Public Works Practices and Stormwater Management

Robert Pitt, Ph.D., P.E., BCEE
Emeritus Professor of Urban Water Systems
Department of Civil, Construction, and Environmental Engineering
The University of Alabama
Tuscaloosa, AL 35487

1

1

Outline of Presentation Topics

- Porous pavement
- Street cleaning
- Catchbasins and inlets
- Scour and sediment transport
- Conclusions

2

2

Interest in Public Works Practices as Stormwater Controls

- Public works practices have been popular tools for stormwater management probably because they already exist (street cleaning and inlets) and fit in the general public works infrastructure management framework for municipalities. In areas having numeric stormwater control goals (especially expressed as percentage reductions for TSS), there is also a need to quantify the benefits of these existing practices.
- Unfortunately, evaluation of the stormwater benefits of these practices is not clear and usually over-estimated.
- One of the main issues is that these source controls (especially of large particulates which these controls focus on), while showing large amounts of removal of debris, has a much smaller benefit at the outfall where the regulations apply. This is due to the poor transport of the large particles from the source areas to the outfalls. Therefore, source area pollutant reductions do not result in the same reductions at the outfalls.

3

3

4

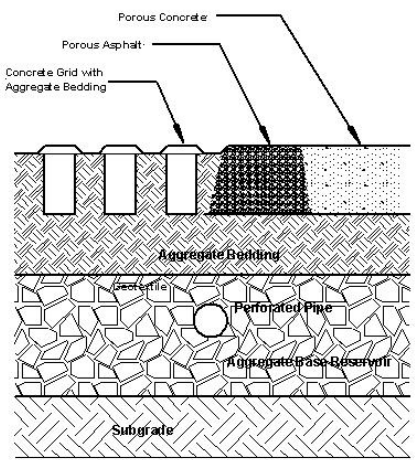
5

Porous pavement test facility at EPA, Edison, NJ

Whoops, a bit too porous! (not EPA site; a sinkhole)

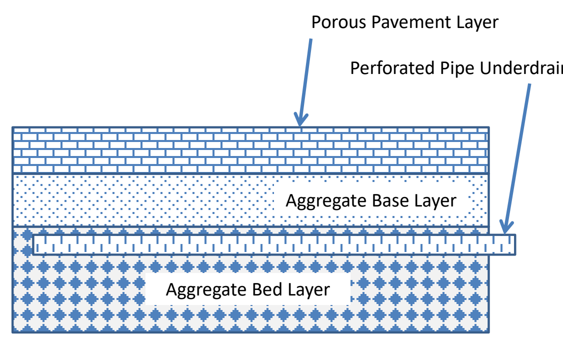
6

Porous Pavement Cross Section

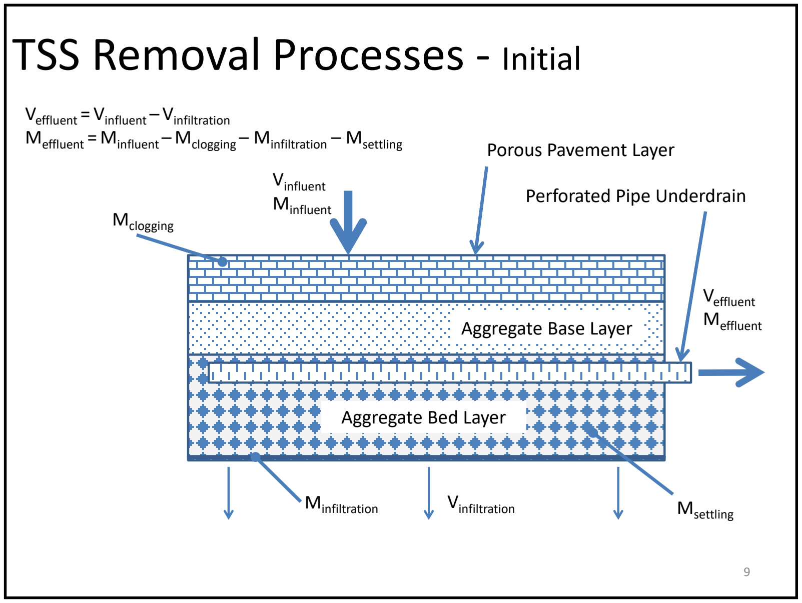


7

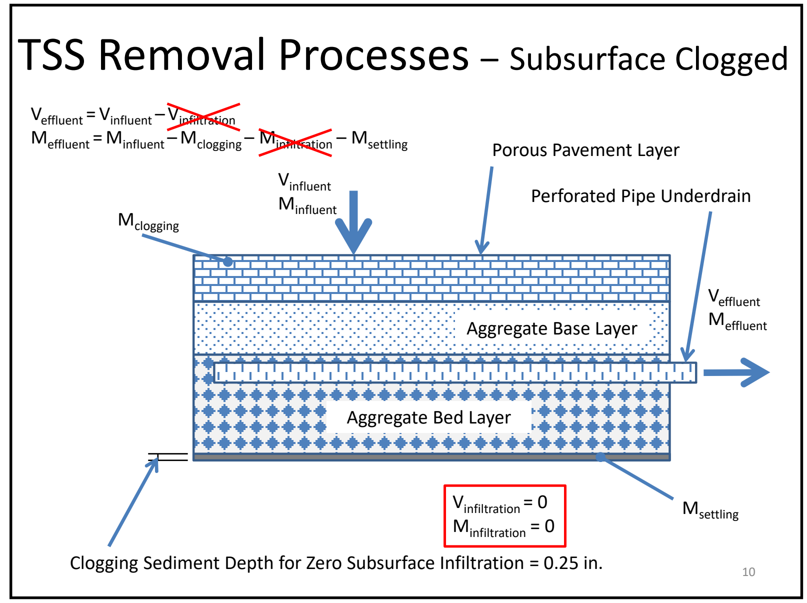
TSS Removal Processes in Porous Pavements



