George Wuerch, Mayor

Anchorage OGS and Street Sweeping as Storm Water Controls: Performance Analysis

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MUNICIPALITY OF ANCHORAGE
WATERSHED MANAGEMENT PROGRAM

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Office of Planning, Development & Public Works

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Acronyms and Abbreviations

ADOT&PF	Alaska Department of Transportation and Public Facilities
BMP	best management practice
DCM	Design Criteria Manual
DPW	Department of Public Works
EPA	United States Environmental Protection Agency
ft	foot
g	gram
gpm	gallons per minute
Kg	kilogram
μm	micron
MOA	Municipality of Anchorage
NPDES	National Pollutant Discharge and Elimination System
OGS	oil and grit separator
SWMM	storm water management model
WMP	Watershed Management Program
WMS	Watershed Management Section

Summary

This report presents the findings from three analyses targeted to answer a series of related questions.

1. Under what circumstances are oil and grit separators (OGS) cost-effective?

In 1999, the Municipality of Anchorage (MOA) Watershed Management Section (WMS) undertook a modeling effort utilizing algorithms from the Environmental Protection Agency (EPA) storm water management model (SWMM) to assess OGS sizing, cost, and efficiency for 382 drainage basins in the Municipality of Anchorage.

This report reviews the results of that effort (MOA, WMS, 1999a) to determine the annual cost per kilogram (Kg) of sediment removed by OGS devices. This report presents the correlation of cost per kg removed, removal efficiency, and basin characteristics.

2. What is the expected effectiveness of commercial grit separators in Anchorage? What removal criteria should be recommended for OGS and commercial grit separators?

In 2000, as part of a stormwater outfall upgrade, the MOA evaluated the feasibility of installing a commercial grit separator on a storm sewer outfall to Chester Creek (CRW, 2000). The design study for this project recommended further evaluation to determine the feasibility of these devices in Anchorage. For this report, data from three commercial grit separator vendors was reviewed for the purpose of recommending a removal criteria for the MOA Design Criteria Manual (DCM).

3. Is street sweeping more cost-effective and efficient than OGS? What is the most efficient sweeping frequency for particle removal?

In 1997, MOA WMS obtained data on street sediment and the sweeping efficiency of current practices (MOA WMP, 1997). For this report, sweeping efficiency values were extrapolated to different sweeping practices and SWMM was used to simulate sediment removal under different street sweeping scenarios that involved variations in sweeping practices and frequencies.

Conclusions and Recommendations

1. Grit Separator Applicability

Grit separator applicability was assessed based on analyses of OGS model results (MOA WMS, 1999a). The analysis of the OGS model results showed that conventional OGS devices are cost effective for a small percentage of basins in Anchorage under known Anchorage sediment and runoff loading conditions. Basins for which OGS appear to be cost effective include:

- Those basins that have greater than 1 acre of arterial road and greater than 20% of the streets in the basin are major arterials
- Small basins (less than 20 acres)that contain paved parking lots between 1 and 5 acres in size

2. Grit Separator Performance Criteria Recommendations

Performance data reported by three commercial manufacturers of grit separating devices were used to estimate annual removal efficiencies in the Anchorage area and develop appropriate DCM performance criteria.

The intent of any revision of the MOA DCM is to specify a removal rate that is reasonably achievable as well as being at least as protective of receiving water as the existing DCM criteria. Based on a review of the vendor supplied data, which varied considerably from vendor to vendor, the rough order of magnitude analysis that was conducted, and the results of this cursory analysis, the recommended performance criteria for the DCM for removal by grit separators are as follows:

- 25 percent removal of particles less than or equal to 100 μm in diameter, on an annual basis
- 80 percent removal of particles greater than 100 μm in diameter, on an annual basis

When conventional OGS are designed to existing DCM standards, it is estimated that 14 percent the total washoff load is removed, 13 percent of the particles less than 100 μm are removed, and, on an MOA-wide basis, the cost is about $8 per Kg removed. When OGS devices are sized to these proposed DCM standards, 26 percent of the annual washoff load is removed, 25 percent of the particles less than 100 μm are removed, and, on an MOA-wide basis, the cost is about $5.50 per Kg removed.

Further recommendations for grit separators, to assure that they will meet these performance criteria throughout their design life, include the following:

- Provide a side discharge bypass weir to bypass large flows. This will prevent scouring, resuspension of sediment, and local flooding
- Provide adequate room for maintenance access, both to the device itself and within the device

Assure that routine cleaning and maintenance is performed to retain functionality

3. Sweeping Recommendations

Street sweeping is much more cost effective, on a dollar per kg removed basis, than are OGS devices. Street sweeping unit costs are in the range of $0.06 to $0.77 per kg of street load removed. When conventional OGS devices are sized according to 1988 DCM standards (MOA DPW, 1988), they are estimated to cost $8 per kg removed, and are effective at removing about 14 percent of the washoff load and 6 percent of the total load on the street. The unit costs of conventional OGS devices removing 30 percent of the washoff load, are in the range of $8 to $25 per kg removed. The following sweeping efficiencies and practices are recommended:

- Timing:
  - Two times, the second within two weeks of the first, during or immediately following breakup and before May 15
  - Twice during summer: once midsummer, between mid-June and mid-July, and once before snowfall, in September or early October
- Sweeper Practices:
  - Mechanical and vacuum sweepers should be used in tandem (one behind the other, mechanical first) on arterial streets. Regenerative air sweepers are not recommended on arterial streets, except as a final pass in late summer before snowfall
  - Mechanical and vacuum sweepers should also be used in tandem on residential streets. Regenerative air sweepers should be considered for residential streets, because these streets have a lighter load of coarse sediments and present better conditions for the suction mechanism of regenerative sweepers than arterial roads

Introduction

Analyses described in this efficiency analysis report were conducted by MWH under Department of Public Works (DPW) WMS Project No. 95004. The analyses and evaluations were performed to meet project requirements defined in the Municipality's National Pollutant Discharge Elimination System (NPDES) stormwater discharge permit. The following subsections summarize project background information, primary report objectives, and report organization.

Project Background

Reviewing, revising, and reporting new street maintenance Best Management Practices (BMPs) for the Municipality is an ongoing process that has been developed under Part II.A.1.b.(6) of the NPDES permit, which reads as follows:

> ***The Municipality of Anchorage shall ensures that its local ordinances and design criteria are consistent with applicable State and Federal regulations, as well as with findings resulting from the assessments required in Part II.A.1.a.(4)(a) [of the NPDES permit].***

Assessing street sediment impacts in the Municipality is an ongoing process that has been developed as per Part II.A.1.a.(4) of the NPDES permit, which reads as follows:

> ***Permittees shall continue to implement and refine the existing program to evaluate the effectiveness of structural and source controls. Information gathered and evaluated through this program shall be used in: estimated the effectiveness of controls; selecting, designing, and maintaining controls; and providing valuable information to management in land use planning and decision-making.***

Part II.A.1.a.(4) goes on to specifically list Oil and Grit Separator BMP assessment and Assessments of Non-Structural Source Controls as assessment projects to be conducted by the Municipality.

This analysis report meets the requirements detailed in Part II.A.1.b.(6) by reviewing and reporting on the results of several MOA assessments, including:

- MOA Street Sediment Loading Assessment Data Report. Document No. WMP APr97001. (MOA WMP, 1997)
- Anchorage Bowl OGS Performance Modeling. Document No. WMP Apr98002. (MOA WMP, 1999a)

- Commercial Parking Lot Sediment Sources: 2001 Data Report. Document No. WMP Apr01001. (MOA WMP, 2001a)

Each of these assessments comprised an individual component of the overall input to this analysis report.

In addition, the WMS assessment program is designed to implement projects that compliment each other. Street sweeping is a non-structural source control that is used to reduce sediment in runoff. For this analysis report, modeling was performed to compare and contrast street sweeping removal efficiency with OGS removal efficiency. Another analysis performed for this report evaluated commercial grit separator devices as an alternative to the conventional OGS structures modeled in the 1999 OGS study (MOA WMP 1999a).

Project Purpose

This analysis was designed to provide developers and street maintenance managers with evaluations regarding the relative effectiveness of OGS and street sweeping in reducing sediment loading to receiving waters. Ultimately, these evaluations may be used to design strategies for developers and street maintenance management.

Problem Statements

This analysis report is intended to present information critical to answering the following watershed management questions concerning street sediment impacts:

- Under what circumstances are OGS cost-effective?
- Is street sweeping more cost-effective and efficient than OGS
- What is the most efficient sweeping frequency for particle removal
- What is the expected effectiveness of commercial oil and grit separators in Anchorage?
- What OGS removal criteria should be recommended?

Limitations of the Analysis

These analyses were performed at an exploratory level and were focused on select aspects of sediment removal by OGS and street sweeping. Assumptions used to determine the importance of these aspects may be only partly correct. Given the limitations of the study, however, it is believed that the results of the analyses are reasonably representative and useful in meeting WMS needs.

The analyses were performed with the participation and funding of the WMS Project Management and Engineering Division of DPW. WMS provided review and oversight of the analytical process and MWH performed the analyses.

Report Organization

This reported summarizes the results of these various evaluations. It is organized in the following manner:

Introduction. Summarizes the context of the 2002 Preliminary Performance Efficiency Analysis, presents a statement of the information required by watershed managers, discusses limitations, and describes the organization of this document.

Analysis of Municipality of Anchorage (MOA) OGS costs and efficiencies. Describes the analytical method and results of OGS costs associated with different removal efficiencies and basin characteristics.

Review of current MOA and Alaska Department of Transportation and Public Facilities (ADOT/PF) street sweeping practices. Describes the current street sweeping practices assumed to be in place. Assumptions about these practices affect the removal efficiencies predicted by the 1999 OGS model report and the street sweeping analysis performed for this report.

Analysis of street sweeping costs and efficiencies. Describes the analytical method and results of simulating different street sweeping scenarios and presents the costs and annual removal associated with these scenarios.

Evaluation of parking lot sediment gradation. Describes results of report that presents parking lot sediment data and compares the data to the initial street sediment loads used in the 1999 OGS model report.

Comparison of sediment removal costs of OGS and Street Sweeping. Compares the cost and removal findings for OGS and street sweeping, as presented in previous sections of this report.

Evaluation of removal efficiencies of commercial grit separators. Presents an evaluation of the potential sediment removal efficiencies of three commercial grit separators based on vendor information, and Anchorage rainfall data, stormwater runoff, and sediment characteristics found in the 1999 OGS model report.

Analysis of MOA OGS Costs and Efficiencies

Currently, the MOA employs conventional OGS devices, as defined in Chapter 2 of the MOA Design Criteria Manual, as a means of treating municipal storm water to remove sediment originating primarily from paved streets. In 1999, the MOA completed an OGS assessment that involved data calibration and computer modeling to predict OGS efficiency (MOA WMP, 1999a). That modeling effort simulated sediment removal by conventional OGS devices based on various assumptions, including sediment buildup, washoff, and street sweeping removal, derived from a 1997 street sediment data report (MOA WMP, 1997). The collected data was used to calibrate parameters for various modeled processes, including sediment buildup, sediment washoff, and street sweeping removal effects. In that modeling effort, 382 outfall basins in Anchorage were modeled. Attributes of the modeled outfall basins are summarized in Table 1.

Table 1 Attributes of Modeled Outfall Basins

Statistic	Basin Area	Road Type				Total Road Area	Impervious Area	Impervious Area	Total Washoff
		1	2	3	4				
	Acres	Acres	Acres	Acres	Acres	Acres	Percent	Acres	Kilograms
Mean	145	7.3	1.5	0.8	1.8	11.4	46	47	18,458
Median	26	2	0	0	0	3	43	12	2,261
Minimum	1	0	0	0	0	0	3	0	1
Maximum	5844	176	66	27	31	278	90	1,399	274,814

Notes:
Road type 1 – residential
Road type 2 – collector
Road type 3 – minor arterial
Road type 4 – major arterial

Removal efficiencies of various OGS sizes (as measured by cross sectional area) were calculated. The OGS efficiencies were calculated on the basis of the amount of sediment removed as a fraction of total annual washoff. The assessment also associated costs with OGS sizes.

The results of that study indicated that:

- 20 to 40 percent of the total annual street sediment load is washed off the streets with rainfall and snowmelt runoff. Rainfall runoff accounts for most of the washoff load (75 to 90 percent). Snowmelt runoff in spring accounts for 10 to 25 percent of the annual load.
- Of the sediment mobilized by stormwater, 96 to 99 percent is less than 100 microns (μm) in diameter.

Based on results of the 1999 OGS study, the size and cost of OGS devices that meet DCM criteria were estimated. Performance under current DCM criteria was evaluated; details are included in Appendix A.

Current DCM criteria that affect OGS sizing include:

- 100 percent removal of sediment greater than 130 microns from the 2-year 6-hour storm
- Minimum device dimensions of 6 feet in width and in length

Table 2 shows the efficiencies and costs associated with outfall basins equipped with OGS devices that meet these design criteria. On a basin by basin basis, the median cost is $26 per Kg removed; on an MOA-wide basis, the cost is about $8 per Kg removed.

Table 2 Removal Efficiencies of Conventional OGS Devices Sized by DCM Standards

	---------- By basin ----------			MOA-wide Overall
	Median	Maximum	Minimum	
OGS size, square feet	34	3015	10	NA
Percent removed – all sediment	14 %	40%	6%	14%
Percent removed sediment >100 μm	77%	100%	66%	78%
Percent removed sediment <100 μm	13%	38%	4%	13%
Cost – $/Kg	$26	$20,200	$0.85	$8

Results of the 1999 OGS study were used to compare costs from basin to basin. OGS sizes required to achieve discrete incremental annual efficiencies (30 percent, 50 percent, etc.) were interpolated from previously modeled results on a basin by basin basis. From the interpolated OGS size, a cost was determined based on the size-cost relationship developed in the 1999 model. A cost per kg of sediment removed was determined for each basin, based on these interpolated efficiency values, and the 1999 modeled washoff mass for each basin. An overall, MOA-wide cost per kg removed was also calculated. A summary of this analysis is presented in Table 3.

Table 3 OGS Size and Cost per Kilogram Removed at Different Efficiencies

Removal Efficiency Percent	OGS Size, Square Feet, for Given Efficiency			Dollars per Kilogram Removed			
	Median[1]	Minimum[1]	Maximum[1]	Median[1]	Minimum[1]	Maximum[1]	MOA-Wide
10	5	0	462	5	0.1	7698	2.4
20	25	0	2,444	6	0.2	5,558	4.2
30	71	2	4,827	8	0.3	7,739	6.4
50	333	7	9,593	20	0.9	23,429	12.8
60	510	12	11,975	26	1.3	33,072	15.1

Notes:
1 – median, minimum, and maximum values for 382 basins

The OGS efficiencies are based on washoff from streets that have been swept, using the then-current sweeping practices. If street sweeping practices change, and become either more or less efficient, OGS efficiencies may change.

As observed in the 1999 model report, most (96 to 99 percent) of the sediment mobilized by stormwater in Anchorage is less than 100 μm in diameter. This size is considered too fine to be practically treated strictly by settling in OGS devices. Model results show that, as a consequence, large OGS sizes are required to settle sediment and correspondingly high costs per unit mass removed are associated with OGS treatment.

Basins for Which OGS are Cost-Effective Treatment

In order to determine whether conventional OGS are more efficient in certain basins, and whether these basins share certain attributes, the cost per kg removed as a function of efficiency and basin attributes (e.g., size of basin, area of different road types) were plotted. These plots are shown in Figure 1. As can be seen in this figure, a basin's total road area (B, Figure 1), road type 4 area (F, Figure 1) and road types 3 and 4 areas (G, Figure 1) showed the strongest correlation with cost per kg removed. Basin percent impervious (A, Figure 1) and area (H, Figure 1) do not show strong correlations with cost effectiveness.

Basins for which OGS achieved a 50 percent removal efficiency at costs less than $20 per kg were considered good indicator candidates for cost effective OGS treatment. A total of 108 out of the 382 basins had costs of less than $20 per kg at 50 percent removal efficiency.

The lowest removal costs associated with 50 percent removal efficiency occur in basins with primarily arterial roads. The following four conditions were found to predict basins in which OGS are most cost effective.

A. Basins in which the area of road types 3&4 (minor and major arterials) per total road area is greater than 25 percent. These are basins in which the majority of the roads are arterial. 109 basins meet this condition; 88 of which had removal costs less than $20 per kg at 60 percent efficiency.

B. Basins in which the area of road type 4 (major arterial) is greater than 20 percent of the total road area in the basin. 88 basins meet this condition; 82 of those had removal costs of less than $20 per kg at 50 percent removal efficiency.

C. Basins in which the combined area of road types 3&4 is greater than 1 acre. 131 basins meet this condition; 101 of which have removal costs of less than $20 per kg at 50 percent remvoal efficiency.

D. Basins in which the total road area exceeds 10 acres. 86 basins meet this condition; 58 of those had removal costs less than $20 per kg.

The proportion of basins meeting these four conditions is shown in Figure 2.

Table 4 Predicting OGS Costs Based on Basin Parameters

Number of Conditions Met	Number of Basins <$10/Kg	Number of Basins <$20/Kg	Number of Basins >$20/Kg
0	0	2	228
1	1	1	14
2	7	22	26
3	36	48	5
4	14	35	1
Total Number of Basins	**58**	**108**	**274**

These four conditions predict 106 out of the 108 basins that have removal costs of less than $20 per kg at 50 percent removal efficiency if two or more conditions are met, only 3 basins are not predicted that in fact do have costs less than $20 per kg removed. As shown in Table 3, if three or more conditions are met, 83, or 77%, of basins with removal costs less than $20 per kg are predicted.

Figure 1 Cost per Mass Sediment Removed - Different OGS Efficiencies versus Basin Attributes

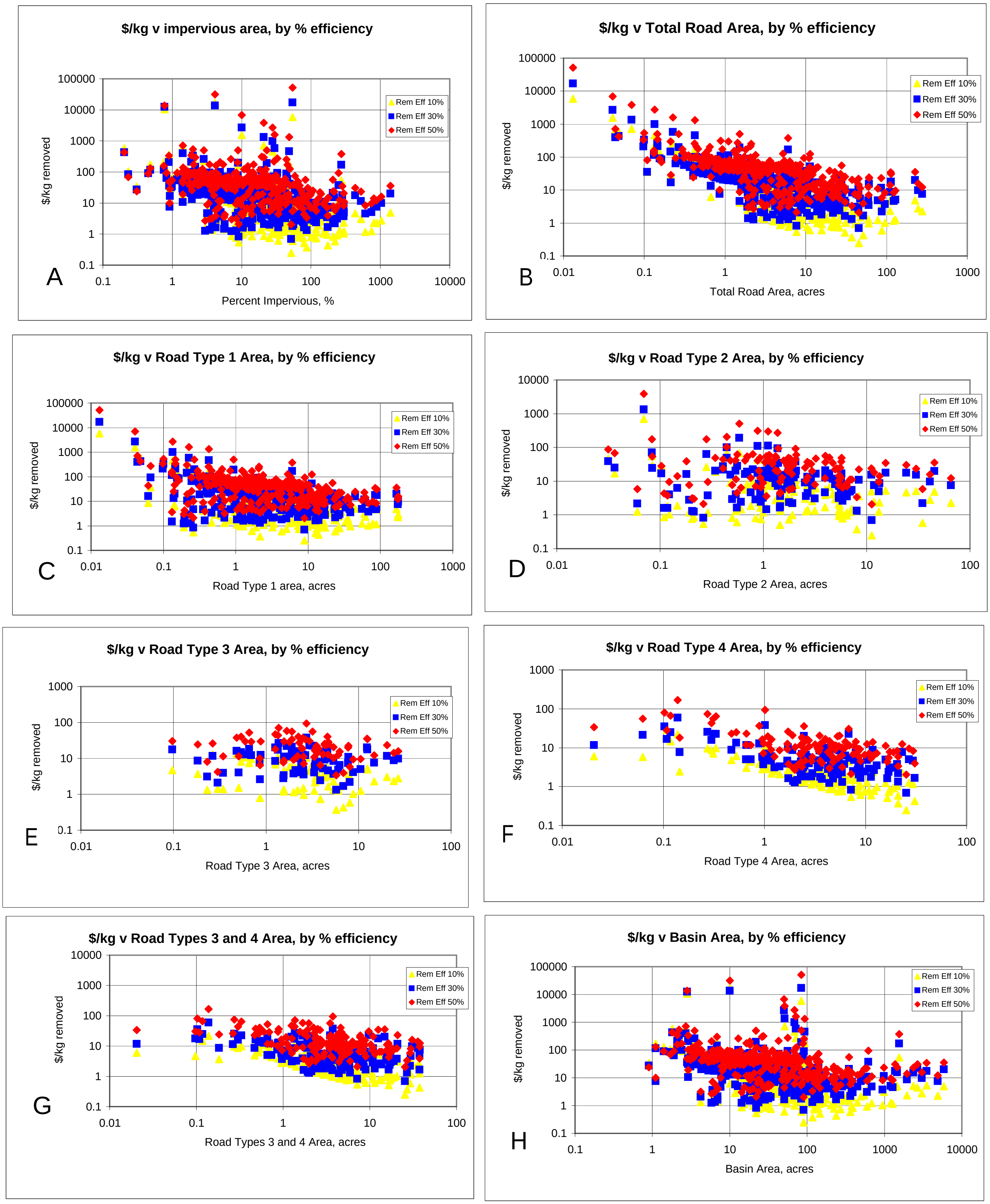
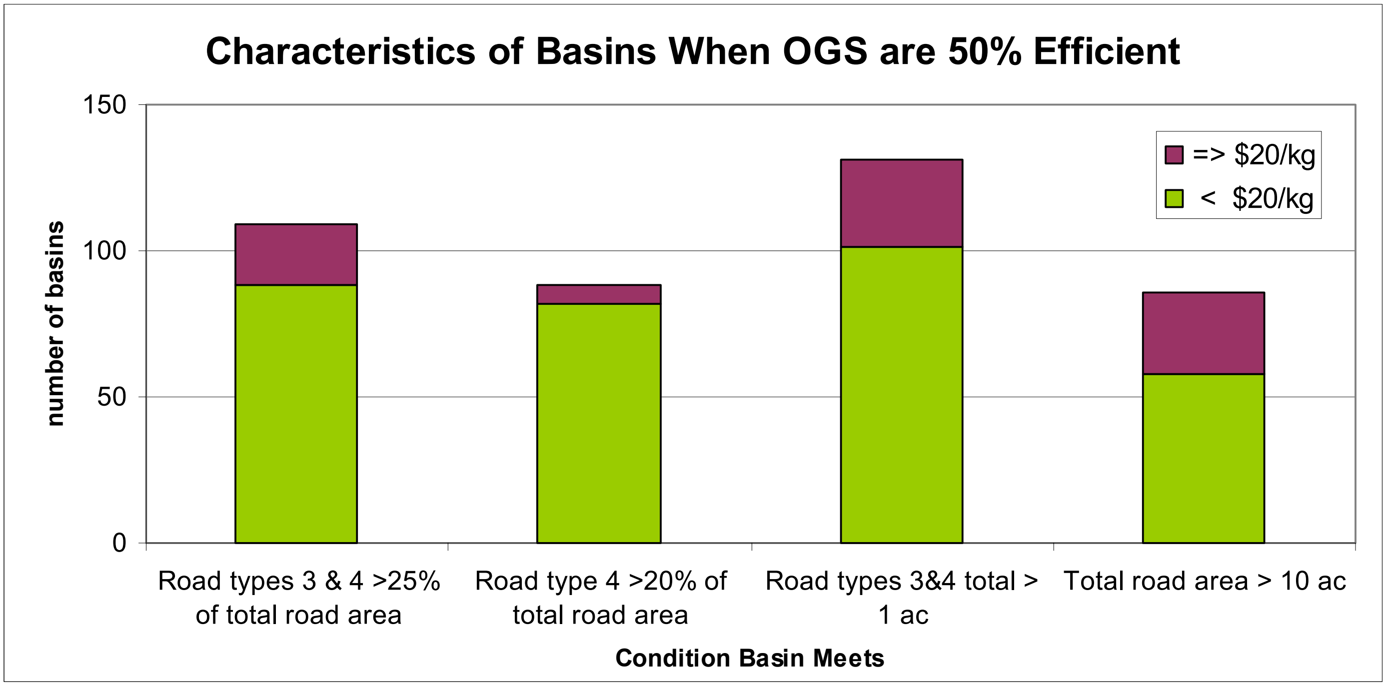


Figure 2 Characteristics of Basins with Costs Less than $20/Kg at 50 Percent Efficiency



Assumptions About Sweeping Practices

The OGS efficiencies presented in the 1999 OGS report (MOA WMS, 1999a) are based on washoff from streets that have been swept, using the then-current sweeping practices. Specifically, the following assumptions were made:

- Sweeping efficiencies were modeled based on MOA street data (MOA WMP, 1997)
- Initial load and buildup rates were modeled based on MOA data (MOA WMP, 1997)
- Street sweeping was simulated by the model as occurring three times per year (8 April, 7 May, and 7 July)

Based on interviews with Shawn McBride, MOA street maintenance, modeled sweep schedules represent current (2002) MOA practice of sweeping twice during/after breakup and once again in the summer as well as the practice when the 1997 data were collected. As time allows in the summer, MOA may perform a second summer sweep.

