff predicted by the model simulation was then compared to the observed runoff from the actual rain simulation experiments.

The permeability of the soil underlying the porous asphalt pavement at the Cottage Lake site was not known. Based on the known properties of the soil (Table 3.1) it was assumed the soil permeability would be fairly high. When the soil permeability was set at high rates (≥0.2 in/hr) however, the model results did not match the obsrved runoff quantities. Therefore, for purposes of calibrating the model to produce a quantity of runoff equivalent to that observed in the rain simulation experiments, the soil permeability was set at zero. A soil permeability of zero inches/hour does not seem realistic, but was required to yield results similar to those observed in the rain simulation experiments.

The results from two model simulations are shown in Figures D.2 and D.3. The simulation shown in Figure D.2 was based on a rain simulation experiment with the following properties: rain intensity of 0.05 in/hr lasting four hours, producing a storm size of 0.2 inches. During this rain simulation experiment the total "rain" input volume was 357 L, and the observed volume of runoff was 36 L, yielding a runoff coefficient of 0.10. The model output from this simulation predicted 33 L of runoff from a total input volume of 340 L, yielding a runoff coefficient of 0.097.

The simulation shown in Figure D.3 was based on a rain simulation experiment with the following properties: rain intensity of 0.25 in/hr lasting 50 minutes, producing a storm size of 0.2 inches. During this rain simulation experiment the total "rain" input