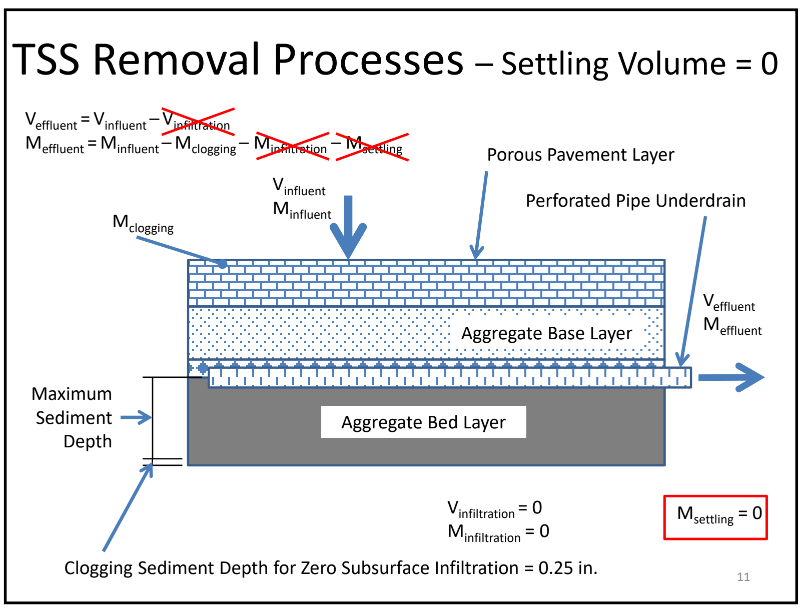
8


TSS Removal Processes - Initial
$V_{effluent} = V_{influent} - V_{infiltration}$
$M_{effluent} = M_{influent} - M_{clogging} - M_{infiltration} - M_{settling}$
Porous Pavement Layer
$V_{influent}$
$M_{influent}$
Perforated Pipe Underdrain
$M_{clogging}$
$V_{effluent}$
$M_{effluent}$
Aggregate Base Layer
Aggregate Bed Layer
$M_{infiltration}$
$V_{infiltration}$
$M_{settling}$
9

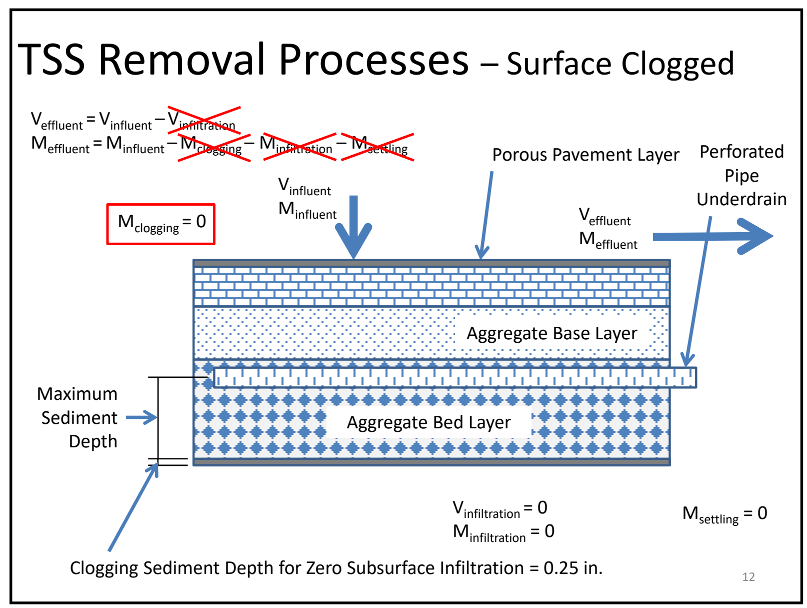
9


TSS Removal Processes – Subsurface Clogged
$V_{effluent} = V_{influent} - V_{infiltration}$
$M_{effluent} = M_{influent} - M_{clogging} - M_{infiltration} - M_{settling}$
Porous Pavement Layer
$V_{influent}$
$M_{influent}$
Perforated Pipe Underdrain
$M_{clogging}$
$V_{effluent}$
$M_{effluent}$
Aggregate Base Layer
Aggregate Bed Layer
$V_{infiltration} = 0$
$M_{infiltration} = 0$
$M_{settling}$
Clogging Sediment Depth for Zero Subsurface Infiltration = 0.25 in.
10

10


TSS Removal Processes – Settling Volume = 0
$V_{effluent} = V_{influent} - V_{infiltration}$
$M_{effluent} = M_{influent} - M_{clogging} - M_{infiltration} - M_{settling}$
Porous Pavement Layer
$V_{influent}$
$M_{influent}$
Perforated Pipe Underdrain
$M_{clogging}$
$V_{effluent}$
$M_{effluent}$
Aggregate Base Layer
Maximum Sediment Depth
Aggregate Bed Layer
$V_{infiltration} = 0$
$M_{infiltration} = 0$
$M_{settling} = 0$
Clogging Sediment Depth for Zero Subsurface Infiltration = 0.25 in.
11

11


TSS Removal Processes – Surface Clogged
$V_{effluent} = V_{influent} - V_{infiltration}$
$M_{effluent} = M_{influent} - M_{clogging} - M_{infiltration} - M_{settling}$
Porous Pavement Layer
Perforated Pipe Underdrain
$V_{influent}$
$M_{influent}$
$M_{clogging} = 0$
$V_{effluent}$
$M_{effluent}$
Aggregate Base Layer
Maximum Sediment Depth
Aggregate Bed Layer
$V_{infiltration} = 0$
$M_{infiltration} = 0$
$M_{settling} = 0$
Clogging Sediment Depth for Zero Subsurface Infiltration = 0.25 in.
12

12

Porous Pavement Factors Affecting Performance

- **Pavement Geometry and Properties**
- **Outlet/Discharge Options**
- **Surface Pavement Layer and Cleaning Data**
- **Native Soil Infiltration Data**

13

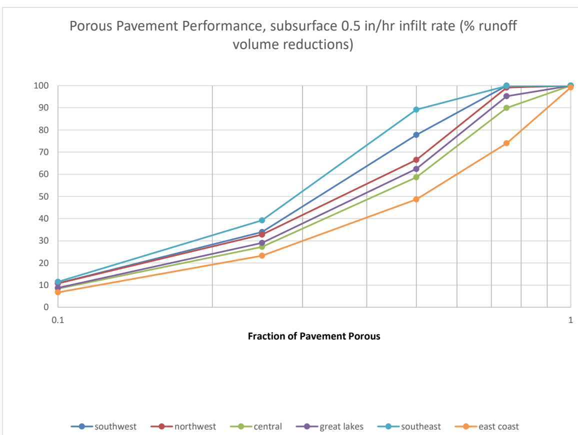
Porous Pavement Issues

- **In Northern Climates, groundwater contamination due to chlorides may be a problem**
- **Porous pavement clogging and cleaning time frames require a multi-year analysis using WinSLAMM to correctly evaluate performance**
- **Clogging due to run-on increases as the porous pavement area to drainage area ratio decreases**