Based on correspondence with Jerry Dunn, ADOT&PF, this sweeping schedule does not correspond with the state's historic sweeping practices on arterial roads. Up until 2001, the state swept once when all ice and snow has melted (before the end of June) and once more during the summer. Starting in 2001, ADOT&PF contracted for three sweepings per year: 10 April to 15 May; 16 May to 15 June; and 23 August to 15 September.

Therefore, the actual 1997 practices, to which "current" street sweeping efficiencies were calibrated, appear to have included the MOA practice of 3 times per year and the ADOT&PF practice of 2 times per year. This calibration was taken as the base or "current" case for a variety of street sweeping scenarios that were modeled for this evaluation.

Analysis of Street Sweeping Efficiency and Cost

Both OGS devices and street sweeping reduce sediment loads in stormwater discharge. Unlike OGS devices, which are associated with piped stormwater system and discrete drainage areas and points of discharge, street sweeping is conducted on a municipality-wide basis.

Modeling Parameters

Street sweeping efficiencies were evaluated using the SWMM model developed for Anchorage in 2002 (MOA WMP, 2002). Inputs included:

- The 1965 annual rainfall series (used to represent the average annual hydrograph)
- Sediment buildup and washoff rates
- Sweeping efficiencies
- Area of four classes of streets (all streets were assumed to be swept, whether they are currently paved or not)

The buildup and washoff rates were based on data collected during 1997 studies in the Anchorage area (MOA WMP, 1997). Various sets of sweeper practice efficiencies were used, depending on the scenario to be modeled. The derivation of sweeper practice efficiencies is described in Appendix B.

Calibration using the 1997 field data produced discrete sweeping efficiencies for four road types and three particle size classes. For this simulation effort, two road types were used, which were composites of road types used in the 1999 OGS study:

MOA sweeps road types 1 and 2 – residential and collector streets, respectively

ADOT&PF sweeps road types 3 and 4 – minor and major arterials, respectively.

Street Sweeping Scenarios

The street sweeping scenarios simulated by SWMM fell into two categories: variations of sweeping frequency in spring and in summer and variations of equipment type and number of passes during each sweep event. Nomenclature and assumptions are as follows:

Sweeping practices refer to the type and combination of types of sweepers used during a single event. These include:

- Mechanical
- Vacuum

- Regenerative air
- A sweep event is an instance in which sweeping equipment is mobilized to the field, generally, within one week.
- A sweeping pass is a single sweep over a given surface area by the sweeping practice employed. A sweeper may make one or more passes in one sweeping event.
- Spring, or breakup, sweeping is conducted from sometime in April up to June 1
- Summer sweeping occurs from June through September

The following scenarios were simulated:

- Scenario 1 – Mechanical sweeper followed by vacuum sweeper (M+V) for each sweeping event, simulating "current practices"
- Scenario 2 – Current practices, but each sweep event has two passes (M+V x2)
- Scenario 3 – Current practices, but use a regenerative air sweeper instead of a vacuum sweeper as the second sweeper in tandem (M+V+R)
- Scenario 4 – Same as Scenario C, but each sweep each sweep event has two passes (M+V+R x2)

Each of these scenarios, 1 through 4, was simulated for different sweep event frequencies. These frequencies were: one or two sweeps per spring preceding one, two, or four sweeps per summer. The scenario matrix is summarized in Table 5.

The derivation of sweeping efficiencies for SWMM simulation of different practices (for scenarios 2, 3, and 4) is presented in Appendix B.

Assumptions for Parked Cars

In order to account for areas left unswept due to parked cars blocking sweeper access, a reduction in surface area swept was assumed. Ten percent of the surface area of residential and collector (street Types 1 and 2) was assumed to be inaccessible to sweepers, but were included in the total surface area on which buildup rates were applied. Only residential and collector streets were affected; parked cars are generally not allowed on minor and major arterials.

Basis of Costs

Sweeping costs from MOA and ADOT&PF for 2001 were used and extrapolated for different sweeper practices, as described in this section. References for costs are included in Appendix C.

Table 5 Summary of Street Sweeping Scenarios Simulated by SWMM Modeling

Scenario:	A	2	3	4
Practice:	M+V	M+V x2	M+V+R	M+V+R x2
Season	Sweeping Frequency			
Spring Summer	1 1	1 1	1 1	1 1
Spring Summer	1 2	1 2	1 2	1 2
Spring Summer	1 4	1 4	1 4	1 4
Spring Summer	2 1	2 1	2 1	2 1
Spring Summer	2 2	2 2	2 2	2 2
Spring Summer	2 4	2 4	2 4	2 4

Key:
M+V – sequential mechanical and vacuum sweepers, one pass per event
M+V x 2 – sequential mechanical and vacuum sweepers, two passes per event
M+V+R – sequential mechanical, vacuum, and regenerative air sweepers, one pass per event
M+V+R x 2 – sequential mechanical, vacuum, and regenerative air sweepers, two passes per event

MOA COSTS

Operating and Maintenance Costs

The following operating and maintenance costs for spring, 2001, were obtained from MOA Street Maintenance (Turk, 2002):

Total Cost Spring 2001 Sweeping $ 524,336 for 2 sweeps in the spring

$ 262,170 for 1 sweep in the spring

Annualized Capital Costs According to Ali Turk, MOA, annualized capital costs of MOA-owned equipment do not appear to be reflected in the costs provided by fleet management. MOA operates 14 sweepers, 10 of which are used simultaneously, on average; they contract out sweeping to an additional four sweepers.

The MOA has 6 mechanical and 8 vacuum sweepers. According to Yukon Equipment (Kimball, 2002), current costs for Elgin vacuum and mechanical sweepers are similar, $165,000 to $170,000. Assuming an interest rate of 6 percent for 15 years, the annualized capital cost is $17,000. A 15-year payback period may underestimate the actual sweeper life. When multiplied times 14 sweepers and divided by 3 sweeps per year, this is $79,280 per sweep. Note that under the different scenarios when sweeping occurs more frequently, this factor, based on a per acre basis for only 3 sweeps per summer, may seem to be double-counted. However, assuming MOA currently has the optimal number of sweepers for its work load, if more sweeps per year are conducted, either (1) more sweepers will be required, thus reflected in increased capital costs or (2) the sweepers will have to be replaced sooner.

Thus the operating plus annualized capital costs for one sweeping of the residential and collector streets in Anchorage is $341,450. The total area of residential and collector streets, from the 1999 OGS modeling report, is 3,342 acres. Based on this, a single pass for residential and collector streets was assumed to be $102 per acre.

ADOT&PF COSTS

ADOT&PF contracts out all of its sweeping; therefore, annualized capital, operational and maintenance costs are all assumed to be included in the contracted sweeping costs obtained from ADOT&PF. ADOT&PF costs for a single 2001 sweeps were $133,600. The total area of minor and major arterial streets, from the 1999 OGS modeling report, is 994 acres. Thus, a single pass for arterial streets was assumed to be $134 per acre.

Sweeping Efficiency

Annual and summer-only street sweeping efficiencies, as opposed to individual sweeper practice efficiencies, were determined using SWMM simulation. Annual and summer-only removal efficiencies were calculated as the amount removed by sweeping divided by the total amount of sediment on the street over the course of year or summer. The total amount is the sum of the amount washed off, the amount swept, and the amount remaining at the end of the summer. That is, the amount swept and removed as a fraction of total annual sediment *including washoff*. This approach was used in order to be consistent from one sweeping scenario to the next. Alternatively, the annual efficiency could be computed as the amount swept divided by the sum of the amount swept and the amount remaining, thus neglecting the washoff amount. As more sediment is picked up through increased sweeping frequency or increased sweeper efficiency, washoff decreases. Since a varying amount of the washoff load is on the street during a sweeping event, neglecting that type of sediment in the denominator may overestimate the actual sweeper removal. In this case, the computed annual efficiency would not be comparable from one scenario to the next.

Thus, the approach for computing overall annual or summer-only sweeping efficiencies is the ration of the amount swept to the total street sediment load.

The costs and removal efficiencies are presented in figures 3a through 6b. Each figure shows mass of sediment removed, cost per kg and total cost for both residential and arterial streets. In general, costs for residential streets are higher because they cover three times the acreage as arterial streets (3,300 acres versus 990 acres) and have somewhat less sediment density for the initial load and significant less sediment buildup density than do arterial streets.

Figures 3 through 6 show the effects of different scenarios involving **one** sweeping event during breakup.

Figures 3 and 4 compare the removal efficiency of different summer sweeping frequencies on an annual and summer-only basis, respectively. Only Scenarios 1 and 3 (M+V and M+V+R) are presented. On both a summer-only and annual basis, the increased removal from one sweep to two is greater than the increased removal from two to four sweeps per summer. In addition, the cost per kg of sediment removed goes up less from one to two sweeps than from two to four sweeps.

Figures 5 and 6 compare the removal efficiency of four different sweeping practices (Scenarios 1 through 4) on an annual basis and summer-only basis, respectively. These figures show the effects of one sweep during spring and two in the summer and show that there are successive, though small, increases in removal from Scenario 1 through 4. Costs per kg removed are lowest for Scenario 1 and Scenario 3. As expected, costs per kg removed are higher for Scenarios 2 and 4, since these involve double passes during a single sweep event.

Figures 7 through 10 show the effects of different scenarios involving **two** sweeping events during breakup.

Figures 7 and 8 are comparable to Figures 3 and 4 in showing the effect of different summer sweeping frequencies. The increased removal of two summer sweeps over one summer sweep is again apparent, and is again greater than the increase in removal from two to four summer sweeps. This carries over when computed on both the annual and summer-only basis, even though more was picked up during spring breakup, leaving somewhat less to pick up during summer.

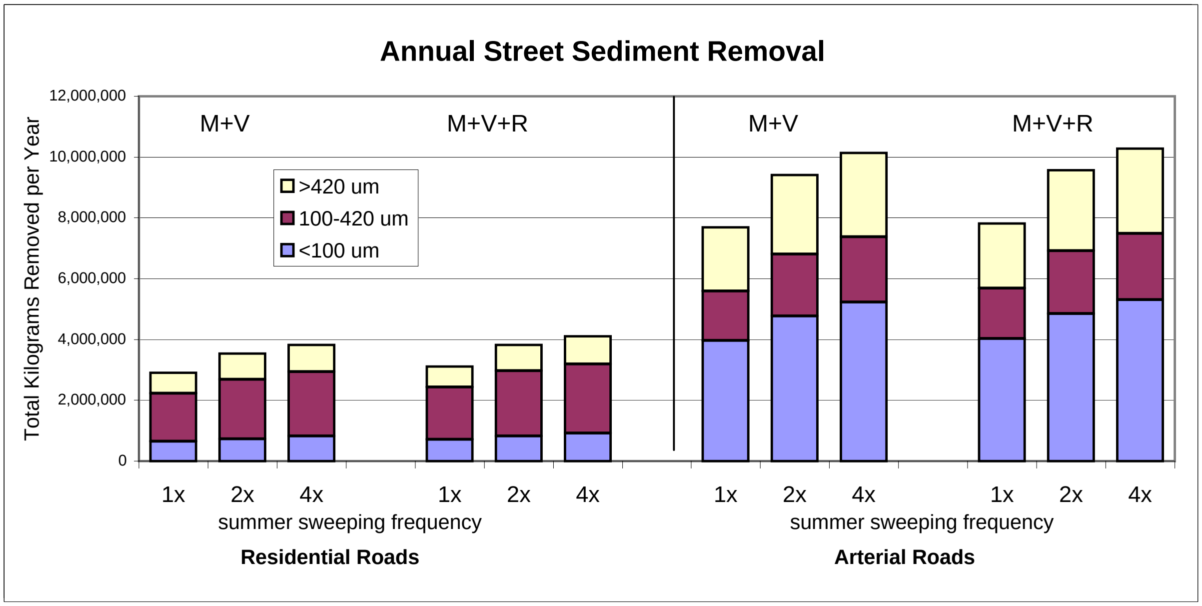
Figures 9 and 10 are comparable to Figures 5 and 6 in showing effects of different sweeping practices.

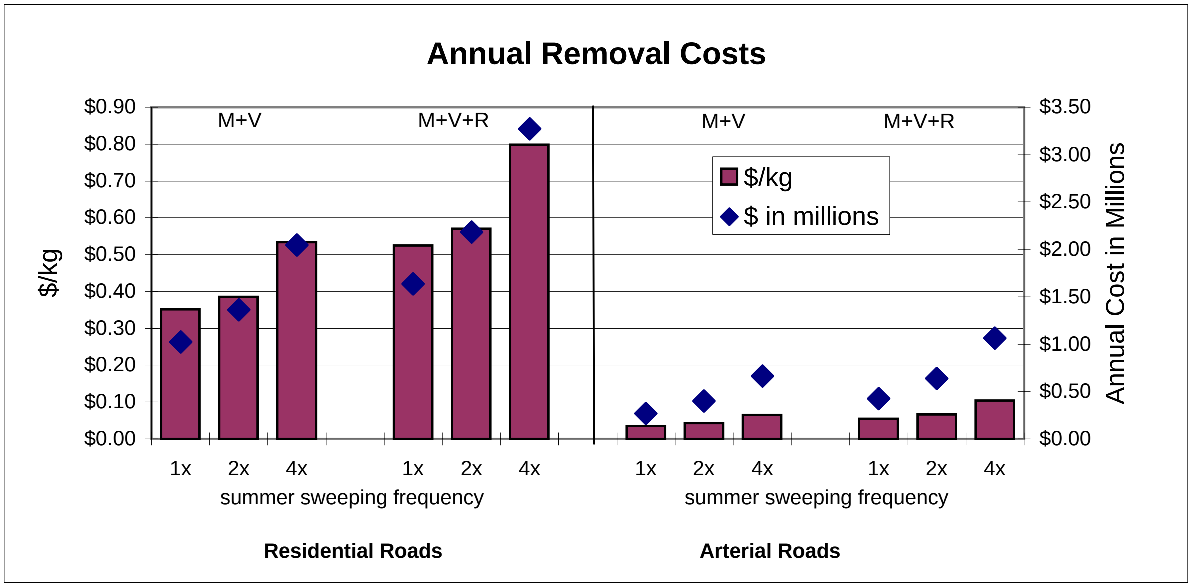
Based on these results, the following sweeping efficiencies and practices are recommended:

- Timing. Streets should be swept:
  - Two times, the second within two weeks of the first, during or immediately following breakup and before May 15
  - Twice during summer: once midsummer, between mid-June and mid-July, and once before snowfall, in September or early October

- Sweeper Practices:
  - Mechanical and vacuum sweepers should be used in tandem (one behind the other, mechanical first) on arterial streets. Regenerative air sweepers are not recommended on arterial streets, except as a final pass in late summer before snowfall
  - Mechanical and vacuum sweepers should also be used in tandem on residential streets. Regenerative air sweepers should be considered for residential streets, because these streets have a lighter load of coarse sediments and present better conditions for the suction mechanism of regenerative sweepers than arterial roads

Figure 3 Comparison of Multiple Summer Street Sweeping Events - Annual Removal with One Spring Sweep





Total annual removal and costs reflect one sweeping event during the spring and three different summer sweeping frequencies: 1 time, 2 times, or 4 times per summer.

Two Sweeping Practices are shown:

M+V mechanical + vacuum in tandem - one pass over a street for both MOA and DOT.

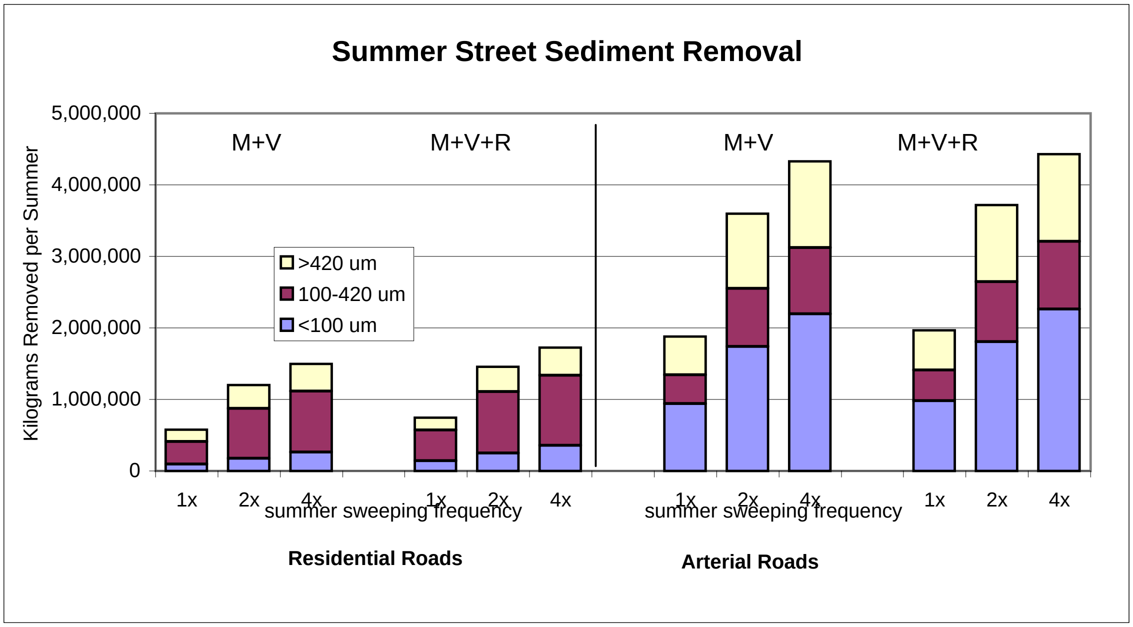
M+V+R mechanical + vacuum + regenerative air - one pass over a street for both MOA and DOT.

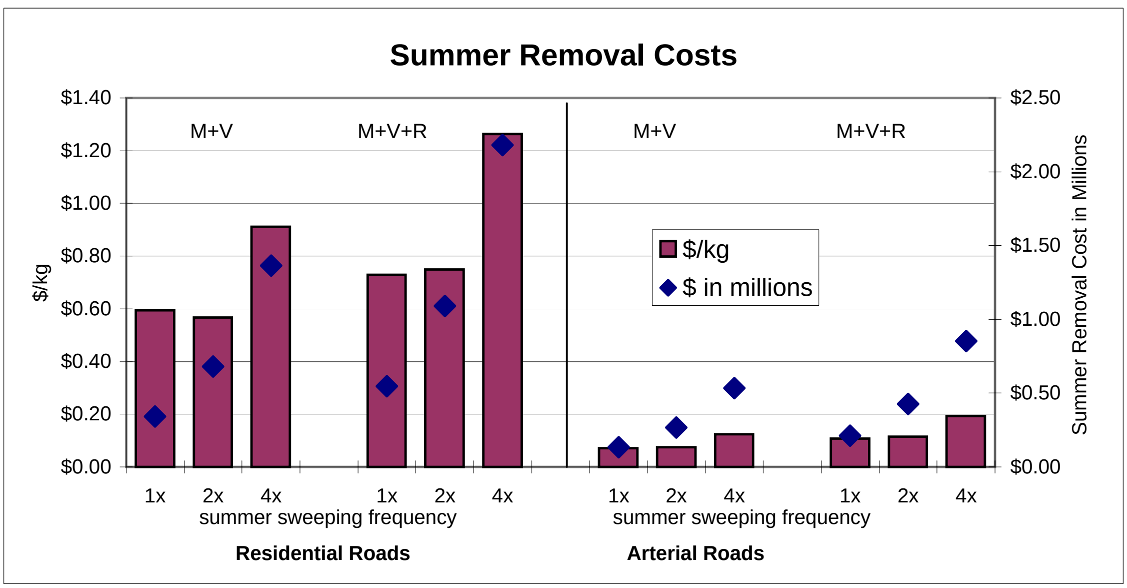
Street sweeping costs represent treatment for all streets, wheither currenlty paved or not.