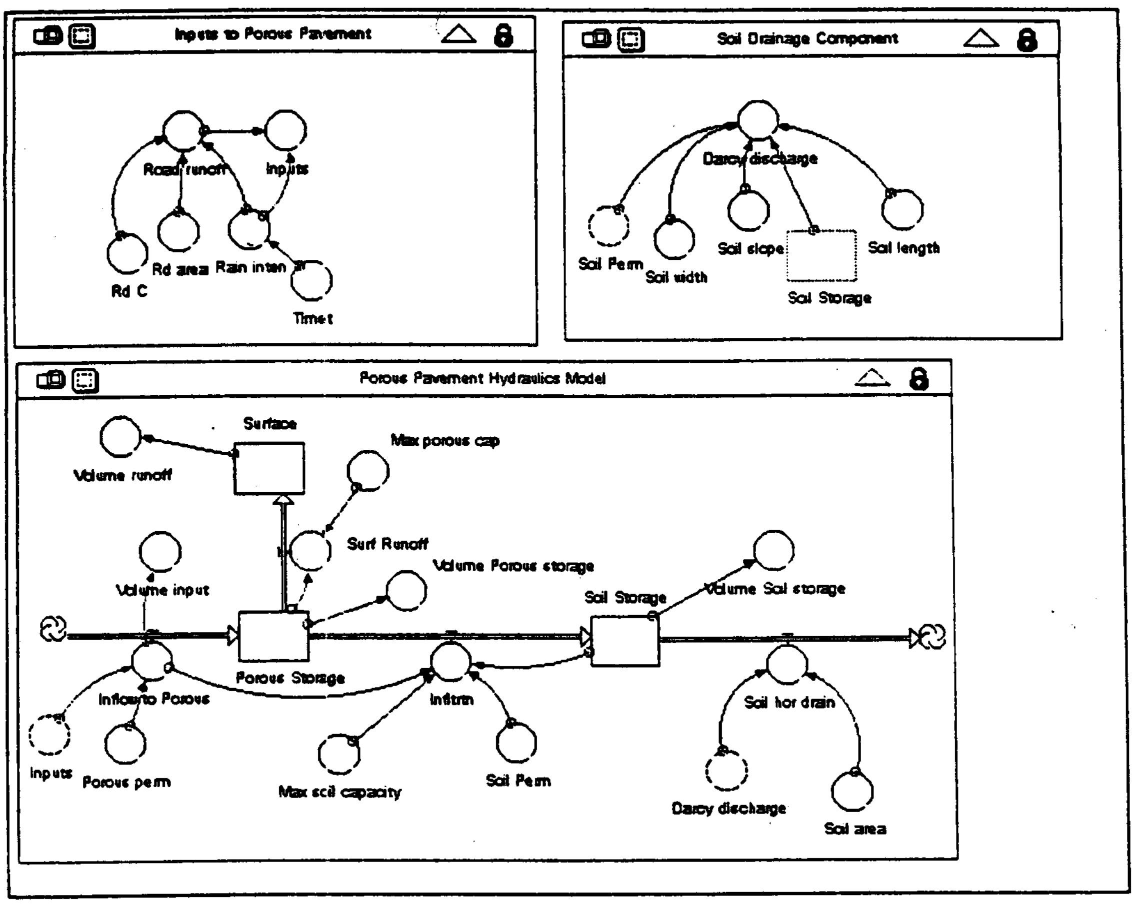

Figure D.1 Modified Porous Asphalt Hydraulics Model

Table D.1 Equations for Modified Porous Asphalt Hydraulics Model

Porous Pavement Hydraulics Model Equations

Inputs to Porous Pavement:
Inputs = Road_runoff+Rain_inten
DOCUMENT: Inputs to porous pavement (in/hr).

Rd_area = 0.013
DOCUMENT: Area of road contributing runoff to shoulder (acres).

Rd_C = 0.9
DOCUMENT: Runoff coeff for road

Road_runoff = ((Rd_C*Rain_inten*Rd_area)/384)*43200
DOCUMENT: Runoff from road. Used rational method to get cfs, then convert to in/hr by dividing by area of porous pavement, and multiply by convertion factor.

Timet = TIME
Rain_inten = GRAPH(Timet)
(0.00, 0.00), (0.25, 0.25), (0.5, 0.25), (0.75, 0.25), (1.00, 0.25), (1.25, 0.25), (1.50, 0.25), (1.75, 0.25), (2.00, 0.25), (2.25, 0.25), (2.50, 0.00), (2.75, 0.00), (3.00, 0.00), (3.25, 0.00),
DOCUMENT: Rainfall intensity (in/hr). For calibration used 0.25 in/hr for whole storm.

Main Model
Porous_Storage(t) = Porous_Storage(t - dt) + (Inflow_to_Porous - Infltrtn - Surf_Runoff) * dt
INIT Porous_Storage = 0
DOCUMENT: Storage of water in porous pavement reservoir (Inches).

Inflow_to_Porous = MIN(Inputs,Porous_perm)
DOCUMENT: Inflow to porous pavement (in/hr).

Infltrtn =
IF(Max_soil_capacity>Soil_Storage)THEN(MIN(Inflow_to_Porous,Soil_Perm))ELSE(IF(Max_soil_capacity<Soil_Storage)THEN(0)ELSE(0))

Surf_Runoff = IF(Porous_Storage>Max_porous_cap)THEN(Porous_Storage-Max_porous_cap)ELSE(0)
DOCUMENT: Surface runoff from porous pavement (in/hr).

Soil_Storage(t) = Soil_Storage(t - dt) + (Infltrtn - Soil_hor_drain) * dt
INIT Soil_Storage = 0
DOCUMENT: Storage of water in soil reservoir in Inches.

Infltrtn =
IF(Max_soil_capacity>Soil_Storage)THEN(MIN(Inflow_to_Porous,Soil_Perm))ELSE(IF(Max_soil_capacity<Soil_Storage)THEN(0)ELSE(0))

Soil_hor_drain = Darcy_discharge/Soil_area
DOCUMENT: Horizontal drainage from soil reservoir, based on Darcy's Law. In/hr.

Surface(t) = Surface(t - dt) + (Surf_Runoff) * dt
INIT Surface = 0
DOCUMENT: Depth of surface runoff from porous pavement (inches).

Surf_Runoff = IF(Porous_Storage>Max_porous_cap)THEN(Porous_Storage-Max_porous_cap)ELSE(0)
DOCUMENT: Surface runoff from porous pavement (in/hr).