14

14

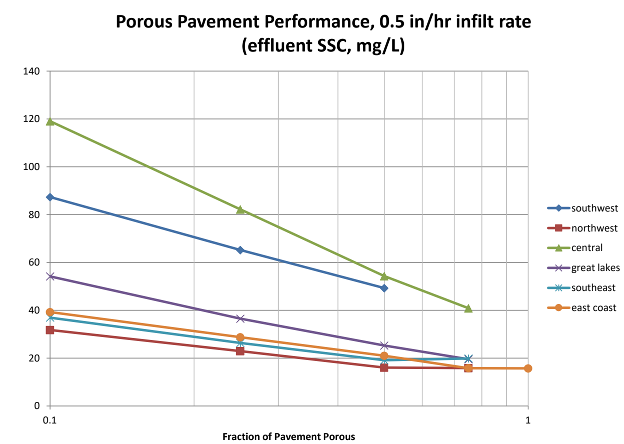
Calculated Production Function for Porous Pavement Infiltration Performance



15

15

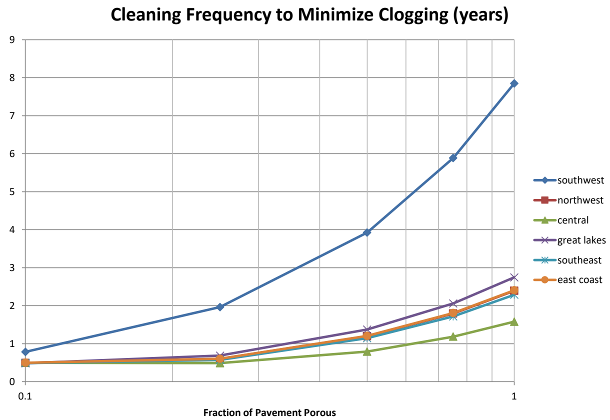
Porous Pavement Effluent SSC (mg/L)



16

16

Calculated Maintenance Requirements for Porous Pavement



17

17

Street Cleaning

18

18

Some Early Street Cleaning Research Projects

- Pitt, R., Demonstration of Nonpoint Pollution Abatement Through Improved Street Cleaning Practices. 1979.
- Bannerman, R. *et. al*, Evaluation of Urban Nonpoint Source Pollution Management in Milwaukee County, WI. 1983.
- Terstriep, M.L., *et. al*, Evaluation of the Effectiveness of Municipal Street Sweeping in the Control of Urban Storm Runoff Pollution. 1983.

19

19

Conclusions of Previous Street Cleaning Studies

- Water Quality Benefits of Street Cleaning is Limited – Best in Spring
- Performance Street Cleaner Effected by Street Load, Particle Size, Street Texture, Method of Operation, Cleaning Frequency, & Parking
- More Effective for Particles > 250 micron
- Role in Aesthetics and Safety

20

20

Major Sediment Source along Highway Test Area

Wisconsin Dept. of Natural Resources

21

Heavy Street Dirt Loadings after Snowmelt

22

23

Street Dirt Chemical Quality (mg/kg)

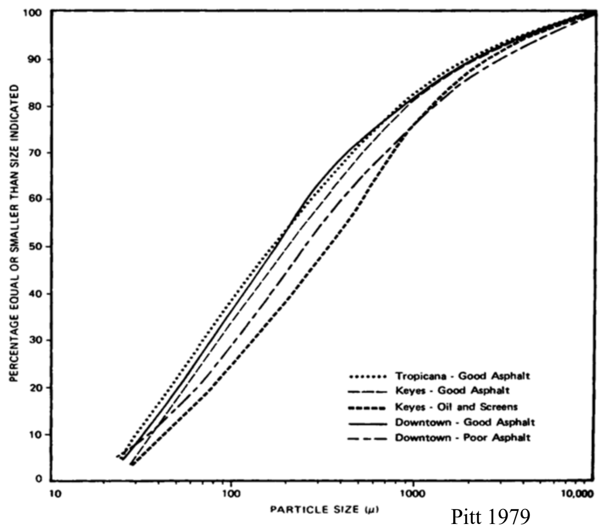
(Milwaukee, WI; San Jose, CA; Bellevue, WA; Toronto, Canada; Reno, NV; Champaign, IL)

Phosphorus (P)	**400 – 1500**
Total Kjeldahl Nitrogen	**290 – 4300**
Chemical Oxygen Demand	**65,000 – 340,000**
Copper (Cu)	**110 – 420**
Lead (Pb)	**530 – 7500**
Zinc (Zn)	**260 – 1200**
Cadmium (Cd)	**<3 – 5**
Chromium (Cr)	**31 – 180**

Pitt, Bannerman, and others

24

Particle Size Distribution of Street Dirt



Pitt 1979

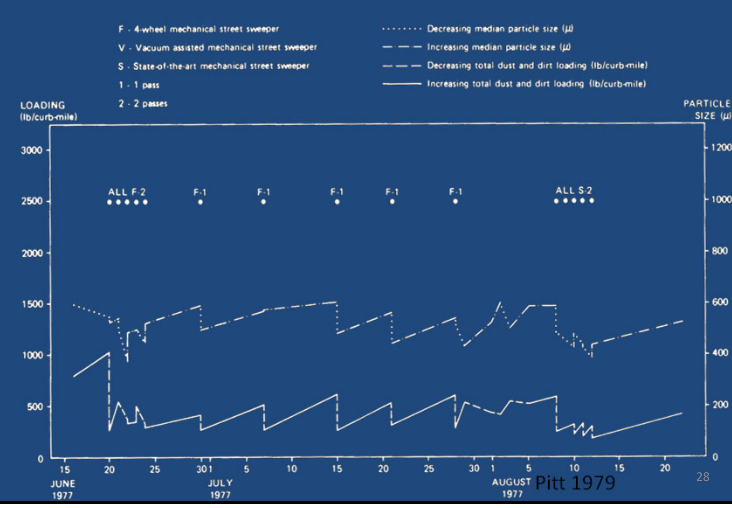
25

Accumulation Functions

26

27

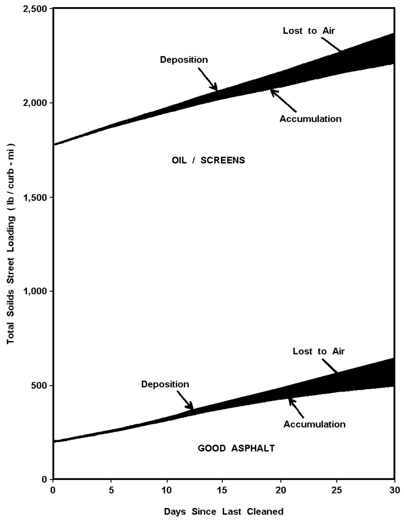
Total Particulate Loading , Keyes – Good Asphalt Test Area