Sweeping modeling assumed 10% of the residential road surface area would not be swept due to parked cars.

Costs reflect operations, maintenance, and amortized capital costs.

Figure 4 Comparison of Multiple Summer Street Sweeping Events - Summer Removal with One Spring Sweep





Total annual removal and costs reflect one sweeping event during the spring and three different summer sweeping frequencies: 1 time, 2 times, or 4 times per summer.

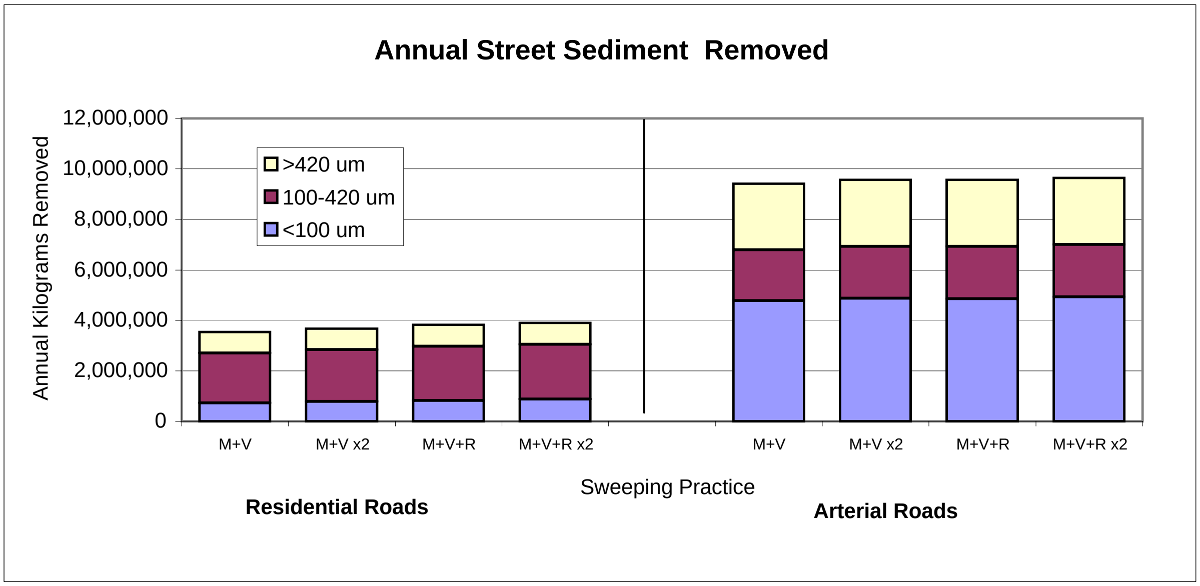
Two Sweeping Practices are shown:
M+V mechanical + vacuum in tandem - one pass over a street for both MOA and DOT.
M+V+R mechanical + vacuum + regenerative air - one pass over a street for both MOA and DOT.

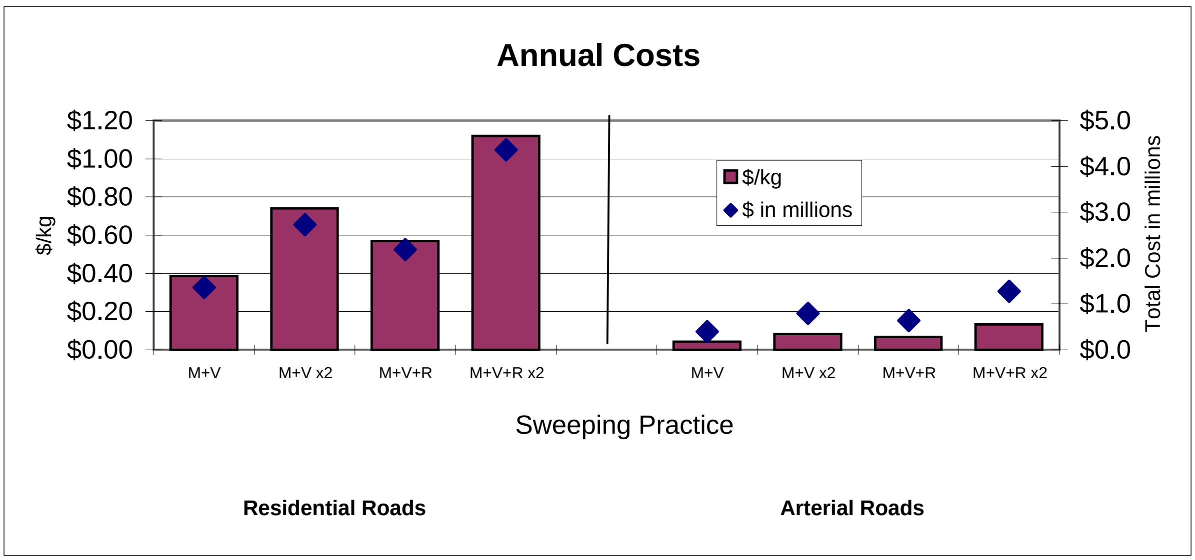
Street sweeping costs represent treatment for all streets, wheither currenlty paved or not.

Sweeping modeling assumed 10% of the residential road surface area would not be swept due to parked cars.

Costs reflect operations, maintenance, and amortized capital costs.

Figure 5 Comparison of Different Street Sweeping Practices - Annual Removal with One Spring Sweep





Four Sweeping Practices are shown:

M+V	mechanical + vacuum in tandem - one pass over a street for both MOA and DOT.
M+V x2	mechanical + vacuum in tandem - two passes over a street for both MOA and DOT.
M+V+R	mechanical + vacuum + regenerative air - one pass over a street for both MOA and DOT.
M+V+R x2	mechanical + vacuum + regenerative air - two passes over a street for both MOA and DOT.

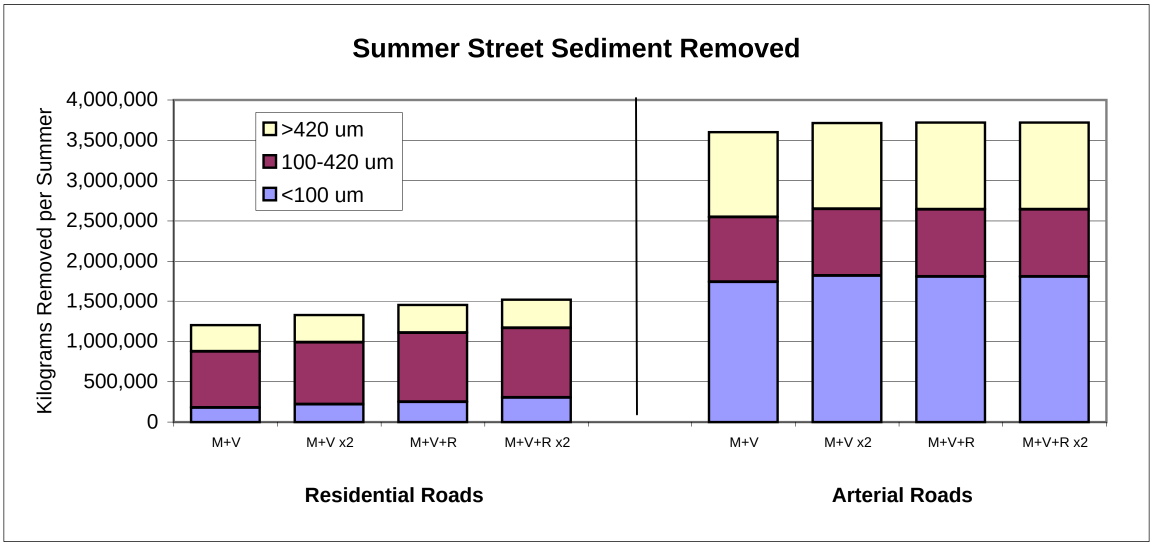
Total annual load and costs reflect one sweeping event during the spring and two summer sweeping events.

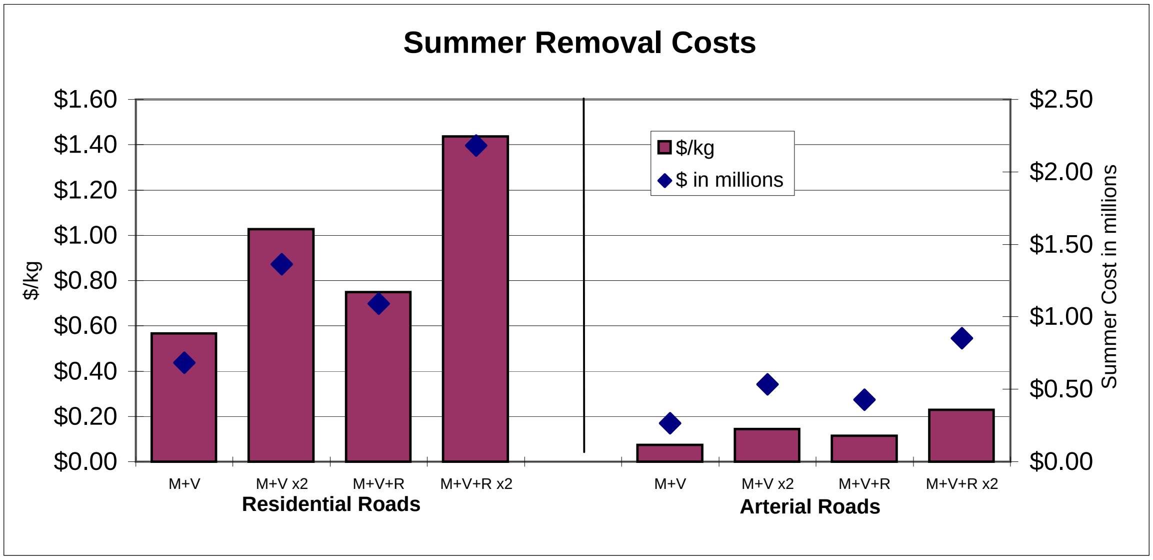
Street sweeping costs represent treatment for all streets, wheither currenlty paved or not.

Sweeping modeling assumed 10% of the residential road surface area would not be swept due to parked cars.

Costs reflect operations, maintenance, and amortized capital costs.

Figure 6 Comparison of Different Street Sweeping Practices - Summer Removal with One Spring Sweep





Four Sweeping Practices are shown:

M+V	mechanical + vacuum in tandem - one pass over a street for both MOA and DOT.
M+V x2	mechanical + vacuum in tandem - two passes over a street for both MOA and DOT.
M+V+R	mechanical + vacuum + regenerative air - one pass over a street for both MOA and DOT.
M+V+R x2	mechanical + vacuum + regenerative air - two passes over a street for both MOA and DOT.

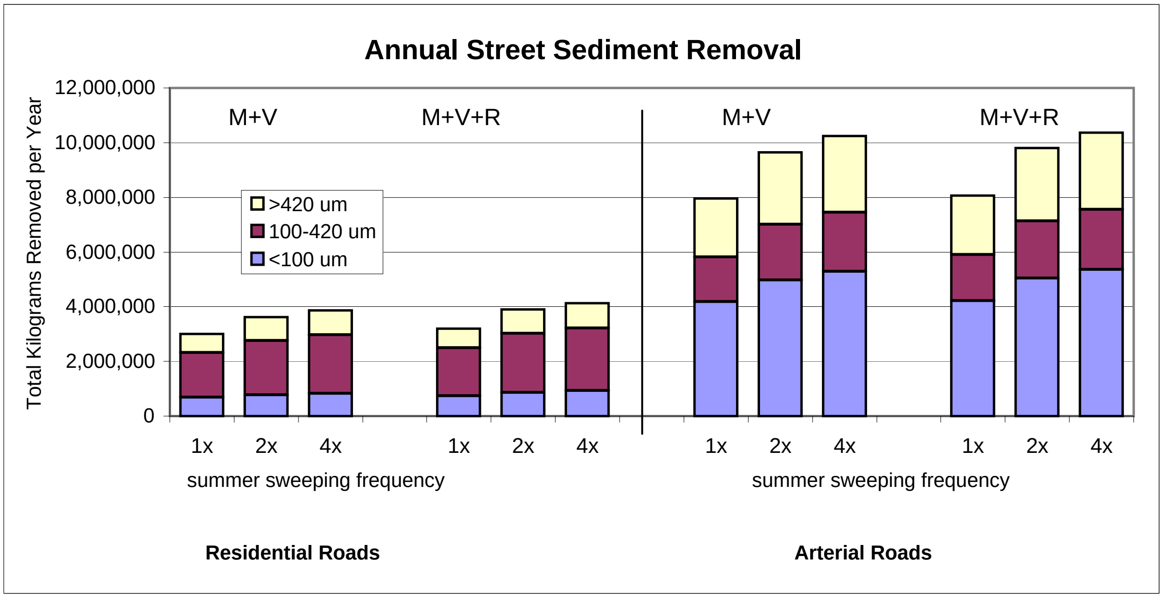
Total annual load and costs reflect one sweeping event during the spring and two summer sweeping events.

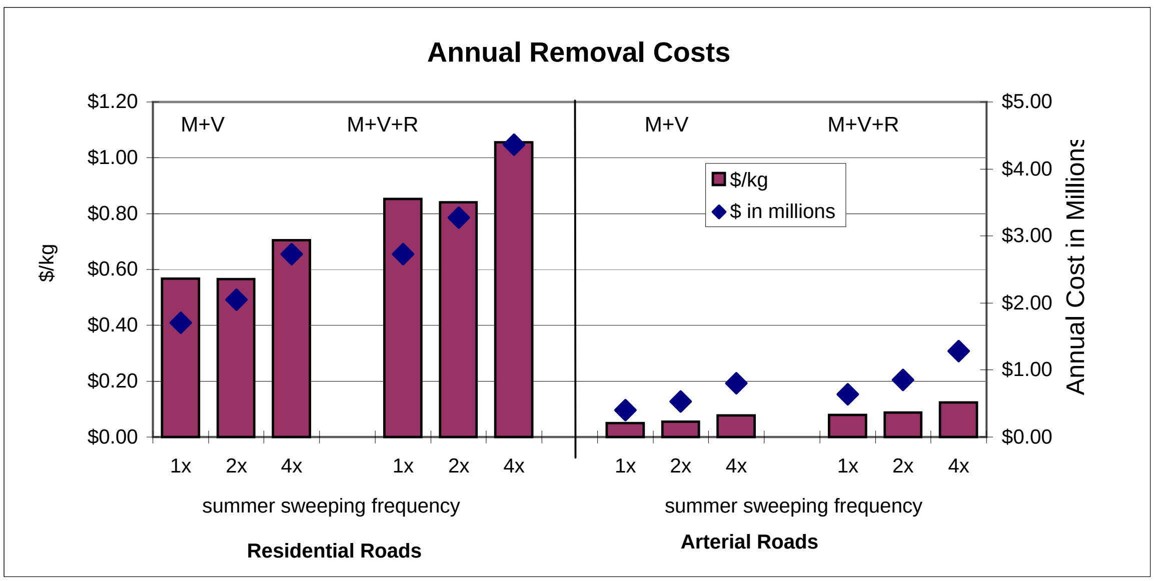
Street sweeping costs represent treatment for all streets, wheither currenlty paved or not.

Sweeping modeling assumed 10% of the residential road surface area would not be swept due to parked cars.

Costs reflect operations, maintenance, and amortized capital costs.

Figure 7 Comparison of Multiple Summer Street Sweeping Events - Annual Removal with Two Spring Sweeps





Total annual removal and costs reflect two sweeping events during the spring and three different summer sweeping frequencies: 1 time, 2 times, or 4 times per summer.

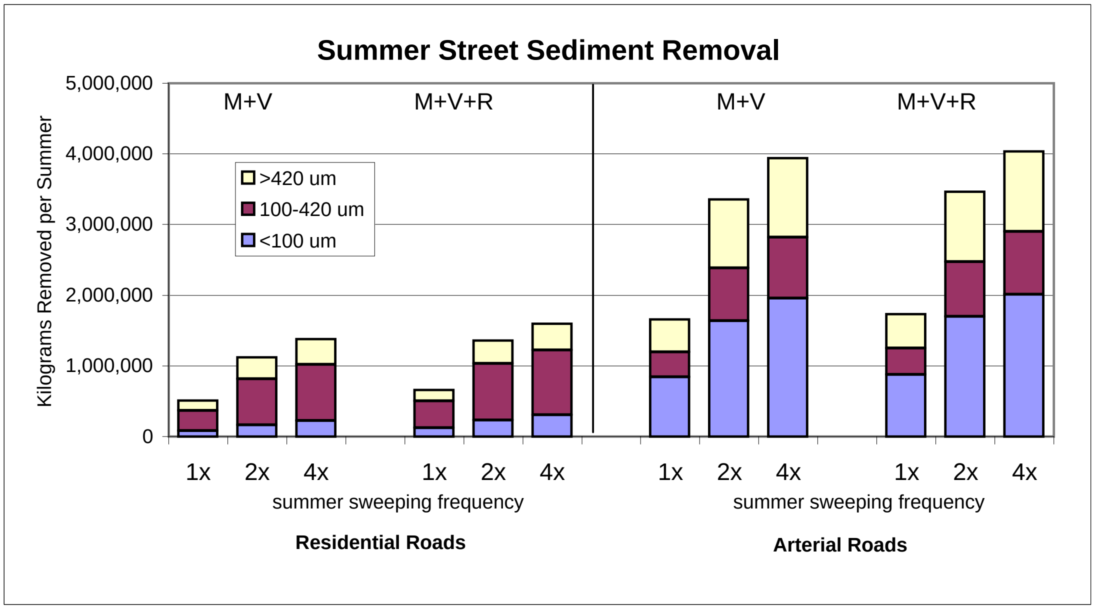
Two Sweeping Practices are shown:
M+V mechanical + vacuum in tandem - one pass over a street for both MOA and DOT.
M+V+R mechanical + vacuum + regenerative air - one pass over a street for both MOA and DOT.

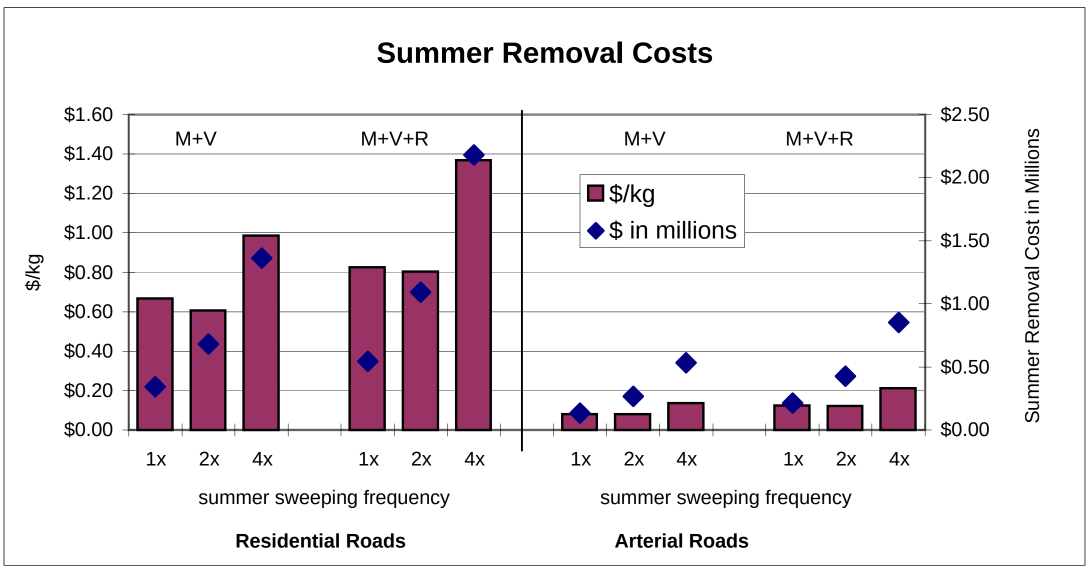
Street sweeping costs represent treatment for all streets, wheither currenlty paved or not.

Sweeping modeling assumed 10% of the residential road surface area would not be swept due to parked cars.

Costs reflect operations, maintenance, and amortized capital costs.

Figure 8 Comparison of Multiple Summer Street Sweeping Events - Summer Removal with Two Spring Sweeps





Total annual removal and costs reflect two sweeping events during the spring and three different summer sweeping frequencies: 1 time, 2 times, or 4 times per summer.

Two Sweeping Practices are shown:

M+V mechanical + vacuum in tandem - one pass over a street for both MOA and DOT.