Max_porous_cap = 0.26
DOCUMENT: Maximum storage capacity of porous pavement (inches). Based on porous void volume (0.15), volume of porous reservoir (112 ft^3), and slope of pavement which limits pavement storage volume. Then divided by area of pavement to give depth of storage.

Max_soil_capacity = 16.8
DOCUMENT: This is the maximum depth of water the soil reservoir can hold (inches). Based on soil porosity and volume of soil reservoir.

Porous_perm = 1750
DOCUMENT: Porous pavement permeability (in/hr) based on field test at shoulder site.

Soil_area = 55296
DOCUMENT: Area of soil reservoir. Recorded in in^2 for conversion purposes.

Soil_Perm = 0
DOCUMENT: Permeability of soil (in/hr); based on estimates from Dunn and Leopold, 1978.

Volume_input = Inflow_to_Porous/12*384*28.3
DOCUMENT: Volume of input at time X (L).

Volume_Porous_storage = Porous_Storage/12*384*28.3
DOCUMENT: Volume of storage in porous pavement (L).

Volume_runoff = Surface/12*384*28.3
DOCUMENT: Volume of surface runoff (L).

Volume_Soil_storage = Soil_Storage/12*384*28.3
DOCUMENT: Volume of storage in soil (L)

Soil Drainage Component
Darcy_discharge =
((Soil_Perm*Soil_width*Soil_slope*Soil_Storage)/2)+((Soil_Perm*Soil_width*Soil_Storage^2)/2*Soil_length)
DOCUMENT: Horizontal discharge from soil reservoir, based on Darcy's Law. In cubic inches per hour.

Soil_length = 96
DOCUMENT: Length of soil reservoir; same as lenght of porous. This is length in direction of flow. Recorded in Inches.

Soil_slope = 0.125
DOCUMENT: There is approximately a 12% slope on shoulders.

Soil_width = 576
DOCUMENT: Width of the soil reservoir; same as width of porous pavement. This is the width perpendicular to flow. Recorded in Inches