Pitt 1979

28

Deposition and Accumulation of Street Dirt

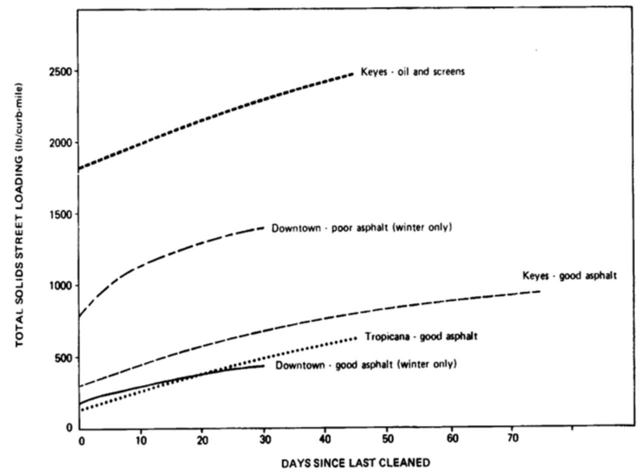


Pitt 1979

29

29

Total Solids Accumulation Since Last Cleaning

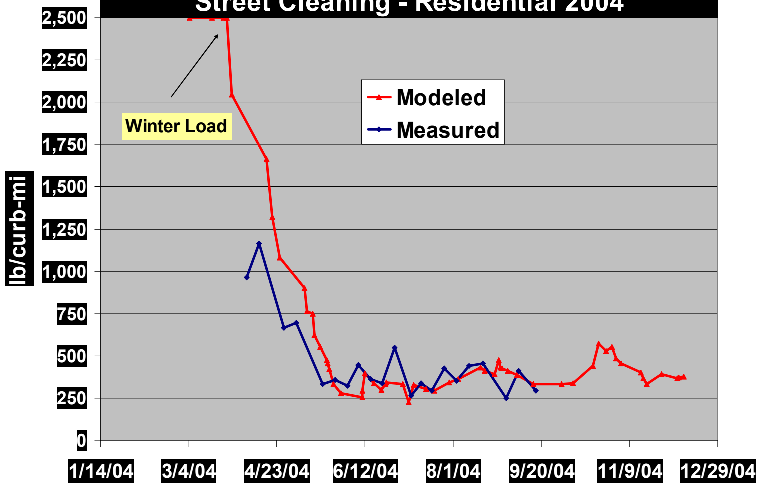


Pitt 1979

30

30

Measured Versus Modeled Street Loads Without Street Cleaning - Residential 2004



31

31

Wash–off Functions and Street Cleaner Effectiveness

32

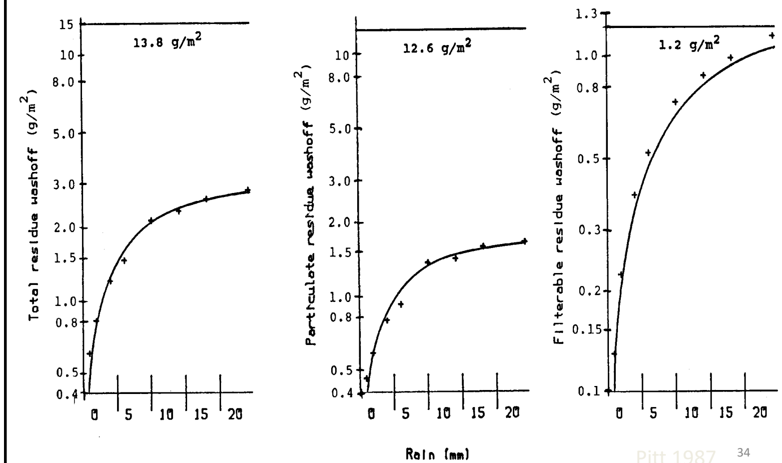
32

Controlled washoff tests in Toronto by Pitt (1987) as part of his PhD research at the University of Wisconsin.

33

33

Washoff Plots for Heavy Rain Intensities, Dirty Streets, and Rough Pavement Textures

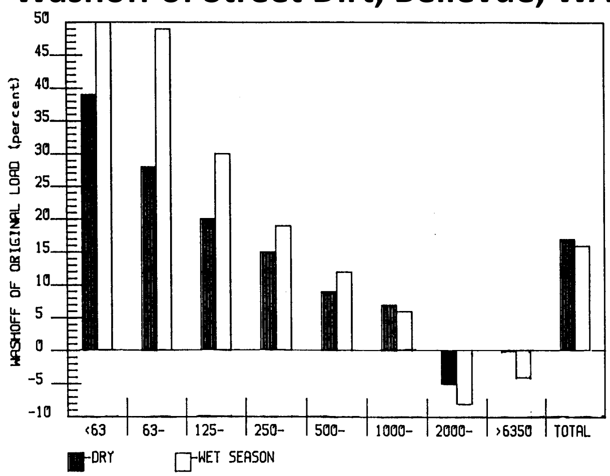


Pitt 1987

34

34

Washoff of Street Dirt, Bellevue, WA

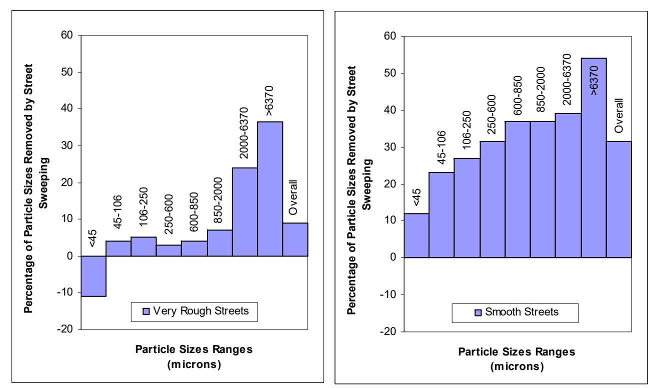


Pitt 1985

35

35

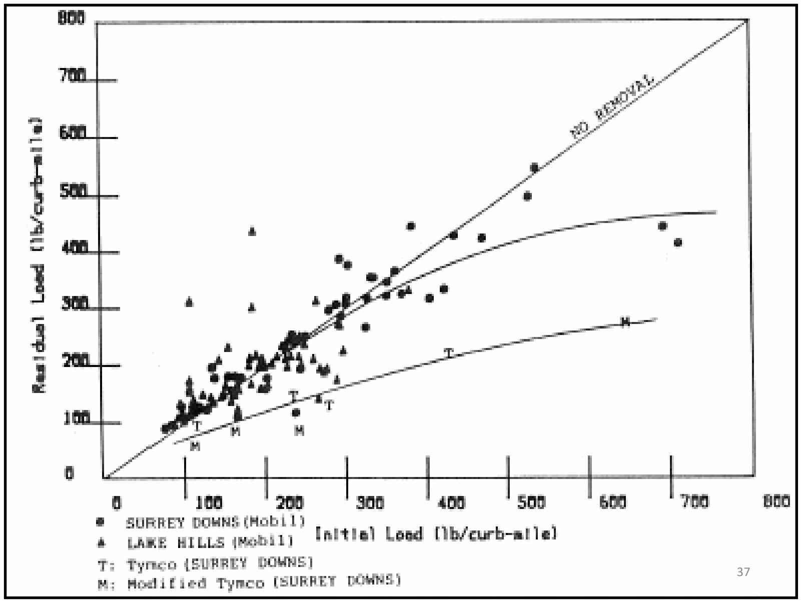
Particulate Removal Using Street Cleaning (Pitt 1985)



The most-effectively removed particles by street cleaners are the least-effectively removed particles during rains.