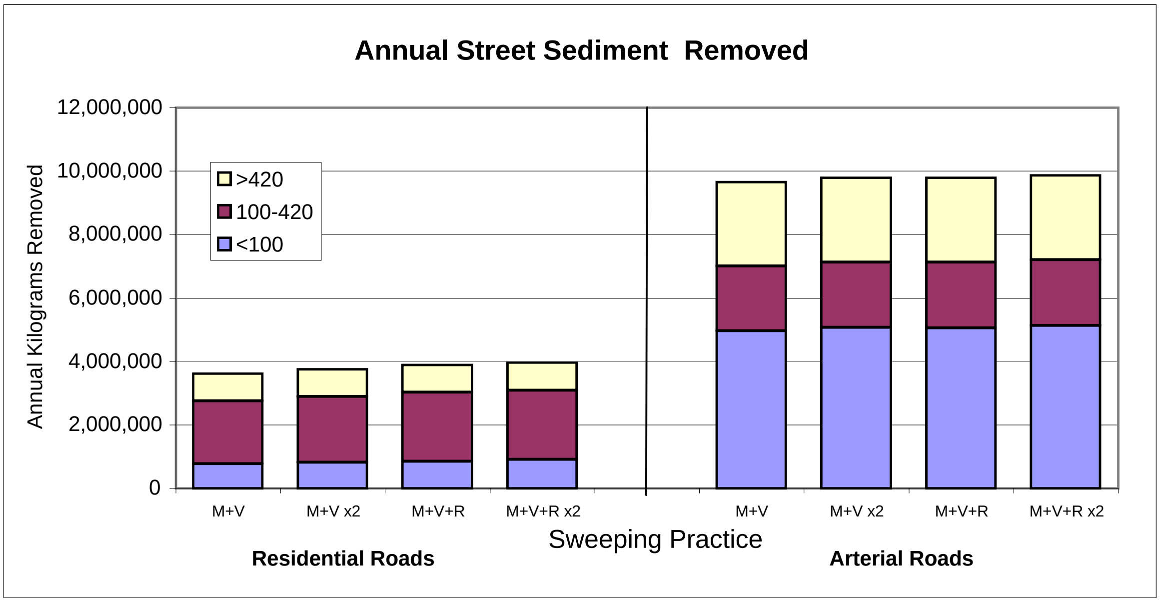
M+V+R mechanical + vacuum + regenerative air - one pass over a street for both MOA and DOT.

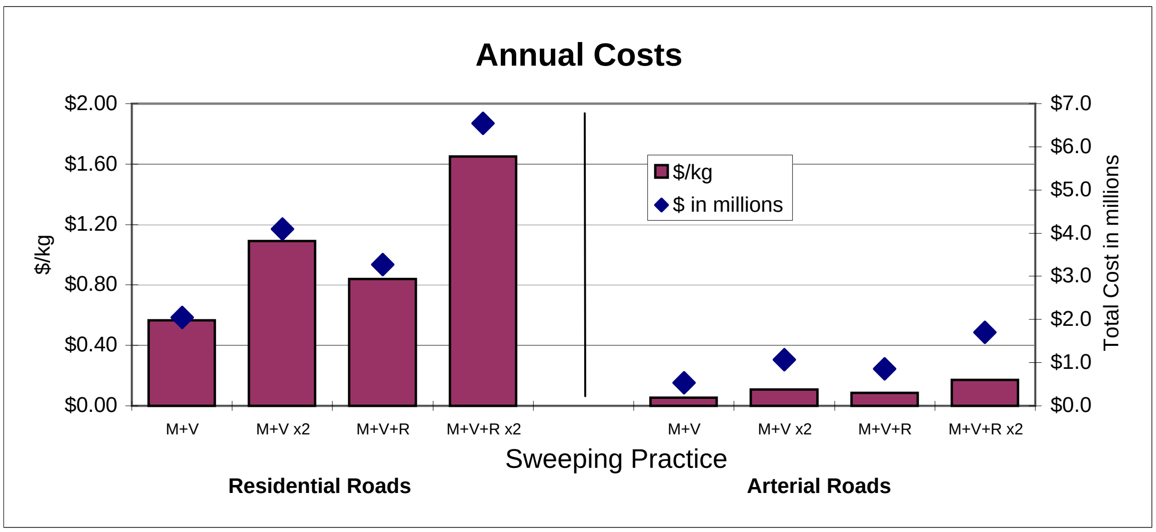
Street sweeping costs represent treatment for all streets, wheither currenlty paved or not.

Sweeping modeling assumed 10% of the residential road surface area would not be swept due to parked cars.

Costs reflect operations, maintenance, and amortized capital costs.

Figure 9 Comparison of Different Street Sweeping Practices - Annual Removal with Two Spring Sweeps





Four Sweeping Practices are shown:

M+V	mechanical + vacuum in tandem - one pass over a street for both MOA and DOT.
M+V x2	mechanical + vacuum in tandem - two passes over a street for both MOA and DOT.
M+V+R	mechanical + vacuum + regenerative air - one pass over a street for both MOA and DOT.
M+V+R x2	mechanical + vacuum + regenerative air - two passes over a street for both MOA and DOT.

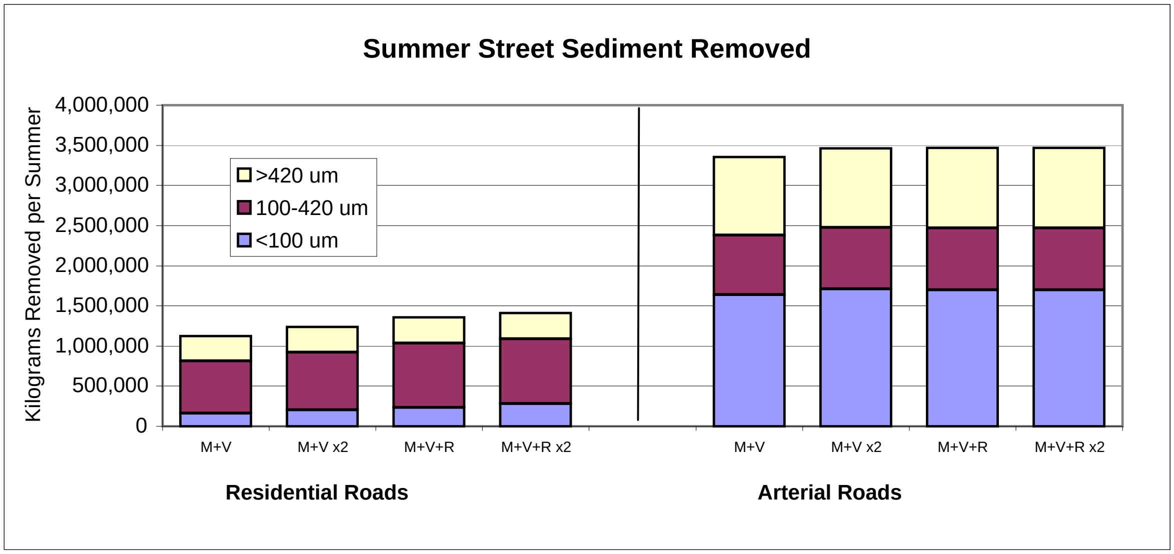
Total annual load and costs reflect two sweeping events during the spring and two summer sweeping events.

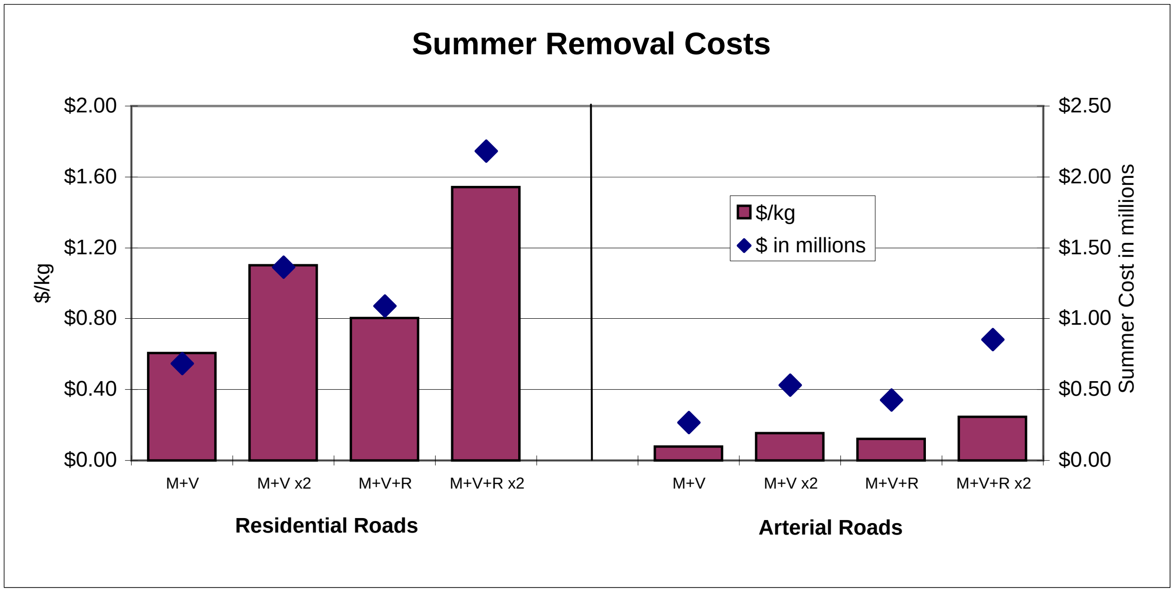
Street sweeping costs represent treatment for all streets, wheither currenlty paved or not.

Sweeping modeling assumed 10% of the residential road surface area would not be swept due to parked cars.

Costs reflect operations, maintenance, and amortized capital costs.

Figure 10 Comparison of Different Street Sweeping Practices - Summer Removal with Two Spring Sweeps





Four Sweeping Practices are shown:

M+V mechanical + vacuum in tandem - one pass over a street for both MOA and DOT.

M+V x2 mechanical + vacuum in tandem - two passes over a street for both MOA and DOT.

M+V+R mechanical + vacuum + regenerative air - one pass over a street for both MOA and DOT.

M+V+R x2 mechanical + vacuum + regenerative air - two passes over a street for both MOA and DOT.

Total annual load and costs reflect two sweeping events during the spring and two summer sweeping events.

Street sweeping costs represent treatment for all streets, wheither currenlty paved or not.

Sweeping modeling assumed 10% of the residential road surface area would not be swept due to parked cars.

Costs reflect operations, maintenance, and amortized capital costs.

Comparison of Street Sediment and Parking Lot Loads

Loading attributable to parking lots were not modeled in either the OGS study or the following street sweeping analysis. The following summarizes parking lot sediment loads in comparison to street sediment loads.

Parking lot sediment data were collected in 2001 (MOA WMP, 2001a) from eight parking lots with three levels of traffic activity (low, medium, and high). Three rounds of data were collected: 21-22 March, representing the initial post-breakup load prior to sweeping; 13 April, representing sediment load after spring sweeping, and 8 October, representing the sediment load at the end of summer

Sediment Mass. The parking lot sediment data show that the initial load at breakup (grams per square foot) is higher in parking lots than on streets. This is likely due to the low vehicle velocity with reduces saltation of sediment. It may also be due to somewhat increased amounts of sand placed in parking lots. Data with which to compare summer sediment buildup or washoff rates are not available. It is likely that the summer buildup rates for parking lots and arterial streets are more similar than the initial load at breakup. Based on this similarity of sediment load, it appears that sweeping practices recommended for arterial streets are applicable to parking lots Because of the higher load on parking lots (1) sweeper efficiency is likely to increase but (2) subsequent passes should be made because the total mass left on the parking surface is expected to be higher.

Sediment gradation. The gradation of sediment on parking lots at breakup was also compared to arterial roads. The percent of the total mass of sediment with particle diameters less than 100 to 106 μm are presented in Table 6. (Parking lot gradations were reported as greater or finer than 106 μm in the 2001 data report; street sediment gradations were reported as greater or finer than 100 μm in the 1999 OGS study. Given that particle sizes range from 10 to greater than 420 μm, 100 to 106 μm is considered to be close enough to represent a comparable split.) Parking lot gradations, with 9 percent of the sediment mass less than 106 μm is comparable to major arterial sediment gradations, in which 10 percent of the sediment mass is less than 100 μm. Note that this is representative of the initial, breakup load only and may not represent the gradation of sediment that builds up over the summer. It is likely that summer parking lot buildup exhibits a lower percentage of coarse-grained sediment, but data to substantiate this speculation have not been collected.

Table 6 Comparison of Sediment Load and Gradation of Sediments on Streets and Parking Lots at Breakup

Initial Spring Load	Fines (1) g/ft^2	Other particles (2) g/ft^2	Total g/ft^2	Fines percent of total mass percent	Data Source
Parking lots – median value	12.4	152.5	163.8	9	MOA WMP, 2001a
Minor Arterial (road type 3)	7.6	35.9	43.5	17	MOA WMP, 1999a
Major arterial (road type 4)	7.4	68.2.	75.6	10	MOA WMP, 1999a

Key:
[1]Equal to or less than 106 μm in diameter for parking lots; equal to or less than 100 μm in diameter for streets
[2]Greater than 106 μm in diameter for parking lots; greater than 100 μm in diameter for streets
g/ft^2 – grams per square foot

Parking lots were not modeled in the 1999 OGS study. That study found that OGS are most suited for basins with greater than 1 acre of arterial road, and greater than 20 percent of the road area comprised of major arterial roads. Parking lot sediment loads resemble loads associated with major arterials. It follows that basins that encompass significant amounts of paved parking have they have the potential for sediment loading in stormwater runoff similar to major arterials and that OGS are also suited for these types of basins. National studies indicate that this is true for basins smaller than 5 acres (______, 19___). This size limitation may be reflect the situation in which large basins with high percent imperviousness (such as basins predominated by parking lots) generate large runoff peaks that are not well treated by OGS devices.

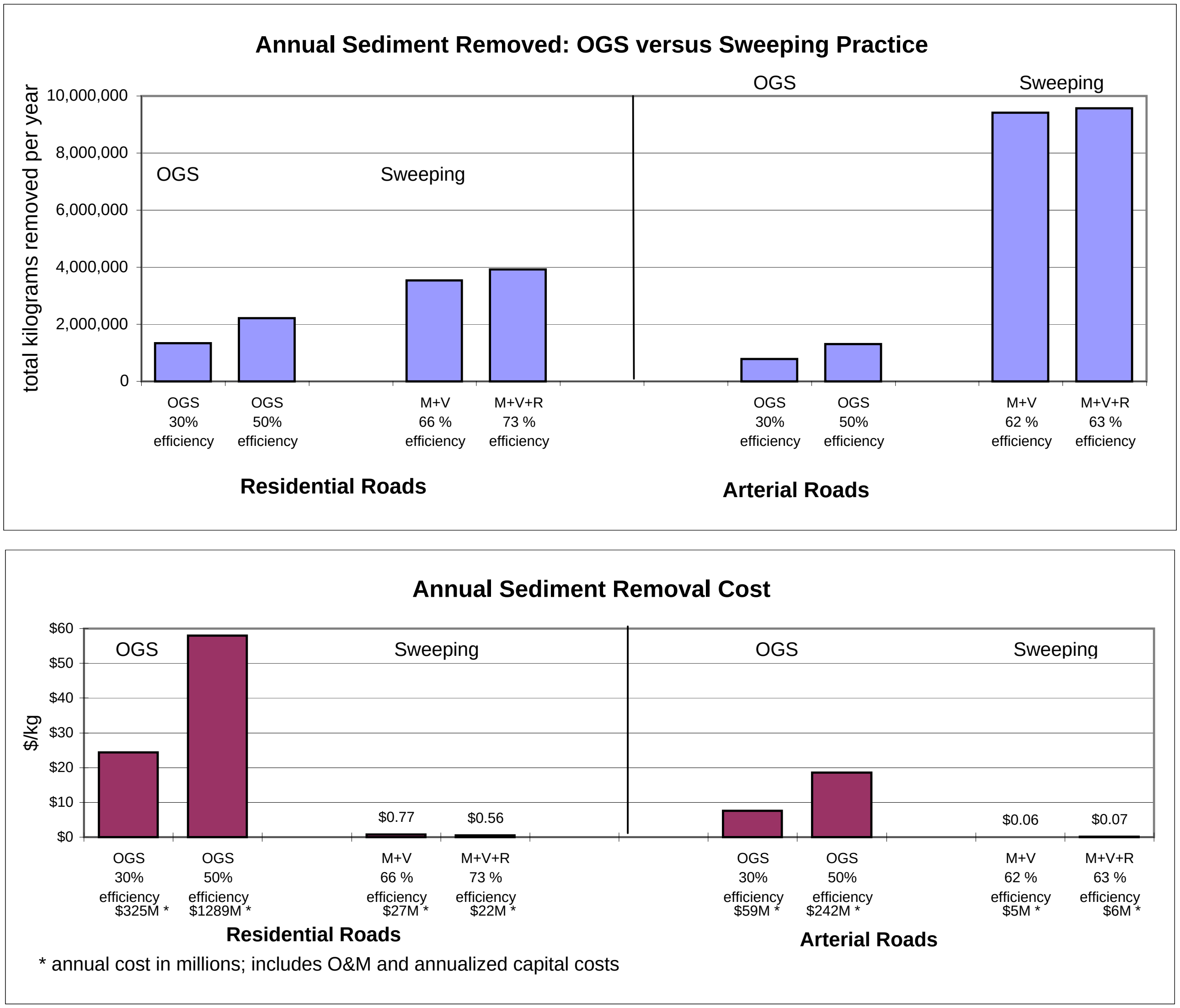
Analysis of Oil and Grit Separator and Sweeping Costs

The costs and annual removals derived in previous sections for OGS structures and street sweeping are presented in Figure 11. Costs and removals by two sizes of OGS are presented: OGS that are sized to remove 30 and 50 percent of the annual washoff load. In practice, efficiencies as high as 50 percent are not generally found. The costs presented assume all 382 outfall basins are equipped with OGS and that they are regularly maintained. Annual street sweeping removal and costs are also presented.

For residential streets, current street sweeping practices (M+V) appears to remove more than twice as much sediment as an OGS operating at 30 percent efficiency. On arterial streets, sweeping appears to remove nearly eight times what an OGS can remove. The cost to remove sediment by an OGS ranges from $8 to $25 per kg removed at 30 percent efficiency and from 19 to 59 per kg at 50 percent efficiency. By contrast, costs for street sweeping, which is over 60 percent efficient, ranges from $0.06 to $0.77 per kg removed.

It should be noted that OGS are installed to capture sediment washed off between sweeping events. Because of continual sediment buildup on the streets from a variety of sources (MOA WMP, 1997), there is no street sweeping schedule that can eliminate washoff. Thus, OGS represent a complimentary treatment, but at a higher unit cost.

Figure 11 Street Sweeper versus OGS Performance



Costs reflect operations, maintenance, and amortized capital costs.

OGS costs represent estimated treatment for all known outfalls in the Anchorage bowl, whether an OGS currently exists there or not.

Street sweeping costs represent treatment for all streets, whether currently paved or not. The amount removed and costs reflect **one sweeping event during the spring** and **two sweeping events during the summer**.

Effects of two Sweeping Practices are shown:

M+V -- mechanical and vacuum sweepers in tandem
M+V+R -- mechanical, vacuum, and regenerative air sweepers in tandem

OGS efficiency calculated as amount trapped by OGS divided by the total washoff.

Street sweeping efficiency calculated as the amount swept divided by the total load on the street. Street sweeping modeling assumed 10% of residential road surface area would not be swept due to parked cars.

Analysis of Commercial Grit Separator Efficiencies

MOA intends to move away from its conventional OGS boxes in favor of commercial cylindrical grit separators. Manufacturers of these commercial devices include CDS, Vortechnics, and CRS StormCeptor. MOA desires to define performance criteria for these devices that is reasonably achievable and protective of surface water quality. This section presents findings of reasonably expected removal efficiencies based on currently available commercial grit separators.

Of particular concern in Anchorage is removal of inorganic particles with diameters less than 100 μm. This size range generally includes clay, silt, and fine sand. National data (USEPA, 1983) indicate that particles smaller than 100 μm in typical stormwater make up between 40 and 60 percent by mass. However, MOA OGS modeling (MOA WMP, 1999a), based on SWMM washoff algorithms, indicate that 96 to 99 percent of sediment in stormwater in Anchorage is comprised of particles smaller than 100 μm. Thus, it is essential that commercial grit separators be capable of removing some fraction of the fine sediment for effective treatment in the Anchorage area.

Product literature from manufacturers is somewhat thin on removal efficiencies for smaller particles. Information was obtained from two manufacturers to evaluate this range of particle sizes. Information from a third manufacturer for somewhat larger diameter sediments was also evaluated. Vendor information and evaluation is included in Appendix D.

Calcualtion of grit removal efficiency is influenced by the following processes:

- Smaller rainfall mobilizes less sediment
- Sediment mobilized by smaller storms is smaller in diameter and harder to treat with conventional OGS devices
- There is not a constant sediment washoff relationship with runoff; the washoff load varies due to different buildup processes and sweeping practices
- As flow increases, treatment efficiency for a given OGS device size decreases
- Large storm flows can remobilize sediment trapped in OGS devices, thus reducing the overall treatment efficiency

The analysis of annual grit removal based on vendor-supplied data provides order of magnitude values for sediment removal only. Analysis results are extremely crude due to a number of factors, including the following:

- removal efficiencies are based on different testing methods from vendor to vendor

- reported efficiencies may only be applicable to a narrow range of flows
- for some vendors, the reported removal efficiencies are based on computer modeling rather than measured performance
- removal mechanisms for particles less than 100 μm are more complex than for larger size particles (e.g., water temperature, interference or synergism with other particles); therefore, different test situations may bias predicted efficiencies high or low

A summary of the different annual removal efficiencies for the three vendors is shown in Table 7.

Table 7 Summary of Annual Removal Efficiencies

	% Removal – Annual Basis				
Particle Size:	**50 μm**	**60 μm**	**100 μm**	**112 μm**	**150 μm**
Vendor:	**Vortechnics**	**StormCeptor**	**StormCeptor**	**CDS**	**Vortechnics**
Peak Flow / Unit Capacity					
0.34		87	83	43 – 48	
0.5				25 – 30	
0.57		82	90		
0.67	73 – 75			13 – 20	93
0.8	63 – 71			12 – 15	90 – 91
0.9		**78**	**86**		
1	**63- 64**			**6 – 8**	**83 – 84**
2	49 – 53			3	17 – 22
2.1		65	78		
4	32 – 42			1	16- 17

Note: See Appendix D for derivation of these values.