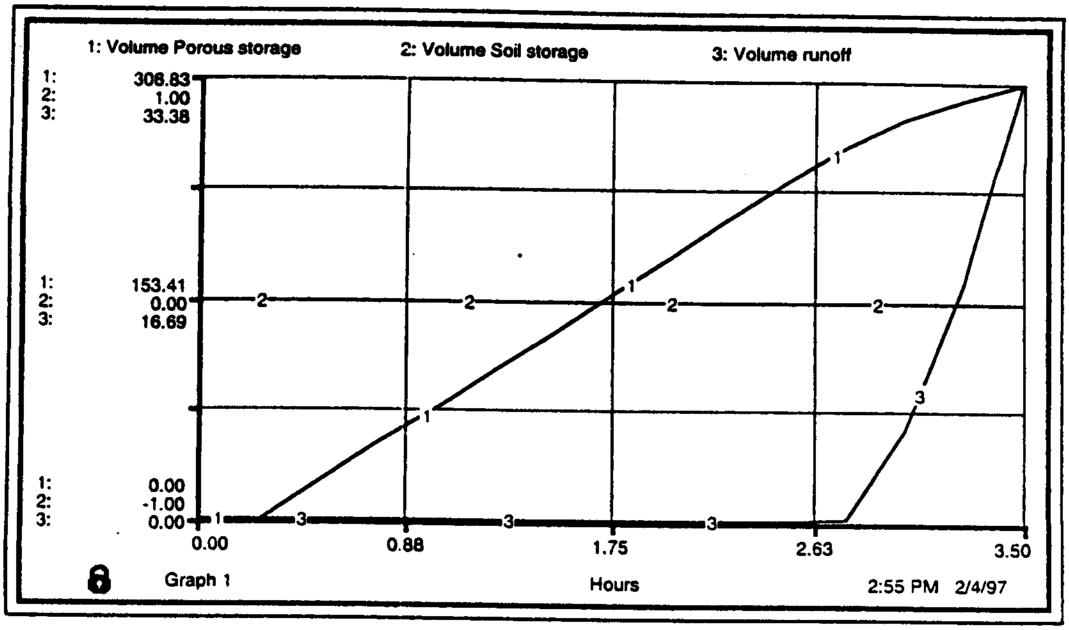

Figure D.2 0.05 In/hr Storm Simulation Results

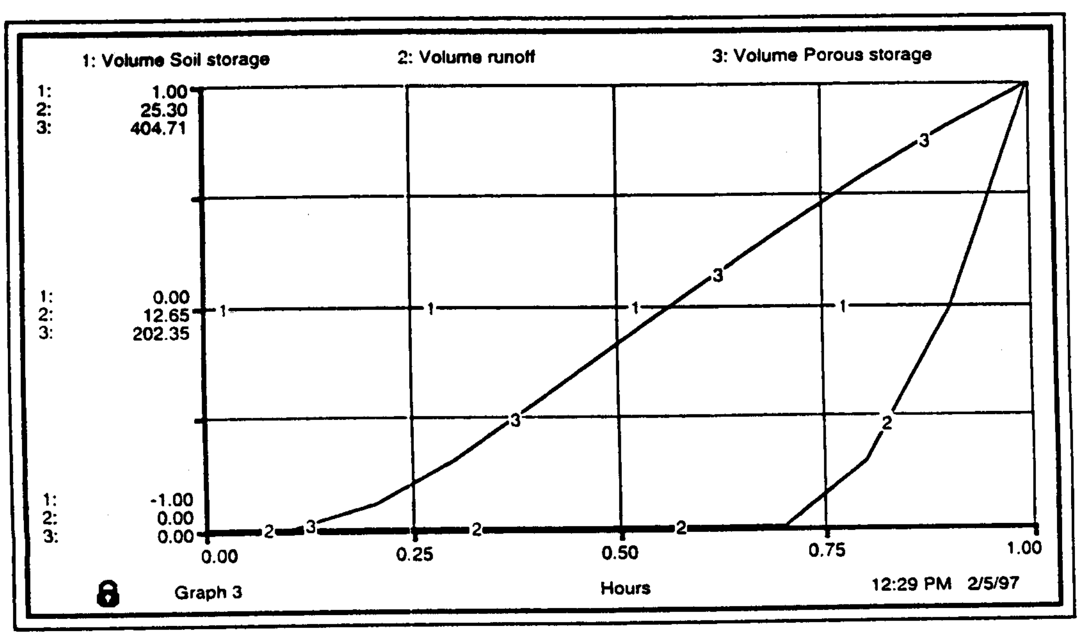

Figure D.3 0.25 In/hr Storm Simulation Results

volume was 365 L, and the observed amount of runoff was 47 L, yielding a runoff coefficient of 0.13. The model output from this simulation produced 25 L of runoff from a total input volume of 430 L, yielding a runoff coefficient of 0.06.

The results of the simulation shown in Figure A.2 are very similar to the observed results in the rain simulation experiment. The amount of runoff from the simulation shown in Figure A.3, on the other hand, was about half that observed in the rain simulation experiment. The difference in the model results based on the varying "storm" conditions indicates the model variables need fine-tuning.

Recommendations for Further Model Modification

Several factors could be included or modified in the model. The rain simulation experiments were conducted during the summer, primarily on days when the sun was shining directly onto the porous asphalt shoulders. It is likely that there were evaporation losses during some of the rain simulation experiments. In order to better calibrate the model, evaporation may need to be included.

The model simulations presented here used a soil permeability rate of zero. The variation in the model outputs under varying conditions indicates that this soil permeability is probably not representative of actual conditions. Soil permeability rates will change somewhat throughout the duration of a storm. Rather than using a fixed soil permeability, it may be necessary to include a first order decay coefficient for the soil permeability.

Finally, the storage capacity of the soil layer and porous pavement is constant in the current model. The storage capacity of both of these compartments will vary. The storage capacity of the soil will be affected by the surface water table. The storage capacity of the porous pavement may be affected if the void spaces become clogged with solids. These factors should be considered in further model developments.