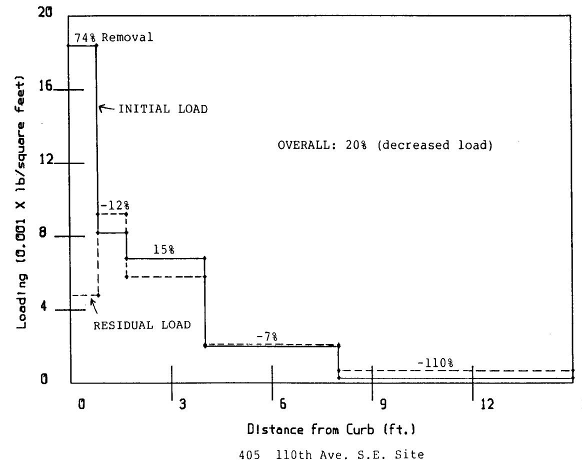
36

36



37

Redistribution of Street Dirt During Street Cleaning



Pitt 1985

38

38

Residential and Commercial Area USGS/WI DNR Street Cleaning Study using Current Equipment

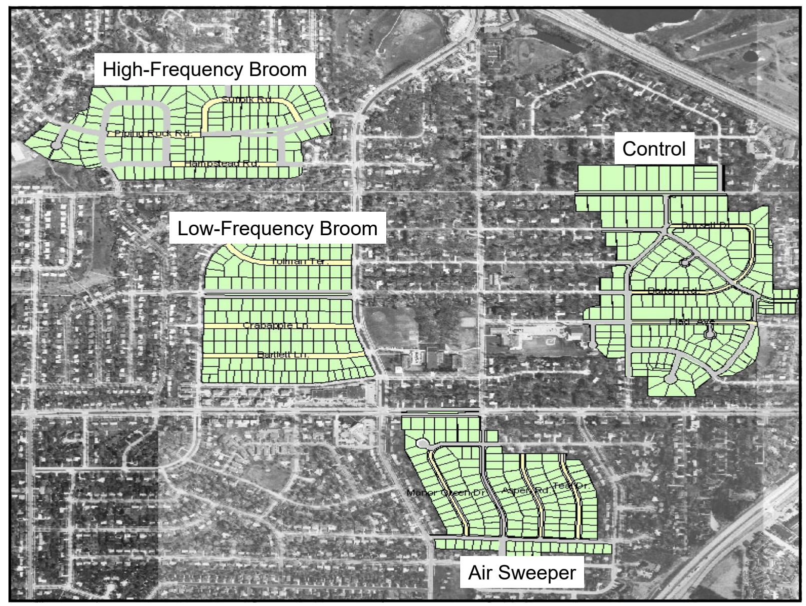
Monitored water quality benefits at outfalls along with street dirt loading.

Objectives: Directly Measure Water Quality Benefits of Street Cleaning

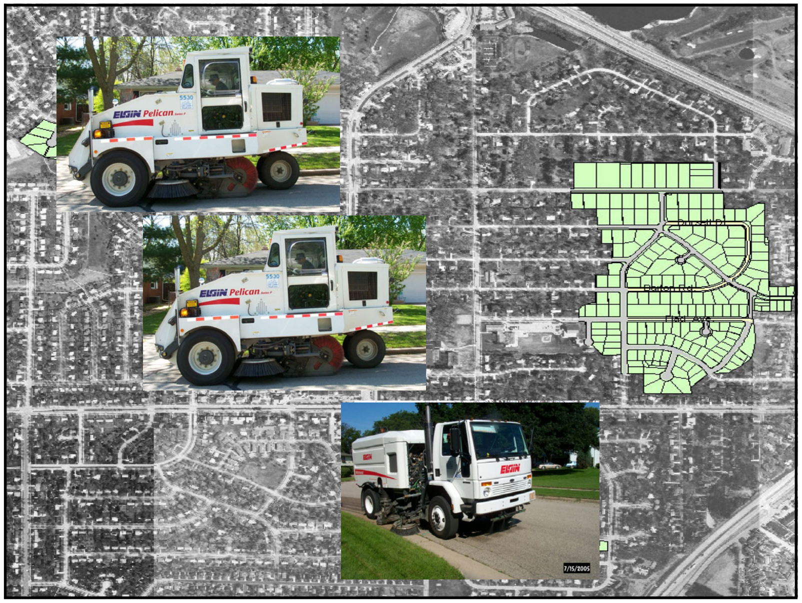
- Pick-up efficiency
- Accumulation Rate of Street Dirt
- Wash-off of Street dirt during event