Based on data from StormCeptor and Vortechnics, it appears that a unit sized for a peak annual event could be capable of removing 63 to 78 percent of the annual mass load of particles less than 100 μm. The rating curves from which these values were calculated appear to be generated by vendor computer modeling, the assumptions of which are not well documented. (No data is available from CDS data for this size of particles.) It is our feeling that efficiencies for these small particle sizes are overstated for actual operations. Because of many unknowns in the individual vendor testing methods, the actual removal efficiencies are expected to be less than these calculated efficiencies, particularly for the smaller size particles. For instance, for wastewater sedimentation, a factor of 1.75 or 2 is applied to results from settling tests for Type 2 (hindered) settling (Metcalf & Eddy, 1972). In addition to problems associated with settling in these devices, resuspension during higher flows occurs that reduces overall removal efficiency. Again, this is particularly significant for the smaller particle sizes because they can be mobilized at lower flows than can larger particle sizes.

With the intent of using these values to provide performance criteria for revisions to the MOA DCM, is recommended that a factor of 3 be applied to the removal efficiencies in Table 7 for particles less than 100 μm. This results in an estimate of overall removal of 21 to 26 percent of sediment less than 100 μm. A target annual removal efficiency of 25 percent appears to be a reasonable recommendation for particles less than 100 μm until further or more studies can be made under Anchorage-specific conditions.

Conversely, for the larger particle sizes, the rating curve used to estimate settling efficiency may have underestimated the removal efficiency. Other variables, such as resuspension, will reduce removal efficiency. Therefore, a target annual removal efficiency of 80 percent appears reasonable for particles greater than 100 μm.

The current DCM criteria (Section 2.120.C.2.c) prescribes removal of 100 percent of particles 130 μm or larger. Based on the results of the 1999 OGS study, for Anchorage, this translates into about 78 percent removal of particles with diameters greater than 100 μm, and 13 percent of all particles 100 μm or smaller (Table 2). The intent of any revision of the MOA DCM is to specify a removal rate that is reasonably achievable, as well as being at least as protective of receiving water as the existing DCM criteria. Based on this review of the vendor-supplied data, and in context with existing criteria, the proposed DCM criteria are as follows:

- 80 percent removal of sediment greater than 100 microns on an annual basis
- 25 percent removal of sediment equal to or less than 100 microns on an annual basis

In general, for sizing grit separators, the criterion for removal of 100 μm or smaller particles is the more stringent of the two criteria.

Expected performance and cost of conventional OGS devices adhering to these criteria are presented in Table 8, based on results from previous OGS modeling. Performance and cost of OGS devices under the current DCM are also presented in Table 8. As can be seen, the expected cost per kg removed under the proposed DCM is expected to be less that the current cost per kg removed, because proportionately more sediment will be removed. Overall, under the new criteria it is expected that 26 percent of the annual sediment load will be removed, as compared with 14 percent under the current design criteria.

Table 8 Performance of Conventional OGS under Current and Proposed Design Criteria for 382 Outfall Basins in Anchorage

	Current DCM Criteria				Proposed DCM Criteria			
	---------- By basin ----------			MOA-wide overall	---------- By basin ----------			MOA-wide Overall
	Median	Maximum	Minimum		Median	Maximum	Minimum	
OGS size, square feet	34	3015	10	NA	48	3573	10	NA
Percent removed – all sediment	14%	40%	6%	14%	27%	57%	26%	26%
Percent removed sediment >100 μm	77%	100%	66%	78%	94%	100%	74%	91%
Percent removed sediment <100 μm	13%	38%	4%	13%	25%	56%	25%	25%
cost – $/kg	$26.25	$20,244	$0.85	$7.94	$16.56	$15,135	$0.59	$5.49

Further recommendations for grit separators, to assure that they will meet these performance criteria throughout their design life, include the following:

- Provide a side discharge bypass weir to bypass large flows. This will prevent scouring, resuspension of sediment, and local flooding
- Provide adequate room for maintenance access, both to the device itself and within the device
- Assure that routine cleaning and maintenance is performed to retain functionality

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Appendix A
Evaluation of OGS Performance When Sized According to MOA Design Criteria

Evaluation of OGS Performance when Sized according to MOA Design Criteria

BACKGROUND

Current Anchorage Design Criteria Manual guidance (MOA DPW, 1988) stipulate OGS devices be designed for a 2-year 6-hour storm. This appendix outlines an approach to using results from the 1999 OGS model to determine the cost and efficiency of OGS devices sized to the MOA DCM.

EXTRAPOLATION TO 2-YEAR 6-HOUR STORM

The model for the 1999 OGS study used 1965 continuous annual hydrograph to produce hourly runoff flows and sediment washoff, and annual OGS efficiencies for a range of OGS sizes for each of 382 outfall basins in Anchorage. The 1965 hydrograph was chosen to represent a typical rainfall/snowfall year in Anchorage. The model results are limited for use with DCM guidance because the 1965 hydrograph does not contain an event as large as the 6-hour 2-year design storm. This leads to an underestimate of both flow and sediment washoff.

Flow. The largest 6-hour rainfall occurred on September 27, 1965, from 2 am to 8 am, with a total depth of 0.37 inches. A comparison of the parameters for that storm to the DCM 2-year 6-hour design storm is shown in Table A-1.

Table A-1 Peak 1965 6-Hour Event compared with 2-Year 6-hour Design Storm Event

Parameter	9-27-1965 storm	2-year 6-hour design storm	Ratio
6-hour total volume	0.37 inches	0.66	1.78
Peak 1-hour	0.1 inches	0.21	2.0

It can be generalized that increases in rainfall are linearly related to increases in runoff, although for higher intensities, this relationship is biased towards higher runoff because of the lack of incremental rainfall abstraction and storage.

Sediment Gradation. A comparison of gradation of sediment washoff from the annual hydrograph to sediment washed off from the peak 6-hour event in 1965 is shown in Table A-2. These values are summarized from the OGS model output. This table shows that for 1965 as a whole, 2 percent of the annual sediment load is greater than 100 µm, while during the peak 6-hour event, 23 percent of the sediment is greater than 100 µm. This illustrates that a greater amount of the sediment washed off in a higher intensity storm is of larger size than that washed off by smaller rainfall events.

Table A-2   Sum of Sediment Loads for All 382 Basins

Sediment Load	Units	Total Washoff	<100 µm	>100 µm
Annual	Mass, 10^6 kg	7,051	6,934	116
	Percent, % of total		98%	2%
Peak 6-hour event	Mass, 10^6 kg	68.43	52.8	15.6
	Percent, % of total		77%	23%
6-hour event as %	Of annual load	1%	1%	13%

The flows and sediment washoff from the September 27 storm were scaled up from 1965 values to extrapolate to the design storm. The exercise was performed on two representative basins for this analysis, Basin 11 and Basin 13. OGS output and extrapolated flows and sediment loads are presented in Figure A-1. The method for scaling flow and sediment are as follows:

Flow. The 1-hour rainfall depths in the September 27 storm were ranked by magnitude and matched to the ranked depths of the design storm's peak 6 hours. A ratio of the design to actual rainfall depth was computed for each of the 1-hour rainfall volumes. This ratio was applied to the hourly runoff for the storm to produce representative flows for the 2-year 6-hour storm event.

Sediment. Sediment washoff loads and gradations corresponding to flows for each of the two basins were extracted from the model output. The relationship between the highest flows and washed off sediment is shown in Figure A-2. A relationship between high flows and washoff of sediment greater than 100 µm in diameter was found for each of the two basins using linear regression techniques. Correlation of sediment washoff with flow was good for sediment particles greater than 100 µm for the upper 6 to 13 percent of the flows, with r-squared from the least squares method ranging from 74 percent to 89 percent. Basin, as shown in Figures A-3 and A-4. (By contrast, r-squared for sediment less than 100 µm for these high flows was only 6 percent.) From the regression parameters derived, washoff for sediment greater than 100 µm corresponding to flows from the 6-hour 2-year design storm were generated.

Figure A-1 Extrapolate 9-27-1965 Event to 2-year 6-hour Design Storm

FLOW

1-HOUR PRECIPITATION

Use to scale up flow

	Design Storm	65 storm	Compute ratio for corresponding ranked 1-hr
1	0.2	0.1	2.00
2	0.12	0.08	1.50
3	0.1	0.06	1.67
3	0.1	0.08	1.25
5	0.07	0.03	2.33
6	0.069	0.02	3.45
	0.659	0.37	1.78

1-HOUR FLOW from Eric's Tables				Flows tiimes Ratio Computed above	
time	Basin 11	Basin 13	Rank	Basin 11	Basin 13
2:59	0.60	0.08	2	0.89	0.12
3:59	0.50	0.07	1	1.00	0.14
4:59	0.86	0.14	3	1.08	0.18
5:59	1.38	0.22	4	1.73	0.27
6:59	1.58	0.23	5	3.69	0.54
7:59	1.78	0.27	8	6.14	0.92
	6.70	1.02		14.52	2.19
	cfs-hrs	cfs-hrs		cfs-hrs	cfs-hrs

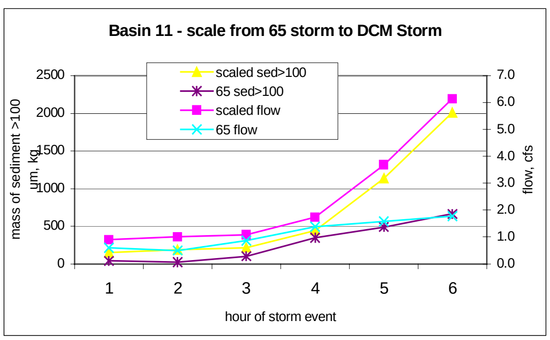
SEDIMENT

For scaling sediment mass, use parametrs from regression equation found in spreadsheet:"Figure Out DCM"

Note: r^2=			intercept	x variable
89%	for Basin 11, sediment 100-420 ur	sediment mass =	-69.07 +	151.13 x flow (cfs)
74%	for Basin 11, sediment >420 um:	sediment mass =	-97.45 +	202.97 x flow (cfs)
75%	for Basin 13, sediment 100-420 ur	sediment mass =	-10.69 +	167.15 x flow (cfs)
82%	for Basin 13, sediment >420 um:	sediment mass =	-15.04 +	225.87 x flow (cfs)

Scale up Sediment

Basin 11		Basin 13	
100-420	>420	100-420	>420
66	84	9.9	12.8
82	105	12.7	16.6
94	122	19.4	25.6
192	254	35.1	46.9
488	651	80.3	108.0
858	1148	143.7	193.6
kg	kg	kg	kg



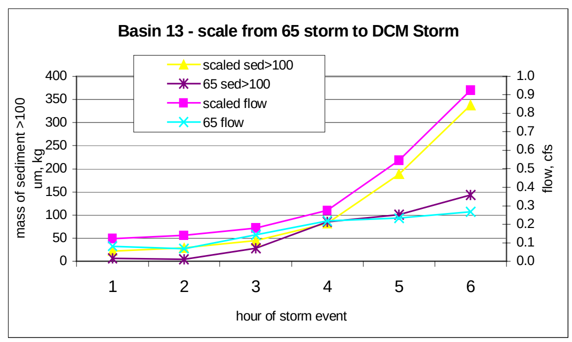
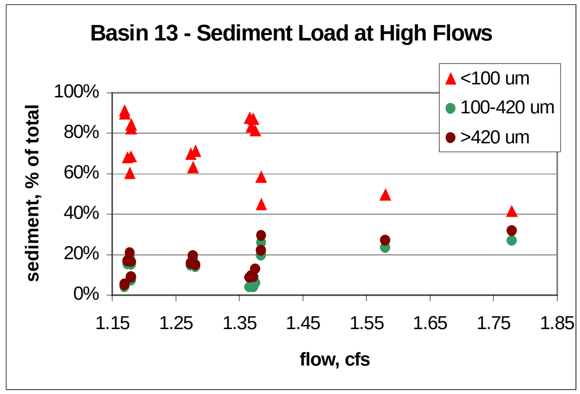


Figure A-2
Top 18 Peak Flows From OGS Model Results for 2 Basins

Basin 11

	sediment mass, g			% of total sediment mass		
flow, cfs	<100	100-420	>420	<100 um	100-420 um	>420 um
1.17	2023	90	108	91%	4%	5%
1.17	1850	102	115	90%	5%	6%
1.17	475	107	118	68%	15%	17%
1.18	343	108	118	60%	19%	21%
1.18	497	111	120	68%	15%	16%
1.18	1040	89	108	84%	7%	9%
1.18	1080	113	120	82%	9%	9%
1.27	655	138	147	70%	15%	16%
1.28	480	135	148	63%	18%	19%
1.28	715	140	150	71%	14%	15%
1.37	3677	165	362	87%	4%	9%
1.37	1381	120	158	83%	7%	9%
1.37	3573	167	366	87%	4%	9%
1.37	2334	174	370	81%	6%	13%
1.38	487	164	184	58%	20%	22%
1.38	278	161	183	45%	26%	29%
1.58	481	228	262	50%	23%	27%
1.78	468	305	360	41%	27%	32%



Basin 13

	sediment mass, g			% of total sediment mass		
flow, cfs	<100	100-420	>420	<100 um	100-420 um	>420 um
0.18	95	28	30	62%	19%	19%
0.19	308	21	26	87%	6%	7%
0.19	69	27	30	54%	22%	24%
0.19	40	25	29	42%	27%	31%
0.19	50	25	29	48%	24%	28%
0.19	341	12	20	91%	3%	5%
0.19	565	16	36	92%	3%	6%
0.19	74	27	31	56%	21%	24%
0.20	110	36	39	59%	20%	21%
0.20	198	11	21	86%	5%	9%
0.21	38	31	36	36%	29%	34%
0.21	206	18	27	82%	7%	11%
0.22	71	40	46	45%	25%	29%
0.22	384	29	59	81%	6%	13%
0.23	210	8	23	87%	3%	10%
0.23	664	27	62	88%	4%	8%
0.23	67	47	54	40%	28%	32%
0.27	65	65	78	31%	31%	38%

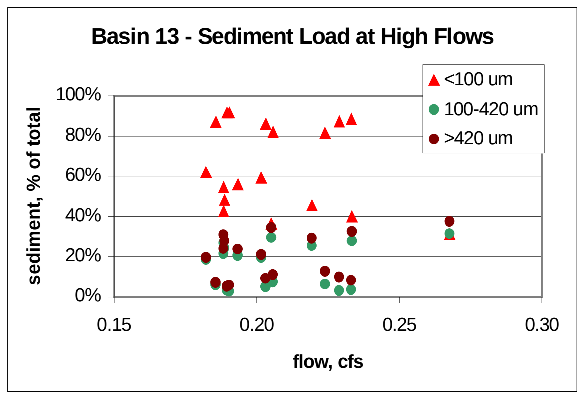


Figure A-3

Basin 11

SUMMARY OUTPUT

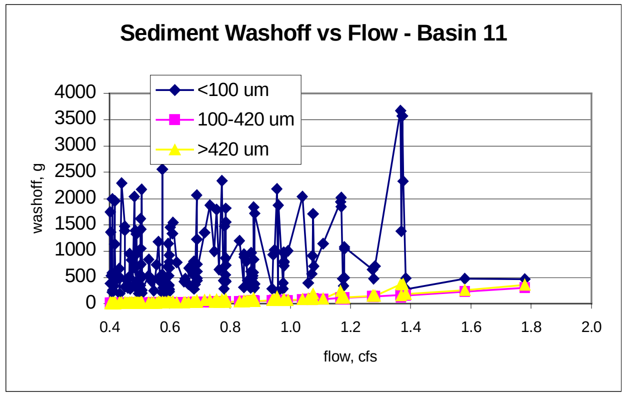
for flows >0.4 cfs
x=flow, cfs
y=sediment 100-420 um

Regression Statistics	
Multiple R	0.945897
R Square	**0.894722**
Adjusted R Square	0.894124
Standard Error	14.34023
Observations	178

ANOVA

	df	*SS*	*MS*
Regression	1	307592.1	307592.0551
Residual	176	36193.04	205.642285
Total	177	343785.1	

	Coefficients	*tandard Err*	*t Stat*	*er 95.*	*pper 95.0%*
Intercept	-69.06985	3.049954	-22.64619389	-75	-63.0507
X Variable 1	151.1329	3.907759	38.6750912	143	158.845



SUMMARY OUTPUT

for flows >0.4 cfs
x=flow, cfs
y=sediment >420 um

Regression Statistics	
Multiple R	0.859678
R Square	**0.739046**
Adjusted R Square	0.737563
Standard Error	33.36119
Observations	178

ANOVA

	df	*SS*	*MS*
Regression	1	554757.2	554757.1634
Residual	176	195882.5	1112.968883
Total	177	750639.7	

	Coefficients	*tandard Err*	*t Stat*	*er 95.*	*pper 95.0%*
Intercept	-97.45461	7.095428	-13.73484603	-111	-83.4515
X Variable 1	202.9659	9.09103	22.32595003	185	220.9074

Figure A-4

Basin 13

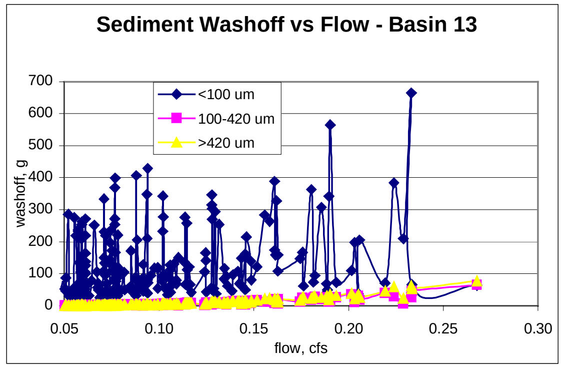
SUMMARY OUTPUT **for flows =>0.05 cfs**
x=flow, cfs
y=sediment 100-420 um

Regression Statistics	
Multiple R	0.865965
R Square	**0.749895**
Adjusted R Square	0.748732
Standard Error	4.396886
Observations	217

ANOVA

	df	*SS*	*MS*	*F*	*ignificance F*
Regression	1	12462.57	12462.57	644.64	1.24E-66
Residual	215	4156.511	19.33261		
Total	216	16619.08			

	Coefficients	*andard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95.0%*	*Ipper 95.0%*
Intercept	-10.69346	0.734852	-14.55184	7.55E-34	-12.14189	-9.245019	-12.14189	-9.245019
X Variable 1	167.147	6.583243	25.38976	1.24E-66	154.171	180.1229	154.171	180.1229



SUMMARY OUTPUT **for flows =>0.05 cfs**
x=flow, cfs
y=sediment>420 um

Regression Statistics	
Multiple R	0.903243
R Square	**0.815848**
Adjusted R Square	0.814991
Standard Error	4.887965
Observations	217

ANOVA

	df	*SS*	*MS*	*F*	*ignificance F*
Regression	1	22757.59	22757.59	952.5114	6.1E-81
Residual	215	5136.822	23.8922		
Total	216	27894.41			

	Coefficients	*andard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95.0%*	*Ipper 95.0%*
Intercept	-15.04297	0.816926	-18.4141	4.4E-46	-16.65317	-13.43276	-16.65317	-13.43276
X Variable 1	225.8696	7.31851	30.86278	6.1E-81	211.4444	240.2948	211.4444	240.2948

SUMMARY OUTPUT **for flows =>0.05 cfs**
x=flow, cfs
y=sediment<100 um

Regression Statistics	
Multiple R	0.248154
R Square	**0.06158**
Adjusted R Square	0.057216
Standard Error	0.044125
Observations	217

ANOVA

	df	*SS*	*MS*	*F*	*ignificance F*
Regression	1	0.02747	0.02747	14.10858	0.000222
Residual	215	0.418608	0.001947		
Total	216	0.446078			

	Coefficients	*andard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95.0%*	*Ipper 95.0%*
Intercept	0.087741	0.004836	18.14323	3.08E-45	0.078209	0.097273	0.078209	0.097273
X Variable 1	0.000107	2.86E-05	3.756139	0.000222	5.1E-05	0.000164	5.1E-05	0.000164

APPLICATION OF DESIGN CRITERIA

Two parts of the DCM guidelines for sizing OGS facilities are discussed in this section: the critical velocity criterion and the removal of inorganic particles criterion.

Critical Velocity – Criteria and Discussion

MOA DCM Section 2.120 – Oil and Grease Separators

2.120 C Design Criteria
1. The critical velocity based on the peak flow for the 2-year recurrence 6-hour duration design storm is 0.62 feet per second.

This velocity criterion helps define the dimensions of the treatment chamber. The cross-sectional area (width times depth) must be large enough so that peak flow will be reduced to 0.62 cubic feet per second. The range of flows from the OGS model was 0.01 to 94 cubic feet per second (cfs). When scaled to the 2-year 6-hour storm, these flows ranged from 0.03 to 188 cfs. Assuming a collection chamber depth of 10 feet (as was used in the OGS model), this results in OGS widths ranging up to 30 feet. The median peak flow for the 382 basins is 0.21 corresponding to a width of 0.34 feet if the collection chamber is 10 feet deep and 0.86 feet if the collection chamber is 4 feet deep. Thus, this criterion does not appear to be a limiting factor for sizing the OGS, compared to other portions of the DCM.

Removal of Inorganic Particles – Criteria and Discussion

MOA DCM Section 2.120 – Oil and Grease Separators
2.120 C 2. The recommended water quality goals for oil and grease separators are:
c. A 100% reduction in the target sediment particles 130 microns in diameter.
2.120 C 3. Facility capacity designed to meet the water quality goals for the 2-year recurrent 6-hour duration storm event

In order to evaluate performance for this criterion, the proportion of sediment 130 microns or greater must be known. However, the OGS model worked with discrete ranges of particles: less than 100 µm, 100-420 microns, and greater than 420 microns. To put this criterion in terms of the ranges in the OGS model, we must determine what portion of the greater than 100 µm category the 130 µm particles represent.

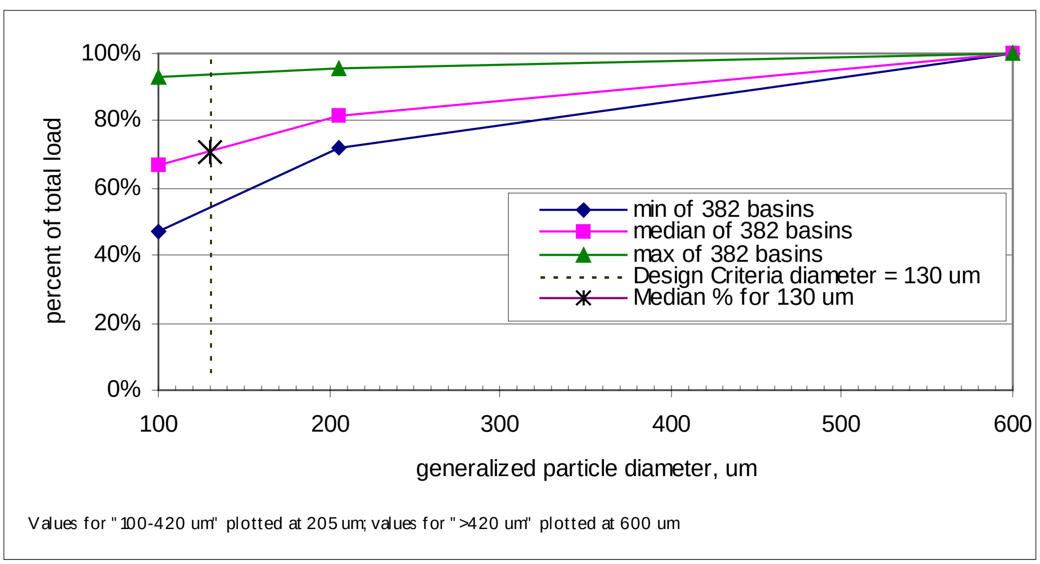
The proportion of particles in each size range varies with flow. At low flows, well over 90% of the sediment mass is represented by sediment less than 100 µm in diameter. However, at higher flows, this proportion changes. For Basins 11 and 13, the proportion of sediment in different size categories with the peak 18 flows is presented in Figure A-2. As can be seen in Figure A-2, the ratio of larger sizes increases at the two highest flows. Sediment greater than 100 µm constitutes over 50 percent of the sediment mass at the highest flows.

The OGS model results for sediment loads in washoff from the 6-hour September 27, 1965 event, for all 382 basins, indicate that 47 to 93 percent of the total sediment mass is constituted by particles greater less 100 µm (Table A-3) and 7 to 53 percent of the sediment load is represented by particles greater than 100 µm. The median value for all basins was 67 percent less than 100 µm, 15 percent in the 100 to 420 µm range and 18 percent in the greater than 420 micron range. As mentioned above, the September 27 event was not as large as the design storm and it is reasonable to assume that for more intense rainfall and runoff, a higher percent of the sediment mass will be constituted by larger particle sizes.

Table A-3 Percent of Particles in Size Ranges in Peak 1965 6-Hour Event for 382 Basins

	Particle	**Size**	
	%<100 µm	%100-420 µm	%>420 µm
Maximum	93%	25%	28%
Minimum	47%	2%	4%
Median	67%	15%	18%

Figure A-5 Percent of Particles in Size Ranges in Peak 1965 6-Hour Event –Values for 382 Basins



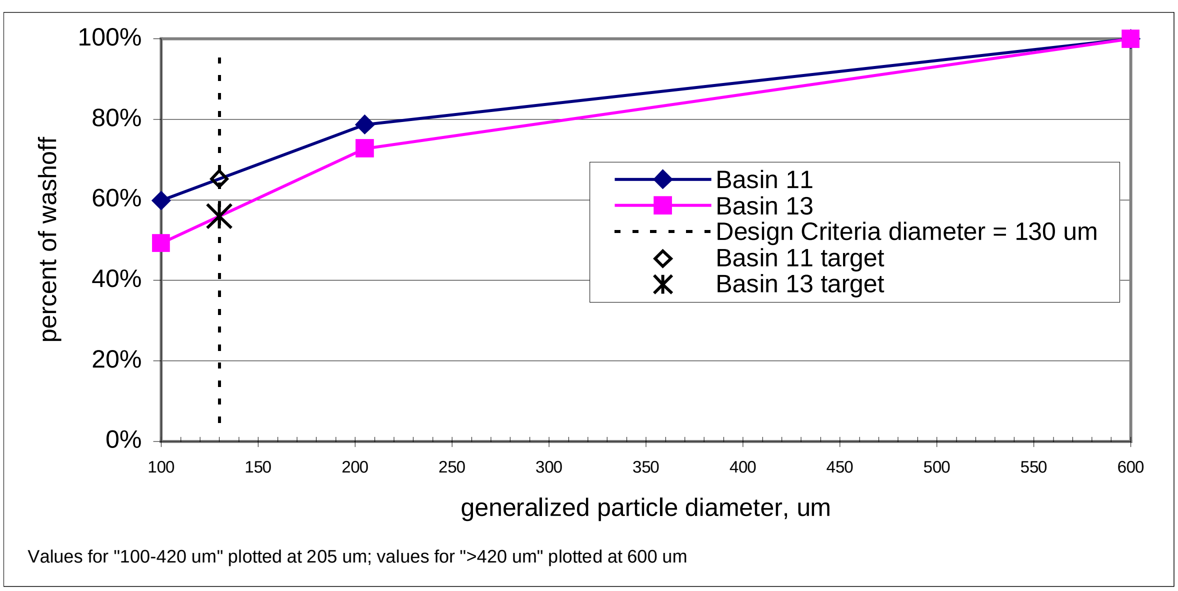
Based on extrapolation from the values for the median at 100 and 204 µm (the geometric mean between 100 and 420 µm), it is estimated that 70 percent of the sediment from the 6-hour event is less than 130 µm, as shown in Figure A-5. Given that 67 percent is less than 100 µm, it follows that 3 percent is between 100 and 130 µm. Since the amount greater than 100 µm is 33 percent, then the amount greater than 130 µm is 30 percent. In order to remove 100 percent of the sediment 130 µm or larger, (30)/33 or 90 percent of the load greater than 100 µm must be removed.

A similar approach based on sediment load for the 6-hour event in basins 11 and 13 yield similar ratios. As shown in Table A-4, for Basin 11, 40 percent of the washoff mass was constituted by particles 100 µm or larger for the September 27 rainfall event; in Basin 13, 51 percent were larger than 100 µm. Based on similar extrapolation described above, it is estimated that 35 percent of the sediment in the 2-year 6-hour event is greater than 100 µm for Basin 11 and 45 percent for basin 13 (Figure A-6).

Table A-4 Percent of Washoff Particles in Size Ranges in Extrapolated 2-yr 6-hr storm – Values for 2 Basins

Basin	<100 µm percent	100-420 µm Percent	>420 µm Percent	Extrapolated <130 µm Percent	Extrapolated >130 µm Percent	Extrapolated >100 µm that must be removed to achieve 100% removal of 130 µm Percent
11	60%	19%	21%	65%	35%	86%
13	49%	24%	27%	56%	44%	87%

Figure A-6 Percent of Washoff Particles in Size Ranges in Extrapolated 2-yr 6-hr storm – Values for 2 basins



For these particular basins, 86 to 87 percent of the sediment load greater than 100 µm must be removed to achieve 100 percent removal of the load greater than 130 µm. This is close to the 90 percent estimated based on the median of the 382 basins. For round numbers, 90 percent removal for the 6-hour 2-year storm was assumed to meet the 130 µm removal criteria.

When this target removal rate is applied to Basins 11 and 13 for the extrapolated 2-hour 6-year storm, OGS sizes are determined. These are presented in Table A-5. (Calculations are shown in Figure A-7 and A-8.)

Table A-5 Peak Design Flow and DCM OGS Size

Basin	Peak Design Flow, cfs	OGS Size, square feet	OGS Size/Peak Design Flow
11	6.14	100	16.3
13	0.92	15	16.2

Figure A-7
Determine OGS Efficiency for Basin 11

				Assumptions:	<100	100-420	>420	um, particle size
					1	2	3	
Given	Q	0.35	ft^3/sec	vs	0.0013	0.0862	0.469	
	L	10	ft	n	0.015			
	y	4	ft	g	32.2			
	Area	100	sq ft					

Net Removal >100 um:	90%
Area / peak flow:	16.3

Given Calculate:

Q	E 1	E 2	E 3	Vu	Td	Vt	EQ 1	EQ 2	EQ 3	ET 1	ET 2	ET 3	alpha 1	alpha 2	alpha 3
0.89	11%	100%	100%	0.01	0.001	11176	0.1	1	1	0.13	1.00	1.00	0.0	0.0	0.0
1.00	10%	100%	100%	0.01	0.001	10031	0.1	1	1	0.12	1.00	1.00	0.0	0.0	0.0
1.08	10%	100%	100%	0.01	0.001	9264	0.1	1	1	0.11	1.00	1.00	0.0	0.0	0.0
1.73	7%	99%	100%	0.02	0.002	5780	0.1	1	1	0.07	0.99	1.00	0.0	0.0	0.0
3.69	3%	84%	100%	0.04	0.004	2713	0.0	1	1	0.03	0.90	1.00	0.0	0.0	0.0
6.14	2%	62%	100%	0.06	0.006	1629	0.0	1	1	0.02	0.75	1.00	0.0	0.0	0.0

	Estimated 2-year 6-hour washoff		est 2-yr 6-hr flow	Using "DCM OGS" --- Efficiency by sed size - Particles > 100 um				
	100-420	>420		<100	100-420	>420	gm rem	% removed
	66.2	84.1	0.89	11%	100%	100%	150.3	100%
	81.6	104.9	1.00	10%	100%	100%	186.5	100%
	94.1	121.6	1.08	10%	100%	100%	215.6	100%
	192.4	253.7	1.73	7%	99%	100%	443.7	99%
	488.0	650.7	3.69	3%	84%	100%	1060.3	93%
	858.5	1148.2	6.14	2%	62%	100%	1678.7	84%
sum over 6-hr storm	1780.7	2363.2					3735	90%

Reference: MOA WMS, 1999a. Volume III, Part II, p 19.

Figure A-8
Determine OGS Efficiency for Basin 13

					Assumptions:	<100	100-420	>420	um, particle size
						1	2	3	
Given	Q	0.35	ft^3/sec		vs	0.0013	0.0862	0.469	
	L	10	ft		n	0.015			Net Removal >100 um: 90%
	y	4	ft		g	32.2			
	Area	15	sq ft						Area / peak flow: 16.2

Given Calculate:

Q	E 1	E 2	E 3	Vu	Td	Vt	EQ 1	EQ 2	EQ 3	ET 1	ET 2	ET 3	alpha 1	alpha 2	alpha 3
0.12	12%	100%	100%	0.01	0.001	12189	0.2	1	1	0.14	1.00	1.00	0.0	0.0	0.0
0.14	11%	100%	100%	0.01	0.001	10717	0.1	1	1	0.13	1.00	1.00	0.0	0.0	0.0
0.18	9%	100%	100%	0.01	0.001	8343	0.1	1	1	0.10	1.00	1.00	0.0	0.0	0.0
0.27	6%	98%	100%	0.02	0.002	5470	0.1	1	1	0.07	0.99	1.00	0.0	0.0	0.0
0.54	3%	84%	100%	0.04	0.004	2754	0.0	1	1	0.03	0.91	1.00	0.0	0.0	0.0
0.92	2%	62%	100%	0.06	0.006	1624	0.0	1	1	0.02	0.75	1.00	0.0	0.0	0.0

	Estimated 2-year 6-hour washoff		est 2-yr 6-hr flow	Using "DCM OGS" --- Efficiency by sed size - Particles > 100 um				
	100-420	>420		<100	100-420	>420	gm rem	% removed
	9.9	12.8	0.12	12%	100%	100%	22.6	100%
	12.7	16.6	0.14	11%	100%	100%	29.3	100%
	19.4	25.6	0.18	9%	100%	100%	44.9	100%
	35.1	46.9	0.27	6%	98%	100%	81.5	99%
	80.3	108.0	0.54	3%	84%	100%	175.9	93%
	143.7	193.6	0.92	2%	62%	100%	282.2	84%
sum over 6-hr storm	301.1	403.4					636	90%

Reference: MOA WMS, 1999a. Volume III, Part II, p 19.

Assuming that the OGS size is related to the peak flow, the ratio of the computed OGS size toe the peak flow for each of these two basis was determined. The ratio, OGS size / peak design flow, averages around 16 for these two basins (Table A-5). When this is applied to the OGS model, we need also to extrapolate the peak 1965 flow to the design flow. Based on the previous analysis, that factor is 2.0 (Figure A-1). This results in the following equation to estimate the OGS size to meet DCM criteria: OGS Area = qpeak x 16 x 2 or OGS Area = qpeak x 32. When this equation was applied to all 382 basins, the annual sediment removal and costs were estimated, these are presented in Table A-6. Overall removal costs were found to be $7.94 per kilogram removed.

Table A-6 OGS Performance – OGS Sized to Meet DCM Criteria for 382 Basins, Assuming A=32*qpeak

	Current DCM Criteria			
	----------	By basin	----------	MOA-wide
	Median	Maximum	minimum	overall
OGS size, square feet	34	3015	10	NA
Percent removed - all sediment	14%	40%	6%	14%
Percent removed sediment >100 µm	77%	100%	66%	78%
Percent removed sediment <100 µm	13%	38%	4%	13%

cost - $/kg	$26.25	$20,244	$0.85	$7.94

The formula used to generate the "1988 Design Guide OGS size" was OGS Area = qpeak x 1.2/0.0185 or OGS Area = qpeak x 64.86. We have not documented how this equation was derived. However, it is similar to the formula for sizing the surface area of a sedimentation pond where A = Qpeak/(Vc * 0.85), in which Qpeak is the 5-minute peak velocity, Vc is the settling velocity of the target particle, and 0.85 is an efficiency (or factor of safety) value. The results of that equation are as follows:

Table A-7 OGS Performance – OGS Sized to Meet DCM Criteria for 382 Basins Assuming A=64*qpeak

	Current DCM Criteria			
	----------	By basin	----------	MOA-wide
	Median	maximum	minimum	Overall
OGS size, square feet	69	6112	10	NA
Percent removed - all sediment	30%	57%	14%	28%
Percent removed sediment >100 µm	97%	100%	74%	94%
Percent removed sediment <100 µm	28%	56%	13%	12%
cost - $/kg	$19.7	$20,127	$0.77	$7.88

This equation appears to oversize the OGS devices somewhat, resulting in a higher removal rate. But, although the multiplier for these two equations (32 versus 64) do not compare favorably, the net result in cost are essentially equivalent at $7.90 per kg removed annually.

REFERENCES

MOA DPW. 1988. Design Criteria Manual. Engineering Division. March.

MOA WMP. 1999a. Anchorage Bowl OGS Performance Modeling. Document No. WMP Apr98002. Prepared by Montgomery Watson. December.

Appendix B
Street Sediment Sweeping Removal Efficiencies

Appendix B Street Sweeping Efficiencies

Sweeper efficiencies were calculated based on the following partitions:

By particle size	less than 100μm, 100-420μm, greater than 420 μm
By road type	types 1&2 and types 3&4
By season	breakup and summer
By practice	M+V, M+V+R, M+V x2; and M+V+R x2

Since SWMM cannot handle seasonal efficiencies in a single run, that is, one sweeper efficiency for one period of the year and a different efficiency for another period of the year, the SWMM model was run twice for a given scenario. The first run was performed using breakup efficiencies and frequencies. The sediment remaining at the end of that run was used as the initial sediment load for the second run, which simulated summer removal and used summer sweeping efficiencies.

For each of the 4 practices, scenarios that involved the same sweeper practice (e.g., M+V, M+V+R) but different frequencies of sweeping events (either 1 or 2 times in the spring and 1, 2, or 4 times in the summer) used the same sweeper efficiencies.

We have the following data:

- Local MOA data that reflect different street load sediment gradations for 4 different road types (1 through 4) and 2 different seasons (breakup and summer buildup).
- Current "M+V" efficiencies calibrated for current data, as described in Scenario 1 below.
- Published removal rates for regenerative air-type sweepers.

Assumptions:

The efficiency of a second pass of the same sweeper combination is assumed to be ½ the efficiency of the first pass. For scenarios 2 and 4, half of the efficiencies of scenarios 1 and 3 were used in "removing" the sediment during the second pass.

No sweeper practice is 100 percent efficient. If a calculated efficiency was 100 percent, a somewhat lower efficiency was used in the model.

Using these data and assumptions, the practices' efficiencies were calculated in the following manner.

Scenario 1 (M+V), representing the "current" case is assumed to involve one mechanical sweeper followed by one vacuum sweeper in a single pass, used the sweeper efficiencies calibrated in the 1999 OGS study. However, since the OGS efficiencies were discrete for each of the 4 road types, efficiencies for road types 1 and 2 were composited into an efficiency for a single road type ("1&2"); similarly for road types 3 and 4. The composite was performed for each of the three grain size categories, based on relative area of each of the road types; that is, a weighted average approach.

Efficiencies for Scenario 2 (M+V x2), which involved two, sequential passes of one mechanical sweeper followed by one vacuum sweeper in a single sweep event, was calculated in the following manner. The amount removed during the first pass was determined using the efficiencies calibrated in the 1999 OGS study. The amount removed during the second pass was determined using one-half the efficiency of the first pass. It is assumed that as the concentration of sediment on the paved surface decreases, so does efficiency. The compound efficiency of these two passes was used for Scenario 2.

Efficiencies for Scenario 3, M+V+R, were calculated assuming a one pass of the M+V sweeper followed by a regenerative air sweeper using published efficiency values adjusted for the grain size categories used in this study. The assumed regenerative air efficiencies are presented in Table B1.

Table B1 Regenerative Air Street Sweeper Efficiencies

Particle Diameter, μm	Removal Efficiency, percent
Less than 100	32
100-420	86
Greater than 420	97

These were applied to the sediment remaining after the first pass of the M+V sweeper practice for all street types for both seasons. The compound efficiency of these two passes was used for Scenario 3.

Efficiencies for Scenario 4, which involved two, sequential passes of the M+V+R practice of Scenario 3.were calculated in the following manner. The amount removed during the first pass was determined using the efficiencies calculated for Scenario 3. The amount removed during the second pass was determined using one-half the efficiency of the first pass. As in Scenario 2, it is assumed that as the concentration of sediment on the paved surface decreases, so does efficiency. The compound efficiency of these two passes was used for Scenario 4.

The street sweeper practice efficiencies presented in Table B2 were used in the SWMM simulation. A summary of the calculations performed to arrive at these efficiencies is included at the end of this Appendix.

Table B2 Street Sweeper Practices Efficiency

Particle Size µm	Road Type	Break up Efficiency, percent		Sum mer Efficiency, percent	
		Calculated	Used *	Calculated	Used *
Scenario 1 Practice: M+V					
less than 100	1&2	42	42	39	39
100-420	1&2	76	76	68	68
>420	1&2	90	90	89	89
less than 100	3&4	88	88	87	87
100-420	3&4	92	92	91	91
>420	3&4	94	94	94	94
Scenario 2 Practice: M+V+R					
<100	1&2	54	54	50	50
100-420	1&2	85	85	79	79
>420	1&2	94	94	94	94
<100	3&4	93	93	92	92
100-420	3&4	96	94	92	95
>420	3&4	97	97	97	97
Scenario 3 Practice: M+V x2					
<100	1&2	60	60	58	58
100-420	1&2	97	96	96	96
>420	1&2	100	98	100	98
<100	3&4	92	92	91	91
100-420	3&4	99	98	99	98
>420	3&4	100	99	100	99
Scenario 4 Practice: M+V+R x2					
<100	1&2	73	73	72	72
100-420	1&2	98	97	98	98
>420	1&2	100	99	100	99
<100	3&4	95	95	95	95
100-420	3&4	99	98	99	98
>420	3&4	100	99	100	99

Note:
* If the calculated efficiency was 100 percent, the efficiency used was reduced. For continuity, this had a cascade effect on smaller particle sizes within the same practice.
Road types 1&2 – residential and collector
Road types 3&4 – minor and major arterials
M+V – sequential mechanical and vacuum sweepers, one pass per event
M+V x 2 – sequential mechanical and vacuum sweepers, two passes per event
M+V+R – sequential mechanical, vacuum, and regenerative air sweepers, one pass per event
M+V+R x 2 – sequential mechanical, vacuum, and regenerative air sweepers, two passes per event

Establish types of sediment on Anchorage streets, based on OGS model
in order to calibrate individual grain size efficiencies with published values
for overall efficiencies

Calculate efficiency on total load (including that hidden by parked cars)

particle size um	Breakup 'Initial' Load * Total g/ft^2		Summer Buildup * Total g/m^2/day	
	Road type	1		
<100	3.8	3.8	0.373	0.4
100-420	3.3	3.3	0.598	0.6
>420	18	18.0	0.241	0.2
Total	25.1	25.1	1.21	1.21
	Road type	2		
<100	3	3.3	0.639	0.6
100-420	7	7.3	0.159	0.2
>420	26	26.1	0.054	0.1
Total	37	37	0.9	0.9

Weighted Average Type 1: 85% <-- based on 832 basins **
% of roads in basins: Type 2: 15%

Road types 1&2	Wtd Avg g/ft^2		Wtd Avg g/m^2/day	
<100	3.7	3.7	0.41	0.41
100-420	3.9	3.9	0.53	0.53
>420	19.2	19.2	0.21	0.21
Total	27	27	1.16	1.16

	Road type 3	
<100	8	2.144
100-420	17	0.770
>420	19	0.810
Total	44	3.72
	Road type 4	
<100	7	9.482
100-420	29	2.089
>420	39	2.750
Total	76	14.32

Weighted Average Type 3: 30% <-- based on 832 basins **
% of roads in basins: Type 4: 70%

Road types 3&4	Wtd Avg g/ft^2		Wtd Avg g/m^2/day	
<100	7		7.28	
100-420	25		1.69	
>420	33		2.17	
Total	66		11.14	

indicates value from OGS model
indicates value from literature

Sweeping Efficiencies from OGS Model Dcoumentation

Efficiency: from OGS study documentation assume this is M/V
Volume 3, page 4, first table under 5

particle size um	road type 1	road type 2	road type 3	road type 4
<100	0.46	0.14	0.92	0.86
100-420	0.67	1	1	0.9
>420	0.89	0.93	1	0.93

Seasonal and Road Type Efficiencies for Scenario 1
aggregate seasonal efficiency based on relative amt in each particle size category

particle size um	breakup road type 1&2	breakup road type 3&4	summer road type 1&2	summer road type 3&4
<100	**42%**	**88%**	**39%**	**87%**
100-420	**76%**	**92%**	**68%**	**91%**
>420	**90%**	**94%**	**89%**	**94%**

* Initial and buildup loads (page 1, shaded) were taken from the OGS study.
Initial loads, in g/ft2, are from Volume 1, page 9
Buildup rates were taken from Volume 3, page 17.