39

39



40



41

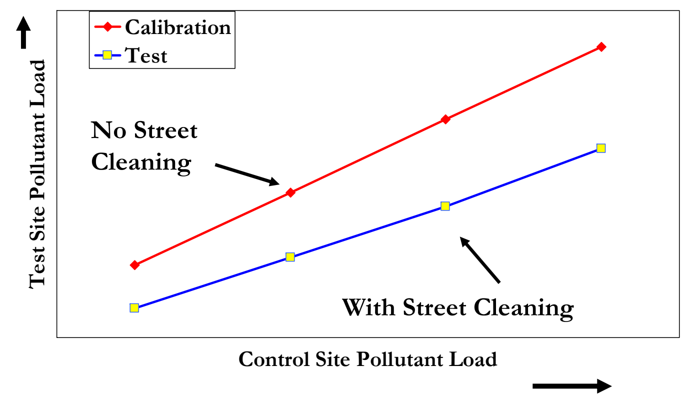
42

Example of Water Samples Collected From Residential Storm Sewers

43

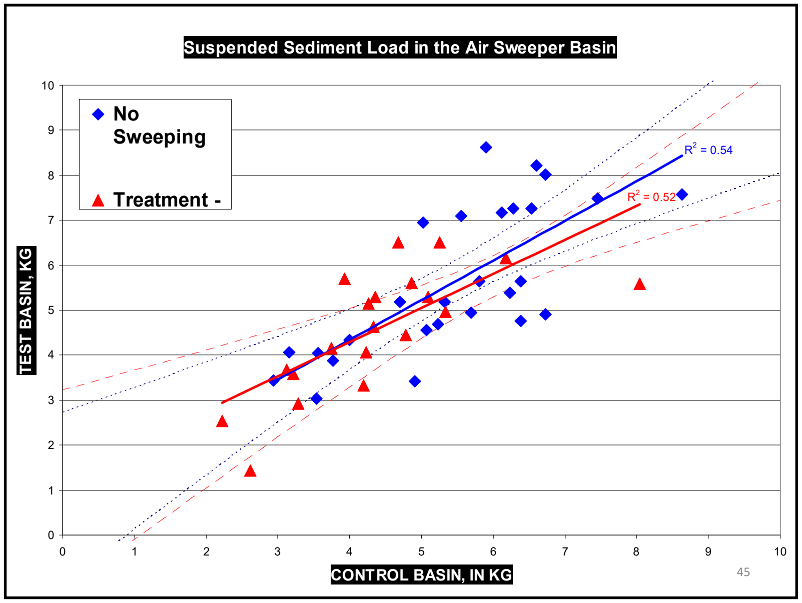
43

Expected Change in Relationship Between Control and Test Site Pollutant Loads

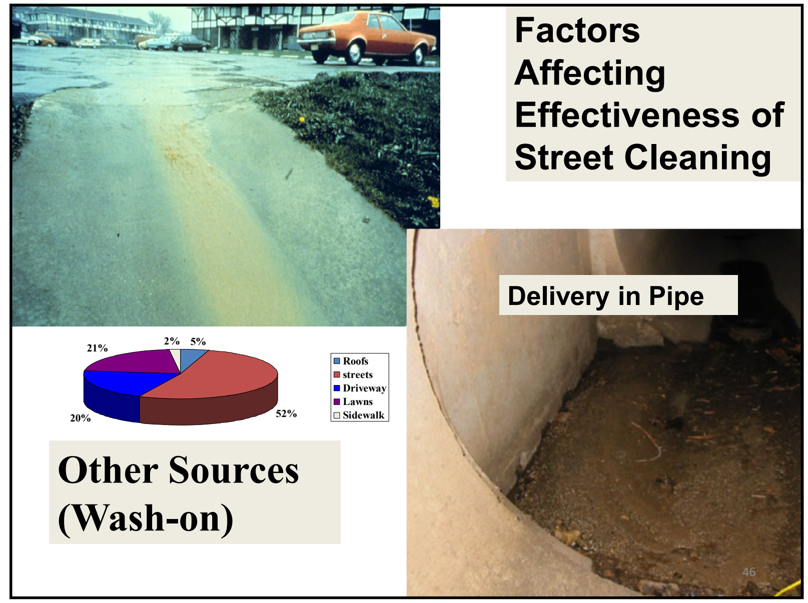


44

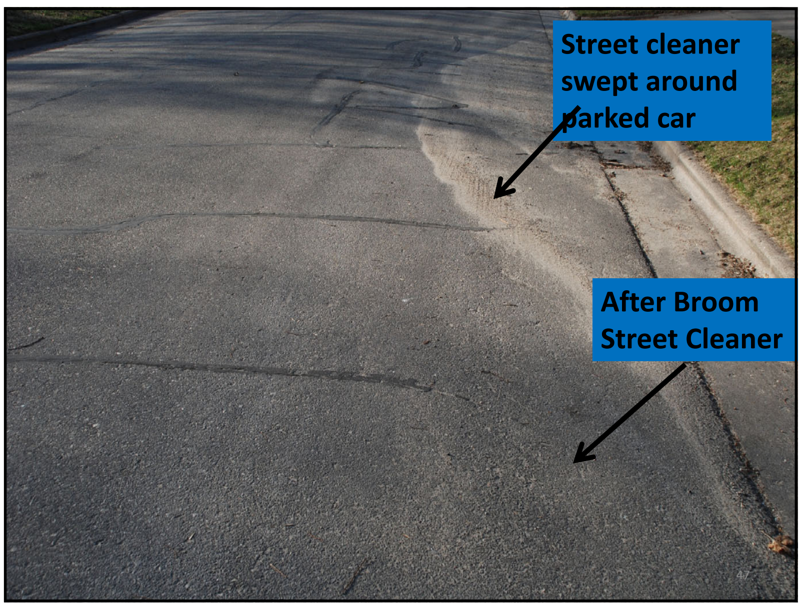
44


Suspended Sediment Load in the Air Sweeper Basin
No Sweeping
Treatment -
R² = 0.54
R² = 0.52
TEST BASIN, KG
CONTROL BASIN, IN KG
0
1
2
3
4
5
6
7
8
9
10
45

45


Factors Affecting Effectiveness of Street Cleaning
Delivery in Pipe
2%
5%
21%
20%
52%
Roofs
streets
Driveway
Lawns
Sidewalk
Other Sources (Wash-on)

46

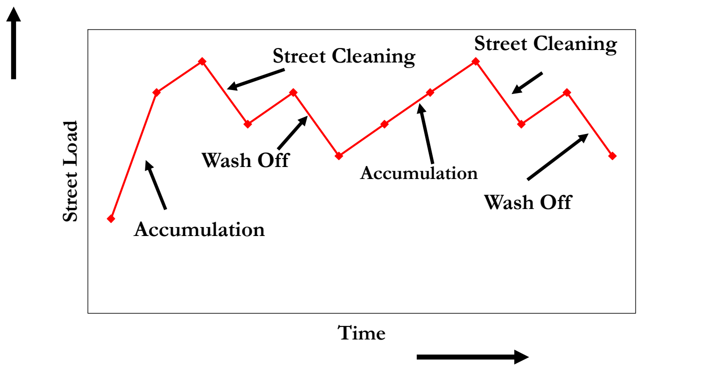

Street cleaner swept around parked car
After Broom Street Cleaner

47


Measure changes in street dirt loads with vacuum cleaners – 2 tons collected during project.
7/8/2005
Street dirt loads measured before and after every cleaning; over time; and before and after rain
48