The initial load and summer buildup were used to prorate the efficiencies by road type and grain size; not as absolute values. Thus, consistent units were not required.

** The area of each road type were taken from the data from the 1999 OGS Study.

computed efficiency used in SWMM model

Seasonal and Road Type Efficiencies for Scenario 3

compute efficiency of regenerative air following M/V to generate Scenario 3 efficiency

Amt removed first pass with M/V

particle size	breakup		summer	
um	1&2	3&4	1&2	3&4
<100	1.56	6.55	0.16	6.30
100-420	2.97	23.34	0.36	1.55
>420	17.26	31.21	0.19	2.03

Amt remaining after first pass

breakup		summer	
1&2	3&4	1&2	3&4
2.2	0.9	0.25	0.98
0.9	2.0	0.17	0.15
2.0	1.9	0.02	0.13

Regenative Air Sweeping Efficiencies from Literature

Assume a regenerative air efficiency

Reference: Sutherland, Roger. Street Sweeper Pick-up Performance
Table 4, for initial loads 1,000 lbs/paved ac
backcalculated for each particle size category

Pulished values:

particle size microns	removal efficiency	% of init load	ncrem % ıf init load
<63	32%	6%	6%
<250	73%	25%	19%
all	91%	100%	75%

amt remv total load	amt removed of increm load
2%	2%
18%	16%
91%	73%

Apply to all roads and seasons, after one pass of M/V

particle size um	removal efficiency
<100	32%
100-420	86%
>420	97%

Amt removed by regen air (after M/V)

particle size	breakup		summer	
um	1&2	3&4	1&2	3&4
<100	0.69	0.29	0.08	0.31
100-420	0.80	1.75	0.14	0.13
>420	1.90	1.86	0.02	0.13

Amt remaining after second pass

breakup		summer	
1&2	3&4	1&2	3&4
1.48	0.62	0.17	0.67
0.13	0.29	0.02	0.02
0.06	0.06	0.00	0.00

Efficiency: Tot removed/original amt - M/V + Regen Air

particle size	breakup		summer	
um	1&2	3&4	1&2	3&4
<100	**60%**	**92%**	**58%**	**91%**
100-420	**97%**	**99%**	**96%**	**99%**
>420	**100%**	**100%**	**100%**	**100%**

Compound Efficiency - Check

breakup		summer	
1&2	3&4	1&2	3&4
60%	92%	58%	91%
97%	99%	96%	99%
100%	100%	100%	100%

computed eff for SWMM

Seasonal and Road Type Efficiencies for Scenario 2

compute second M/V pass efficiency to generate Scenario 2 efficiency

assume this is M/V for second pass

-- taken as 50% of the first pass efficiency

particle size	road type			
um	1	2	3	4
<100	0.23	0.07	0.46	0.43
100-420	0.335	0.5	0.5	0.45
>420	0.445	0.465	0.5	0.465

aggregate seasonal efficiency based on relative amt in each particle size category

second pass after M/V

particle size	breakup		summer	
um	1&2	3&4	1&2	3&4
<100	**21%**	**44%**	**19%**	**43%**
100-420	**38%**	**46%**	**34%**	**7%**
>420	**45%**	**47%**	**45%**	**47%**

Amount removed - 2nd pass of M/V

particle size	breakup		summer	
um	1&2	3&4	1&2	3&4
<100	0.45	0.40	0.05	0.42
100-420	0.35	0.94	0.06	0.01
>420	0.88	0.90	0.01	0.06

Amt remaining after second pass

breakup		summer	
1&2	3&4	1&2	3&4
1.72	0.51	0.20	0.56
0.57	1.10	0.11	0.14
1.08	1.01	0.01	0.07

Efficiency: Tot removed/original amt - M/V two times

particle size	breakup		summer	
um	1&2	3&4	1&2	3&4
<100	**54%**	**93%**	**50%**	**92%**
100-420	**85%**	**96%**	**79%**	**92%**
>420	**94%**	**97%**	**94%**	**97%**

Compound Efficiency - Check

breakup		summer	
1&2	3&4	1&2	3&4
54%	93%	50%	92%
85%	96%	79%	92%
94%	97%	94%	97%

Seasonal and Road Type Efficiencies for Scenario 4

compute second M/V+R pass efficiency to generate scenario 4 efficiency

assume this is M/V+R for second pass

-- taken as 50% of the compound efficiency calculated for scenario 3

particle size	road type			
um	1	2	3	4
<100	30%	46%	29%	45%
100-420	48%	49%	48%	49%
>420	50%	50%	50%	50%

aggregate seasonal efficiency based on relative amt in each particle size category

second pass based on 50% of compound efficiency calculated for M/V+R (Secnario 3)

particle size	breakup		summer	
um	1&2	3&4	1&2	3&4
<100	**32%**	**40%**	**34%**	**44%**
100-420	**49%**	**49%**	**48%**	**43%**
>420	**50%**	**50%**	**50%**	**50%**

Amount removed - 2nd pass of M/V+R

particle size	breakup		summer	
um	1&2	3&4	1&2	3&4
<100	0.48	0.25	0.06	0.29
100-420	0.06	0.14	0.01	0.01
>420	0.03	0.03	0.00	0.00

Amt remaining after second pass

breakup		summer	
1&2	3&4	1&2	3&4
1.0	0.4	0.11	0.37
0.1	0.1	0.01	0.01
0.0	0.0	0.00	0.00

Efficiency: Tot removed/original amt - M/V+R two times

particle size	breakup		summer	
um	1&2	3&4	1&2	3&4
<100	**73%**	**95%**	**72%**	**95%**
100-420	**98%**	**99%**	**98%**	**99%**
>420	**100%**	**100%**	**100%**	**100%**

Compound Efficiency - Check

breakup		summer	
1&2	3&4	1&2	3&4
73%	95%	72%	95%
98%	99%	98%	99%
100%	100%	100%	100%

Appendix C
Street Sweeper Background Information

Municipality of Anchorage
Street Maintenance Department
Spring 2001 Sweeping

Ali - 7/12/02
MOA has 14 sweepers { 6 mechanical, 8 vacuum }
contractor 4 " all vacuum
18 total

MOA Personnel
March 01, 2001 – June 30, 2001

Ali - 7/11/02

Labor Cost	$ 221,553	Fleet Service figures an annual cost
Equipment Cost	$ 218,893	— cost per hour charge includes maintenance
Material Cost	$ 20,791	
MOA Cost	$ 461,237	at any one time - 10 sweepers on street (average)

Contract Sweeping
March 01, 2001 – June 30, 2001

Contract Cost	$ 63,099	- Schedule different than MOA - equip is similar but not specified performance based

Total Cost Spring 2001 Sweeping **$ 524,336**

"Turker, Ali X." <TurkerAX@ci.anchorage.ak.us> on 06/13/2002 02:36:50 PM

To: "'Margaret.langdon@mwhglobal.com'" <Margaret.langdon@mwhglobal.com>
cc: "McBride, Shawn R." <McBrideSR@ci.anchorage.ak.us>, "Branham, Devin C." <BranhamDC@ci.anchorage.ak.us>, "Southard, Daniel R." <SouthardDR@ci.anchorage.ak.us>, "Robinson, Maury F." <RobinsonMF@ci.anchorage.ak.us>

Subject: MOA's Sweeping Method

Dear Miss Langdon,
I understand that you have received the Spring 2001 Sweeping statistics you had requested. Shawn McBride who is one of the Street Maintenance operations supervisors is responsible with the Spring and Summer sweeping program. He is out of the office until next week.

The sweeping program is composed of two segments; Spring and Summer. The Spring program starts in April as early as possible and/or as the road and weather conditions cooperate. We utilize the mechanical type sweepers at that time. These type of sweepers are more effective and powerful in picking up the relatively heavier/coarser sediments/sand leftover from the Winter operations. However, there is still some sediments could not be picked by the mechanical sweepers. Therefore, we usually run another sweeper called "Regenerative Air Sweeper" right behind the mechanical one to pickup the remnants.

We sweep all the areas designated in the Anchorage bowl once. Then we sweep the same areas one more time with the same set up.

Once we are done with the Spring program, the Summer sweeping program begins usually about the middle of May. We utilize "Vacuum Sweepers." They are more effective in sweeping relatively lighter sediments, dust, and leaves. We sweep the designated areas once.

Should you have ~~any comments~~ and/or questions, please do not hesitate to contact me or Mr. McBride at 343-8100.

Regards,

Ali Turker
Information Systems Technician

Office of Planning, Development, and Public Works
Street Maintenance Department
P.O. Box 196650
Anchorage, Alaska 99519-6650

turkerax@ci.anchorage.ak.us
907- 343-8374 (Voice)
907- 343-8280 (Fax)

first sweep when still snow + ice on ground

Try to get done

Second sweep done before end of May (20-21 May this year)

when regen air used?

Regen air used all over town
mechanical + regen sweeper

later on in year - in residential area
may only regen air

Vacuum sweepers

Summer sweep
dep - weather + need
run continuously
alternate w/
chip seal, other
work
work N to South

sometimes out through whole town 2X) - go out if there's a spill - or dust complaints

"Wheaton, Scott R." <WheatonSR@ci.anchorage.ak.us> on 04/13/2001 06:37:48 AM

To: 'Bill Rice' <William.J.Rice@mw.com>
cc:

Subject: FW: Sweeping Costs

Bill,

fyi. we will use this info in our BMP analysis this year so hold on to it. also can you see if you can get similar from Dan Southard (MOA)? thanks. see you monday (did we set a time?). ///srw

> -----Original Message-----
> From: Jerry Reed [SMTP:Jerry_Reed@dot.state.ak.us]
> Sent: Thursday, April 12, 2001 10:01 AM
> To: Scott Wheaton; Jerry_Reed@dot.state.ak.us
> Subject: Sweeping Costs
>
> We have two contractors sweeping 3 "areas":
>
> Knik Sweeping does areas 1 and 2 for a total of 374 lane miles.
> A&G Sweeping does area 3 and has 92.7 lane miles.
>
> The total cost is $133,600 for both contractors per sweep. We used to
> only do two sweeps per year but now we are going to be doing three . . .
> so 3 x $133,600 = $400,800 (+ any extra sweeping we may have them do on
> an hourly basis)
>
> cya
> Jerry
>

DOT 2001
sweeping cost = $400,800

Enviro —
(1) doesn't work when surface wet
(2) rutted roads - poor vacuum seal
(3) excludes fugitive dust

maintenance

KURAHASHI & ASSOCIATES,INC.

KURAHASHI & ASSOCIATES, INC.

Street Sweeper Pick-up Performance

For more information, contact:

Roger Sutherland, (formerly of Kurahashi and Associates, Inc. (KAI), and now vice president of Pacific Water Resources.)
Pacific Water Resources
4905 SW Griffith Drive #200
Beaverton, OR 97005
Wk: 0-503-671-9709

July 1995

As part1 of KAI's work for the Port of Seattle on the stormwater quality analysis of the Sea-Tac International Airport, we conducted an "All Known and Reasonable Technologies" (AKART) search into stormwater quality management practices and passive stormwater treatment devices. The overall results of that search will be discussed in a separate memorandum to you on that more general topic. The purpose of this memorandum is to specifically address street sweeping as a stormwater quality management practice.

Previous Research

The Nationwide Urban Runoff Program (NURP) studies of street sweeping effects on stormwater quality published in 1983 (Reference 1) concluded that street sweeping proved to be largely ineffective in its ability to reduce the event mean concentration of pollutants found in urban runoff. This conclusion is largely based on the fact that the street sweepers used and tested were not able to effectively pick-up very fine accumulated sediments that have been found to be highly contaminated with most of the pollutants observed in urban runoff. The reason? Broom sweepers of this era were effective at picking up litter and large dirt particles, but harmful contaminants are concentrated primarily in the fines-the particles less than 63 microns. Not only were these fine particles left behind in the pavement after broom sweeping, but once the heavy covering of sediment was gone, the fines and their contaminants were even more likely to wash into storm drains during the next rain.

Therefore, the focus of this memorandum is to document any improvements in the newer street sweeping equipments ability to effectively pick-up accumulated sediments including fine sediments. It is also important that we compare the performance of any new equipment or operations to that of the NURP era sweepers to determine just how much change has actually occurred.

Promising Sweeping Technologies

Our search has resulted in three promising technologies that appear to provide significant improvements over the performance of the NURP era sweepers. The first technology is the use of a tandem sweeping operation. A tandem operation involves the combined use of a mechanical (i.e. broom and conveyor belt) sweeper followed immediately by a vacuum-assisted sweeper. The pick-up performance of a tandem operation using a Mobil broom sweeper followed by a TYMCO vacuum sweeper was monitored for over a year in a mediumdensity residential area located in Southeast Portland, Oregon. (Editor's Note: the term 'vacuum' used by the author is a generic one. Although the TYMCO sweeper used a vacuum-assisted sweeping process, their machine is actually a 'regenerative air-type' sweeper, not a 'vacuum-type' sweeper. Vacuum-type sweepers exhaust their debris-laden air into the atmosphere, rather than recirculating it like a regenerative-based sweeper.) The detailed description of this study and its results can be found in Reference Number 2. A brief summary of this monitoring effort and its results are provided in Reference Number 3 . The pick-up performance data obtained from the Portland tandem sweeping operation forms the basis of the comparison of this technology to others presented later in this memorandum.

The second technology is the stand alone use of a regenerative air sweeper. Regenerative air sweepers use air blown on to the pavement and immediately vacuumed into the machine to entrain and remove accumulated sediments. Regenerative air machines were in their infancy during the NURP era and to the author's knowledge were not extensively tested in any of the NURP sites. Regenerative air sweepers are generally considered to do a good job of removing fine sediment providing the accumulated loading are not too great. KAI measured the pick-up performance of the Port of Seattle's Elgin Crosswind regenerative air sweeper at Sea-Tac on April 21, 1995 . The results of these tests forms the basis of the comparison of this technology to others presented later in this memorandum.

The third technology is the stand alone use of a new highly effective vacuum-assisted sweeper called the Enviro Whirl I developed and manufactured by Enviro Whirl Technologies Inc., located in Centralia, Illinois. The Enviro Whirl I was developed from an earlier technology designed to vacuum and contain spilled coal dust along railroad tracks. As a result, the Enviro Whirl I appears to be extremely effective in picking up fine sediments and containing those sediments by filtering air emissions down to four microns which represents significant air quality benefits also. The rotating sweeper brooms located in the powerful vacuum head appear to have combined the benefits of a tandem sweeping operation into a single machine. In fact, as a direct result of the publication of the American Sweeper article (Reference Number 3) the author was contacted by both the manufactures and local distributor of the Enviro Whirl I. On April 24, 1995, at no expense to the Port of Seattle, KAI staff traveled to Las Vegas, Nevada (site of an air quality conference) to independently measure the pick-up performance of the Enviro Whirl I. The results of these tests forms the basis of the comparison of this technology to others presented later in this memorandum.

It should be noted that as a result of the pervious Portland study mentioned earlier, we were able to document the pic-up performance of a newer mechanical (i.e. broom) sweeper which was a 1988 Mobil. These results are also shown for comparison purposes.

The pick-up performance for the NURP era sweepers was based on the author's previous analysis (Reference Number 4) of the Bellevue, Washington NURP data (Reference Number 5). The author was a consultant to the City of Bellevue during the NURP study and has directed access to the street sweeper pick-up performance data collected as part of that historic study. The standard mechanical street sweeper tested in Bellevue was a Mobil probably manufactured around 1978.

Analysis Procedure

The street sweeper's ability to significantly interact with the accumulation and washoff of contaminated sediments readily available on directly connected impervious surfaces like streets actually determines the overall effectiveness of a street sweeping operation evaluated over a designated period of time. The Simplified Particulate Transport Model (SIMPTM) can accurately simulate this complicated interaction of accumulation, washoff, and street sweeper pick-up over a period of time (Reference Number 6). In fact, SIMPTM is being used to characterize the annual storm water quality loadings from Sea-Tac International Airport and the pollutant reduction effectiveness of using the Elgin Crosswind regenerative air sweeper or the Enviro Whirl I sweeper (Reference Number 7). However, what is of interest in this memorandum is: 1) how SIMPTM model's street sweeper pick-up performance; 2) how that model compares to real pick-up performance data; 3) how the calibrated model parameters vary for the various technologies described in this memorandum, and; 4) the estimated pick-up effectiveness of each of these technologies for several hypothetical initial loading conditions. The last item will form the most useful basis of comparison between NURP era sweepers, the newer mechanical sweeper, and the three promising sweeping technologies described

Pick-Up Performance Model

The street sweeping component of the SIMPTM model was based on the results of Pitt's street sweeping study conducted in San Jose, California and published by USEPA in 1979 (Reference Number 8). This model was confirmed in additional studies conducted by Pitt and Shawley (Reference Number 9) and Pitt and Sutherland (ReferenceNumber 10).

Figure I illustrates the street cleaning component and equations used by SIMPTM. For each size group, the amount removed (Prem) is proportional to the accumulation (P) in excess of the base residual (SSmin) by a sweeping efficiency (SSefi):

$$\mathbf{Prl, = SS, (P- SSrl.r.) \text{ for } P > SSrr}$$

The above-mentioned studies found that street sweeping removes little, if any, material below a certain base residual which was found to vary by particle size. Above that base residual, the street sweepers removal effectiveness is described as a straight line percentage which was also found to vary by particle size. Therefore, to describe a unique street sweeping operation one simply needs to know the operations SSmin and SSeff values for each of the eight particle size ranges simulated by SIMPTM.

Figure 2 shows an example of how the simple model component actually compares to real pick-up performance data. The plotted points are the data obtained from the monitoring of the tandem street sweeping operation on Portland's Sellwood drainage basin. Please note that the colTelation coefficient squared for the eight particle size fits ranged from 94.3% to 99.9% which means the model is doing an excellent job of reproducing the actual observations. These high explained variations were typical of all of the model fits to the pick-up data from the various sweeping technologies.

Tables I and 2 present the calibrated model parameters SSmin and SSeff, respectively, for each of the five sweeping technologies presented in this memorandum. In Table 1, note the dramatic improvements in reducing residual loadings for all the newer technologies when compared to the NURP. Both tandem sweeping and the Elgin Crosswind regenerative air are very impressive, but the across-the-board zero residual loadings for the Enviro Whirl I is hard to believe because it is perfect.

Table 2 also shows some impressive removal efficiencies above the residential loadings. Once again, please note the dramatic changes from the NURP era sweepers performance. The effectiveness of the Elgin Crosswind (regenerative air) and the Enviro Whirl I for the finer particle size groups may not look that impressive in the table. However, remember that these two machines are operating on all initial loadings for Group Number 1 and 2, and the Enviro Whirl is operating on all loadings for all groups. In fact, if the SSeff values for the Enviro Whirl were 1.0, the street sweeper performance would be perfect or 100% of everything available would have been picked up.

Pick-Up Performance Comparison

Working with the average particle size distribution observed in the fifteen street dirt accumulation samples collected at sites throughout the Sea-Tac International Airport from September 30, 1994 through April 21, 1995 (i.e. see Table 3) and assumed initial loadings, the projected street sweeper pick-up efficiencies are presented in Table 4. The assumed initial loadings represent the entire range of conditions that could be reasonably observed at Sea-Tac or throughout the Seattle area. The average accumulation value observed at Sea-Tac was 200 Ibs/paved acre with an observed range of 8 to 1,130 Ibs/paved acre. The maximum accumulation observed during the Bellevue NURP was approximately 500 Ibs/paved acre. The average Bellevue accumulation was approximately 250 Ibs/paved acre. The 1,000 Ibs/paved acre would generally represent a site heavily influenced by erosion from construction, an area of poor pavement condition, or an area adjacent to a source of erodible sediment.

Conclusions

Table 4 clearly shows that all of the newer street sweeping technologies are significantly more effective than the NURP era sweepers. So the findings of the NURP in regards to street sweeping lack of effectiveness may not be valid today. Also, note that in lower loading conditions (i.e. 10 to 100 Ibs/paved acre) which are common at Sea-Tac and throughout the Seattle and Portland metropolitan areas, the Enviro Whirl I sweeper pick-up is extremely effective especially in less than 63 microns . The tandem sweeping operation becomes competitive with and appears to surpass the effectiveness of the Enviro Whirl I at higher initial loadings. Note that the regenerative air machine is also quite effective in total removal effectiveness at these higher loadings but it's effectiveness in removing the fine sediment lags behind the other two promising technologies.

Two important items should be noted The first is that this comparison in Table 4 is based on an assumed particle size distribution which is not very fine but somewhat coarse. The Enviro Whirl I would be much more effective at higher initial loadings if the initial particle size distribution were finer. The second is that the Enviro Whirl manufacturer informed us following our Las Vegas testing that the sweeper was not operating at maximum effciency because there was too much air in the tires and the vacuum was losing an inch of suction all around the head. In addition, a portion of one of the rotating broom's bristles were found later to be missing. As a result the Enviro Whirl sweeper will be visiting the Northwest in September of 1995 when further performance tests will be conducted. A demonstration of this impressive machine's sweeping abilities is being scheduled with the Port of Seattle and other Seattle governmental agencies.

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TABLE 2

CALIBRATED SSeff COMPARISON

Data from Various Studies, Pounds per Pound

Particle Size Group	Size Range (microns)	Street Sweeping Technology: NURP Mech.	Newer Mech.	Tandem Sweeping	Regenerative Air	Enviro-Whirl
Grp 1	<63	44%	100%	93%	32%	70%
Grp 2	-125	52%	100%	95%	71%	79%
Grp 3	-250	47%	92%	93%	94%	64%
Grp 4	-600	50%	57%	69%	100%	88%
Grp 5	-1000	55%	48%	84%	100%	95%
Grp 6	-2000	60%	59%	88%	100%	91%
Grp 7	-6370	78%	51%	96%	94%	93%
Grp 8	>6370	79%	70%	87%	92%	97%

TABLE 3

PARTICLE SIZE DISTRIBUTION

Sea-Tac International Airport Average Accumulation Data

Particle Size Group	Size Range (microns)	Mass Fraction Before Sweeping
1	<63	6%
2	-125	7%
3	-250	12%
4	-600	19%
5	-1000	9%
6	-2000	12%
7	-6370	24%
8	>6370	11%

TABLE 4

SIMULATED STREET SWEEPER PICK-UP EFFICIENCY

Units are pounds (removed) per pound (initial)

Total Initial Loading (lbs/pvd acre)	Maximum Range Size (microns)	Street Sweeping Technology: NURP Mech.	Newer Mech.	Tandem Sweeping	Regenerative Air	Enviro-Whirl
	< 63	0%	0%	0%	32%	70%
10	< 250	0%	0%	0%	39%	79%
	ALL	0%	31%	35%	50%	89%
	< 63	0%	0%	61%	32%	70%
100	< 250	0%	30%	70%	70%	79%
	ALL	28%	55%	82%	87%	89%
	< 63	17%	60%	80%	32%	70%
250	< 250	18%	70%	84%	72%	79%
	ALL	45%	66%	88%	89%	89%
	< 63	30%	80%	87%	32%	70%
500	< 250	33%	83%	85%	72%	79%
	ALL	53%	70%	90%	90%	89%
	< 63	37%	90%	90%	32%	70%
1000	< 250	40%	90%	91%	73%	79%
	ALL	57%	71%	91%	91%	89%

?

91%

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INQUIRY DATE
INQUIRY NO.
SALESPERSON Richard Kimball

EST. SHIPPING DATE	SHIPPED VIA	F.O.B.	TERMS
		Anchorage	

QUANTITY	DESCRIPTION	PRICE	AMOUNT
	Budget Pricing on Sweepers		
1	Crosswind Sweeper.	135-	$140,000.00
1	Whirlwind "	165-	$170,000.00
1	Eagle Sweeper -	165-	$170,000.00
1	Broom Bear "	165-	170,000.00

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Appendix D
Evaluation of Commercial Grit Separator Performance Data

Evaluation of Commercial Grit Separator Performance Data

This appendix presents an analysis of sediment removal efficiencies for the Anchorage area based on data made available by three vendors of grit separator devices: Vortechs, StormCeptor, and CDS.

Sizing grit separators for target levels of removal of annual sediment loads, rather than removal from discrete storm events, is a design goal favored by stormwater managers (CWP, 200_). Therefore, this analysis was performed, where possible, to determine annual removal efficiencies.

Vortechs provided a rating curve. This was used in conjunction with OGS model output (flow and sediment load) on two example basins to determine estimated annual removal efficiencies.

StormCeptor removal data was derived from output of proprietary computer modeling. StormCeptor provided results from their simulation for annual removal from runoff for a parking lot design in Anchorage. Their method provided removal rates for particles of 20 µm, 60 µm, 100 µm, and 400 µm. The results of the proprietary modeling are presented here.

CDS was the only vendor that provided laboratory data for the removal efficiency of its product. Unfortunately, no information was available from them for particle sizes less than 100 µm. In a manner similar to the method used with Vortechs data, annual removal efficiency for 112 µm and greater particles was estimated.

Vortechnics

The steps used to estimate the annual removal rate of a Vortechnics grit separator were as follows:

1. Choose a unit size, generally based on surface area or rated flow capacity. If MOA DCM is used, a 6-hour 2-year design event is prescribed. When this is translated into runoff from a given drainage basin, a peak flow is determined and this is used to size the OGS devices. For use with the 1965 hydrograph, the peak 1-hour 1965 flow was extrapolated to a peak 5-min flow and this was used as the design flow rate. 1965 was used as the "average" hydrology year; however, it does not contain an event as large as the DCM 20year 6-hour storm. Therefore, a unit sized for the peak 1965 flow would be undersized for the design storm. Conversely, the result of using this approach is to underestimate the annual efficiency of the unit, so this approach is conservative.
2. Obtain the corresponding treatment efficiency provided by the unit, such as a rating curve for sediment removal, by grain size, at different flow rates. This is necessary since

most flows through the device will be less than the design flow,

the analysis is performed for the annual load

the removal efficiency is expected to be higher at lower flows

A rating curve allows an evaluation of all the flows through the device, not just the design flow. Performance-based efficiencies are summarized in Vortechnics literature for 50 and 150 µm particles in Table D-1.

Table D-1 Vortechnics Reported Removal Efficiencies

Operating Rate gpm/sf	Removal Efficiency %		
	50 µm	150 µm	Typical gradation
10	86	100	96
20	70	99	88
30	58	98	81
40	48	92	77
50	35	89	64
60	21	81	59
70	12	74	50
80	6	52	36
90	3	18	19
100	2	8	8

Source: Technical Bulletin No. 1 Vortechnics™ Stormwater Treatment System Performance (attached)

3. Generate an annual runoff hydrograph with specified sediment loading, by grain size, to route through the chosen grit separator. This was done for 2 basins, based on output from the 1999 OGS model for the 1965 hydrograph.

4. Route these flows through the separator, determining the amount of sediment removed on an annual basis

5. Determine the peak load it can treat. Note that any flows above the rated capacity will be bypassed and their sediment loads will not be treated

6. Add up the amount of sediment removed on an annual basis and divide by the total sediment load to determine the annual removal rate

To get a rating curve for different sized units, repeat these steps for a larger or smaller size unit. Generally, the bigger the grit separator, the more efficient it will be at removing the annual sediment load. Therefore, using the steps outlined above on different sized grit separators for a given annual hydrograph will result in different annual removal rates.

Discrete flow rates were used to calculate discrete operating rates for the selected size of the grit removal unit. Each operating rate was paired with its corresponding removal efficiency, as supplied by the grit separator vendor. For each hourly rainfall amount and flow rate, a unit amount of sediment is determined. When this is multiplied times the percent of all flows that is represented by that hourly rainfall amount, and the results summed over all hourly amounts, the total annual removal is determined. When this total is divided by the annual sediment load, an annual removal rate is determined. Assuming the sediment load is constant for different flow rates, this approach yields a rough estimate of the annual removal efficiency.

The analysis performed for Anchorage conditions assumed that sediment in stormwater less than 100 μm would be treated as represented by the Vortechnics rating curve for 50 μm diameter particles and that particles greater than 100 μm would be treated as represented the Vortechnics rating curve for 150 μm diameter particles. This analysis further assumed that the grit separator was sized according to Vortechnics recommendations for the 2-year 6-hour peak flow rate. The results are shown in Tables D-2 and D-3.

Table D-2 Vortechnics™ System Net Annual Removal Efficiency – OGS Model Flows and Sediment Load for Basin 11 from the 1965 Annual Hydrograph

flow, sediment data from OGS model - 1965 hydrograph

1.78	cfs	peak 1-hr flow for 1965
0.567	Assumed Ratio of Peak 5-min:Peak 1 hr flow	
1.01	cfs	peak 5 min flow
65	gpm/ft^2	target design ratio
12.3	sf	reqd chamber area

		total	<100	>100
Total washoff	g	589,337	567,159	22,179
Total removed	g	383,948	365,557	18,390
Percent Removed	%	65%	64%	83%

conversion cfs to gpm		448
1	design for multiple of peak 6-hour event	
1.78	DESIGN 1-hr flow	

Flow			% of total annual flow		Sediment Load, mass			Sediment Load, %		Device Removal Eff, %		Amount Removed	
					total	<100	>100	<100 um	>100 um	50 um	150 um	<100 um	>100 um
cum %	cfs	gpm	%	No of hrs	g	g	g	%	%	%	%	g	g
18%	0.00022	0.10	18%	554	4887	4887	0	100%	0%	86%	100%	4203	0
37%	0.00112	0.50	19%	567	11252	11252	0	100%	0%	86%	100%	9677	0
58%	0.004	2.00	20%	610	29257	29256	0	100%	0%	86%	100%	25161	0
68%	0.013	6.00	10%	301	24424	24424	0	100%	0%	86%	100%	21004	0
80%	0.067	30	12%	362	77186	77156	30	100%	0%	86%	100%	66354	30
85%	0.13	60	5%	151	59472	59357	115	100%	0%	86%	100%	51047	115
89%	0.22	100	4%	122	61981	61693	287	100%	0%	86%	100%	53056	287
94%	0.45	200	5%	157	112943	111134	1809	99%	1%	86%	100%	95575	1809
100%	1.786	800	6%	172	207936	187998	19937	97%	3%	21%	81%	39480	16149
Total:			100%	2,996	589,337	567,159	22,179					365,557	18,390

Table D-3 VortechnicsTM System Net Annual Removal Efficiency – OGS Model Flows and Sediment Load for Basin 11 from the 1965 Annual Hydrograph

flow, sediment data from OGS model - 1965 hydrograph

0.27	cfs	peak 1-hr flow for 1965
0.567	Assumed Ratio of Peak 5-min:Peak 1 hr flow	
0.153	cfs	peak 5 min flow
65	gpm/ft^2	target design ratio
1.9	sf	reqd chamber area

		total	<100	>100
Total washoff	g	87,840	83,939	3,900
Total removed	g	56,555	53,275	3,279
Percent Removed	%	64%	63%	84%

conversion cfs to gpm	448
1	design for multiple of peak 6-hour event
0.27	DESIGN 1-hr flow

Flow			% of total annual flow		Sediment Load, mass			Sediment Load, %		Device Removal Eff, %		Amount Removed	
					total	<100	>100	<100 um	>100 um	50 um	150 um	<100 um	>100 um
cum %	cfs	gpm	%	No of hrs	g	g	g	%	%	%	%	g	g
12%	0.00004	0.02	12%	206	432	432	0	100%	0%	86%	100%	372	0
25%	0.00011	0.05	13%	228	742	742	0	100%	0%	86%	100%	638	0
35%	0.00022	0.1	10%	163	818	818	0	100%	0%	86%	100%	704	0
41%	0.000	0.2	6%	97	673	673	0	100%	0%	86%	100%	579	0
52%	0.001	0.5	12%	204	2280	2280	0	100%	0%	86%	100%	1960	0
61%	0.002	1	8%	144	2982	2982	0	100%	0%	86%	100%	2564	0
75%	0.022	10	14%	236	13950	13936	14	100%	0%	86%	100%	11985	14
86%	0.04	20	11%	190	18440	18317	123	99%	1%	86%	100%	15753	123
93%	0.09	40	7%	126	19974	19451	523	97%	3%	70%	99%	13616	518
100%	0.28	125	7%	117	27548	24308	3240	88%	12%	21%	81%	5105	2625
	Total:		100%	1,711	87,840	83,939	3,900					53,275	3,279

In order to illustrate the effects of larger or smaller grit separators and their corresponding annual removal rates, different sizes were also evaluated using the same methodology described above. Table D-4 presents the estimated annual removal rate for different sized Vortechnics grit separators. The different sizes are denoted by what fraction of the peak flow they were sized for. For instance, if the design storm over the basin results in a peak flow rate of 12 gpm, and a device as sized for 24 gpm, the ration of the unit capacity to the peak flow to the device capacity is 2.

Thus, when a similar analysis was performed with different sizes of grit separators, the separator was shown to be more efficient when oversized (that is, the ratio of peak flow:unit capacity is less than 1) and less efficient when undersized, as summarized in Table D-4.

Table D-4 VortechnicsTM System Net Annual Removal Efficiency at Different Unit Capacities

Peak Flow Rate/Unit Capacity	Peak Flow Unit Capacity	Annual Removal of 50 µm Particles for 2 basins (Percent)	Annual Removal of 150 µm Particles for 2 basins (Percent)
4	0.67	73 – 75	93
2	0.8	69 – 71	90 – 91
1	1	63 – 64	83 – 84
0.8	2	49 – 53	17 – 22
0.67	4	32 – 42	16 - 17

StormCeptor

The StormCeptor grit separator was evaluated for application to a parking lot in Anchorage (Herman, 2002). StormCeptor performed proprietary modeling to illustrate annual removal efficiencies for four particle sizes, using Anchorage rainfall data and different sizes of their products. The parking lot had a computed design storm of 0.6 cfs (Herman, 2002). Table D-5 summarizes the efficiencies predicted by the StormCeptor model, using Anchorage rainfall data. Note that this is vendor-supplied information, derived from modeling based on proprietary removal ratings not supplied by the vendor.

Table D-5 StormCeptor™ System Annual Removal Efficiency

StormCeptor Model Number(s)	Model Rated Capacity	Peak Flow Rate[1]/Unit Capacity	Annual Removal of 20 μm Particles (Percent)	Annual Removal of 60 μm Particles (Percent)	Annual Removal of 100 μm Particles (Percent)
7200	2.47	0.07	77	90	95
4800, 60000	1.77	0.34	72	87	93
2400, 36000	1.06	0.57	64	82	90
900, 1299, 1800	0.64	0.9	57	76	86
450	0.28	2.1	45	65	78

Note: [1] Peak flow for modeled basin was 0.6 cfs. See attached StormCeptor model results.

CDS Technologies

The CDS grit separator was evaluated for application to the discharge of piped stormwater from a 300-acre basin in Anchorage (Herman, 2002), with a design storm of 32 cfs. CDS performed its own analysis of removal efficiency for this application but since it was based on a single storm, annual removal rates could not be generalized. Published values for CDS removal efficiencies, taken from attached literature, are shown in Table D-6. No data are available for particle sizes less than 112 μm.

Table D-6 - CDS Reported Removal Efficiencies

Flow Rate as % of Unit Capacity	Removal Efficiency %	
	112 μm	225 μm
20	56	82
40	28	64
60	12	42
80	5	27
100	0	12

Source: CDS TSS Removal Efficiency for C Street Outfall Upgrade (attached)

Annual removal efficiencies for two basins were calculated in the manner descried for the Vortechnics product; the results are shown in Table D-7 and D-8. Because StormCeptor data is not available for particles less than 100 µm only, removal efficiencies for particles greater than 100 µm was estimated. For this preliminary effort, it was assumed that all particles in stormwater greater than 112 µm in diameter will be separated according to the rating curve (Table D-6) for the 112 µm particles.

As was done for the Vortechs devices, removal efficiencies were estimated for different sized separator units. The results of this analysis are presented in Table D-9. These results indicate that oversizing the CDS units is required in order to obtain high removal efficiencies. In addition, using the rating curve for 112 µm particles to represent the removal rate of all particles greater than 100 µm is quite conservative and most likely underestimates the removal efficiency of the CDS devices.

Table D-7 CDS Net Annual Removal Efficiency – OGS Model Flows and Sediment Load for Basin 11 from the 1965 Annual Hydrograph

flow, sediment data from OGS model for 1965 hydrograph

1.78	cfs	peak 1-hr flow for 1965
0.567	Assumed Ratio of Peak 5-min:Peak 1 hr flow	
1.01	cfs	peak 5 min flow
65	gpm/ft^2	target design ratio
12.3	sf	reqd chamber area

		total	<100	>100
Total washoff	g	589,337	567,159	22,179
Total removed	g	1,385	0	1,385
Percent Removed	%	0%	0%	6%

conversion cfs to gpm		448
1	design for multiple of peak 6-hour event	
1.78	DESIGN 1-hr flow	

Flow			% of total annual flow		Sediment Load, mass			Sediment Load, %		Device Removal Eff, %		Amount Removed	
					total	<100	>100	<100 um	>100 um		112 um	<100 um	112 um
cum %	cfs	gpm	%	No of hrs	g	g	g	%	%	%	%	g	g
18%	0.00022	0.10	18%	554	4887	4887	0	100%	0%		100%		0
37%	0.00112	0.50	19%	567	11252	11252	0	100%	0%		100%		0
58%	0.004	2.00	20%	610	29257	29256	0	100%	0%		100%		0
68%	0.013	6.00	10%	301	24424	24424	0	100%	0%		100%		0
80%	0.067	30	12%	362	77186	77156	30	100%	0%		100%		30
85%	0.13	60	5%	151	59472	59357	115	100%	0%		100%		115
89%	0.22	100	4%	122	61981	61693	287	100%	0%		79%		227
94%	0.45	200	5%	157	112943	111134	1809	99%	1%		56%		1013
100%	1.786	800	6%	172	207936	187998	19937	97%	3%		0%		0
Total:			100%	2,996	589,337	567,159	22,179					0	1,385

Table D-8 CDS Net Annual Removal Efficiency – OGS Model Flows and Sediment Load for Basin 13 from the 1965 Annual Hydrograph

flow, sediment data from OGS model for 1965 hydrograph

0.27	cfs	peak 1-hr flow for 1965
0.567	Assumed Ratio of Peak 5-min:Peak 1 hr flow	
0.153	cfs	peak 5 min flow
65	gpm/ft^2	target design ratio
1.9	sf	reqd chamber area

		total	<100	>100
Total washoff	g	87,840	83,939	3,900
Total removed	g	331	0	331
Percent Removed	%	0%	0%	8%

conversion cfs to gpm		448
1	design for multiple of peak 6-hour event	
0.27	DESIGN 1-hr flow	

Flow			% of total annual flow		Sediment Load, mass			Sediment Load, %		Device Removal Eff, %		Amount Removed	
					total	<100	>100	<100 um	>100 um		112 um	<100 um	112 um
cum %	cfs	gpm	%	No of hrs	g	g	g	%	%	%	%	g	g
12%	0.00004	0.02	12%	206	432	432	0	100%	0%		100%	0	0
25%	0.00011	0.05	13%	228	742	742	0	100%	0%		100%	0	0
35%	0.00022	0.1	10%	163	818	818	0	100%	0%		100%	0	0
41%	0.000	0.2	6%	97	673	673	0	100%	0%		100%	0	0
52%	0.001	0.5	12%	204	2280	2280	0	100%	0%		100%	0	0
61%	0.002	1	8%	144	2982	2982	0	100%	0%		100%	0	0
75%	0.022	10	14%	236	13950	13936	14	100%	0%		100%	0	14
86%	0.04	20	11%	190	18440	18317	123	99%	1%		79%	0	97
93%	0.09	40	7%	126	19974	19451	523	97%	3%		42%	0	220
100%	0.28	125	7%	117	27548	24308	3240	88%	12%		0%	0	0
Total:			100%	1,711	87,840	83,939	3,900					0	331

Table D-9 CDS™ System Estimated Net Annual Removal Efficiency

Peak Flow / Rated Capacity [1]	Annual removal of particles>100 µm (Percent)
0.5	25
0.67	13
0.8	12
1	6
2	3
4	1

Discussion

When comparing the products, is it important to note that these results are not directly comparable from vendor to vendor. Some of the confounding factors include:

- Removal efficiencies are based on different testing methods from vendor to vendor
- Reported efficiencies may only be applicable to a narrow range of flows
- Reported efficiencies are based on computer modeling rather than measured performance

- Removal mechanisms for particles less than 100 μm are more complex than for larger size particles (e.g., Water temperature, interference or synergism with other particles); therefore, different test situations may bias predicted efficiencies high or low

A summary of the different annual removal efficiencies for the three vendors is shown in Table D-10.

Table D-10 Summary of Annual Removal Efficiencies

	% Removal - Annual Basis				
Particle Size:	**50** μm	**60** μm	**100** μm	**112** μm	**150** μm
Vendor:	**Vortechnics**	**StormCeptor**	**StormCeptor**	**CDS**	**Vortechnics**
Peak Flow / Unit Capacity	**(1)**	**(2)**	**(2)**	**(3)**	**(1)**
0.34 / 4		87	83	43 – 48	
0.5 / 2.1				25 – 30	
0.57 / 2		82	90		
0.67 / 1	73 - 75			13 – 20	93
0.8 / 0.9	63 – 71			12 – 15	90 – 91
0.9 / 0.8		**78**	**86**		
1 / 0.67	**63- 64**			**6 – 8**	**83 – 84**
2 / 0.57	49 - 53			3	17 – 22
2.1 / 0.5		65	78		
4 / 0.34	32 - 42			1	16- 17

(1) Based on use of Vortechnics removal rates and flows, sediment from OGS model; Table D-4
(2) From StormCeptor modeling for small basin in Anchorage; Table D-5
(3) Based on use of CDS removal rates and flows and sediment loads from OGS model; Table D-9

Based on data from StormCeptor and Vortechnics, it appears that a unit sized for a peak annual event could be capable of removing 63 to 78 percent of the annual mass load of particles less than 100 μm. The rating curves from which these values were calculated appear to be generated by vendor computer modeling, the assumptions of which are not well documented. (No data is available from CDS data for this size of particles.) It is our feeling that efficiencies for these small particle sizes are overstated for actual operations. Because of many unknowns in the individual vendor testing methods, the actual removal efficiencies are expected to be less than these calculated efficiencies, particularly for the smaller size particles. For instance, for wastewater sedimentation, a factor of 1.75 or 2 is applied to results from settling tests for Type 2 (hindered) settling (Metcalf&Eddy, 1972). In addition to problems associated with settling in these devices, resuspension during higher flows occurs that reduces overall removal efficiency. Again, this is particularly significant for the smaller particle sizes because they can be mobilized at lower flows than can larger particle sizes.

With the intent of using these values to provide performance criteria for revisions to the MOA DCM, is recommended that a factor of 3 be applied to the removal efficiencies in Table D-10 for particles less than 100 μm. A target annual removal efficiency of 25 percent appears to be a reasonable recommendation for particles less than 100 µm until further or more studies can be made under Anchorage-specific conditions.

Conversely, for the larger particle sizes, the rating curve used to estimate settling efficiency may have underestimated the removal efficiency. Other variables, such as resuspension, will reduce removal efficiency. Therefore, a target annual removal efficiency of 80 percent appears reasonable for particles greater than 100 µm.

References

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Herman, John. CRW Engineers. 2002. Personal communication with MWH.

Metcalf & Eddy. 1972. Wastewater Engineering. McGraw-Hill. New York.