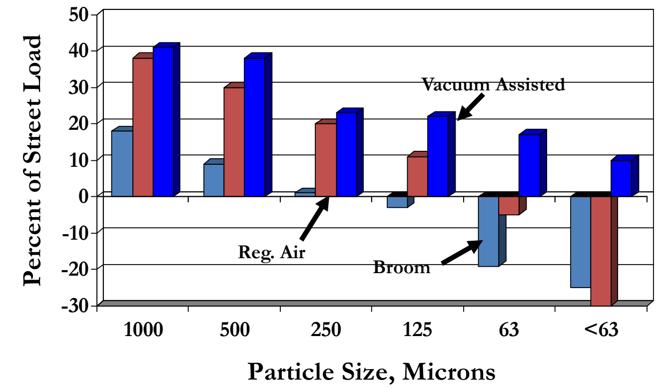
48

Accumulation and Removal Sawtooth Pattern Based on Street Load Data



49

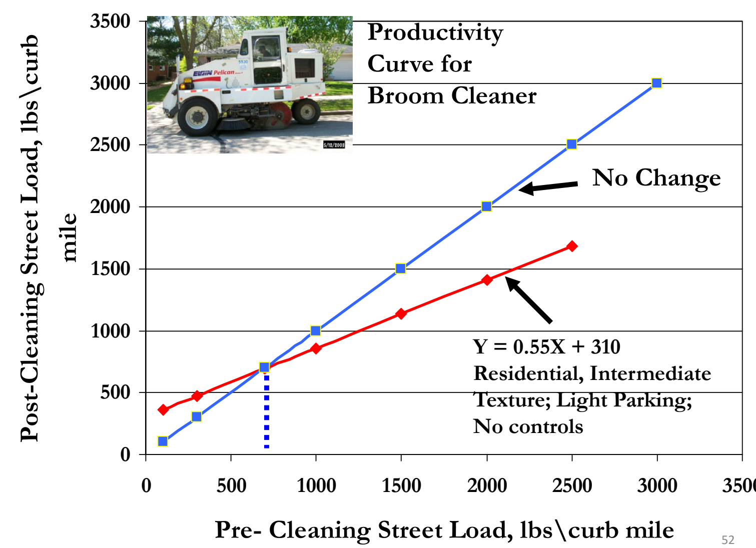
Average Percent Reduction in Street Dirt by Particle Size



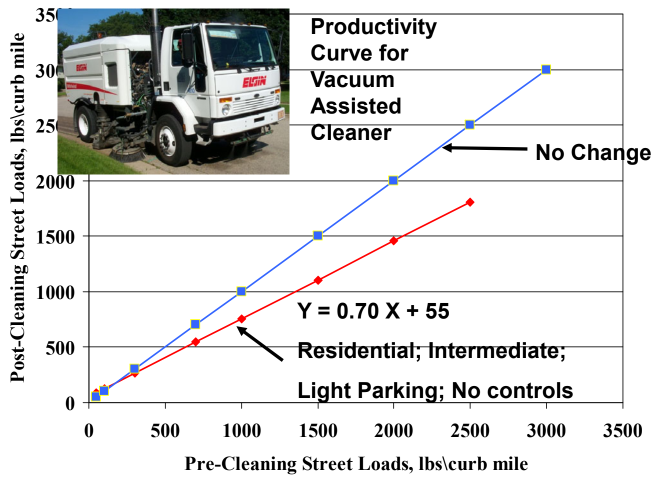
50

Street Cleaning Effectiveness Reduced Because Gutter Broom Makes More Fine Particles Available for Wash Off

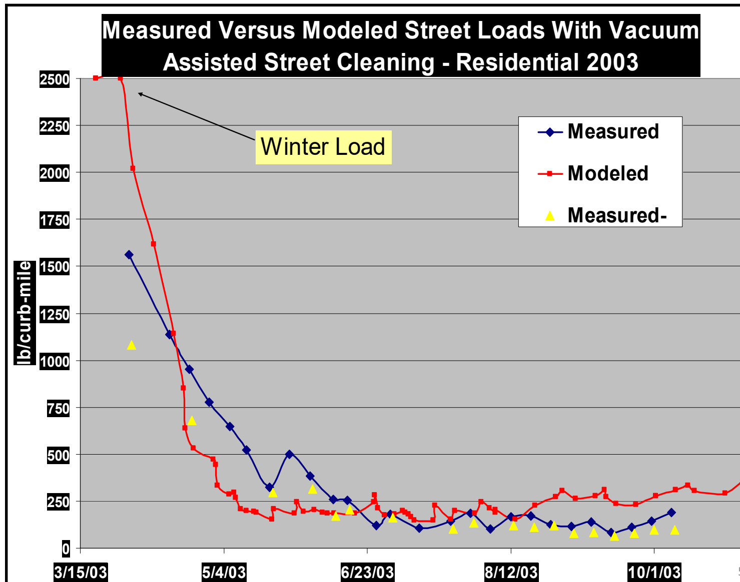
51



52



53



54

Variables in Street Cleaning Analysis

User Select:

- Frequency
- Parking Density
- Parking Controls
- Machine Type

Pre-Determined:

- Winter Load
- Rainfall File
- Street Texture
- Land Use

55

Effect of Cleaning Frequency on Annual TSS Reduction in Medium Density Residential

Cleaning Frequency	Broom Street Cleaner		Vacuum Assisted Street Cleaner	
	Light Parking	Medium Parking	Light Parking	Medium Parking
March & April – 1\Week	5	3	5	5
1 \ 4 Weeks	3	1	6	2
1 \ Week	8	4	18	9

56

USGS/WI DNR Street Cleaning Study on High Traffic Street

- Vacuum before and after street cleaning – production function
- Vacuum for accumulation and washoff
- Water quality site with no cleaning
- Vacuum assisted machine

57

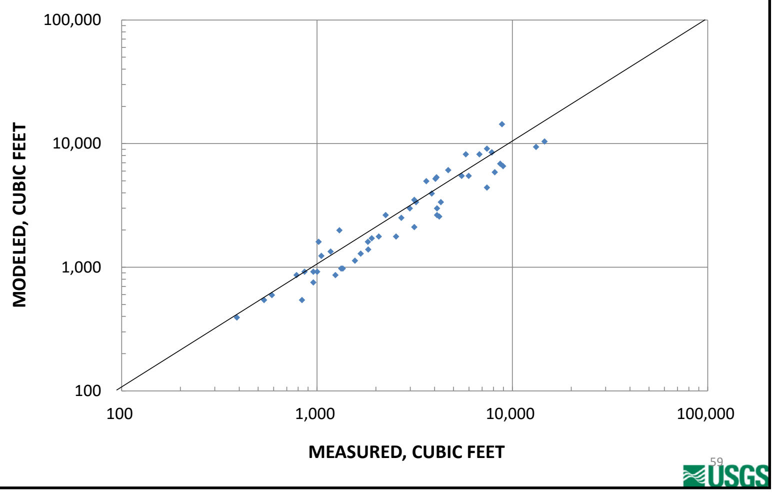
57

Measuring Change in Street Dirt Load on East Washington

58

58

Measured versus Modeled Runoff Volume at the End of Pipe



59

59

Another WI DNR/USGS Street Cleaning Project: Freeway Milwaukee, WI Test Site: I 794

60

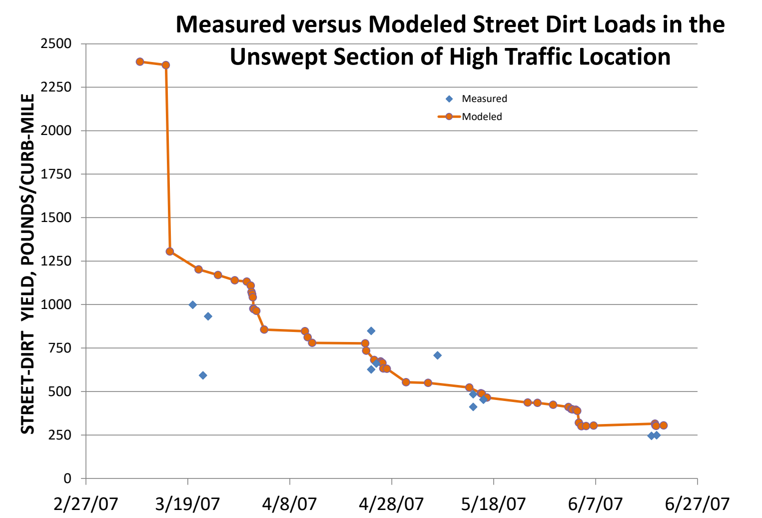
60

Comparison of Measured and Modeled Water Volumes and TSS Loads for Two Highway Sites in Milwaukee

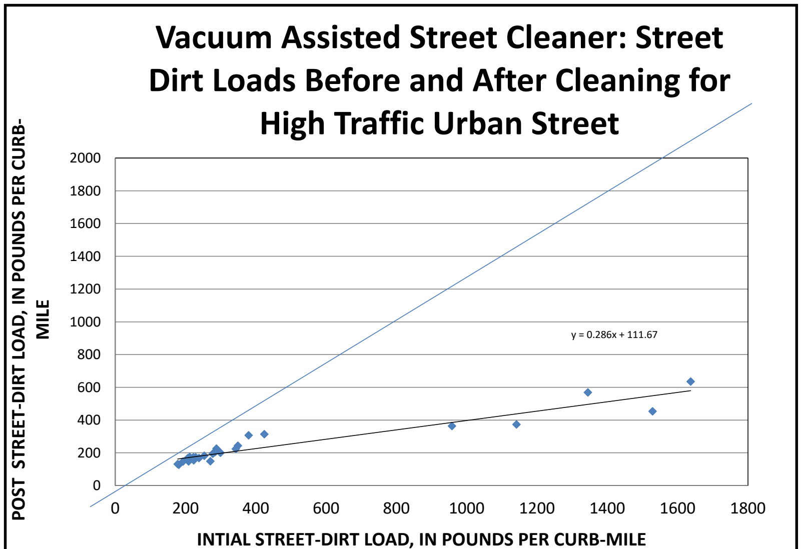
Site	Runoff Volumes, cubic feet			TSS Loads, lbs.		
	Measured	Modeled	Difference	Measured	Modeled	Difference
North Site	19,976	20,401	-2%	121	85	30%
South Site	7,888	7,825	1%	52	53	-1%

61

61



62



63

TSS Reductions for Selected Frequencies on Expanded I-39 with and without large grass turf areas

Street Cleaning Frequency	Percent TSS Reduction Using Vacuum Assisted Machine		
	No Turf	40% Turf Draining to Freeway	40% Turf Not Draining to Freeway
1\week	70	49	65
1\4 weeks	61	42	55
1\8 weeks	54	38	49

64

64

Vacuum-Assisted Street Cleaner Performance (entire paved area cleaned with no other contributing areas)

65

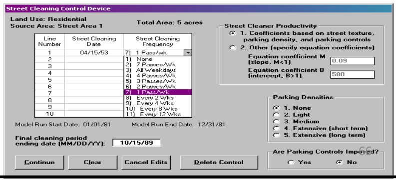
65

What Have We Learned?

1. Spring Clean-up is Important.
2. Must Keep Street Cleaning for Safety and Aesthetics

3. Water quality benefits of street cleaning are small enough to be hard to measure.

4. Calibrated WinSLAMM provides good estimates of TSS reduction for vacuum assisted and broom street cleaner machines



66

Catchbasins and Inlets (and additional comments on delivery of stormwater particulates through drainage systems)

67

67

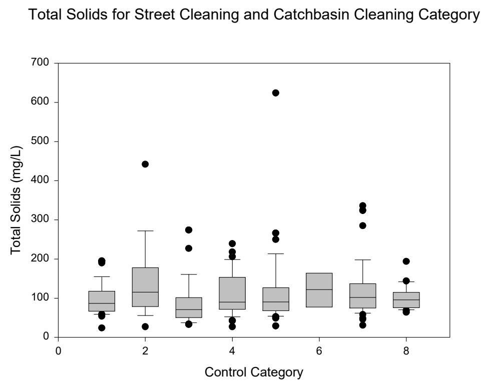
Early Research Results

- A New Jersey study (Pitt, et al, 1994) found average removal rates of 32% for suspended solids using catchbasins with a suitable sump.
- Pitt & Shawley (1982) found cleaning catchbasin twice per year reduced total residue yields between 10% and 25%.
- Pitt & Field (2004) found sediment in catchbasins were the largest particles washed from streets.

68

68

These categories represent different combinations of street cleaning and available catchbasin sump volumes during many years monitoring at Bellevue (Pitt 1985). There are no significant differences in TSS concentrations at the outfalls between any of these categories.



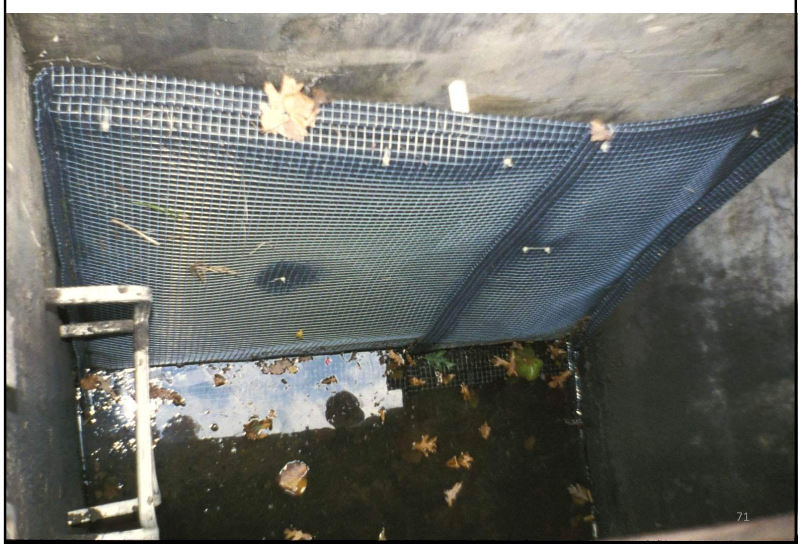
69

69

Gross floatables currently most important wet weather flow pollutant in many urban areas, and most inlet devices are effective in their control (if hooded or screened).

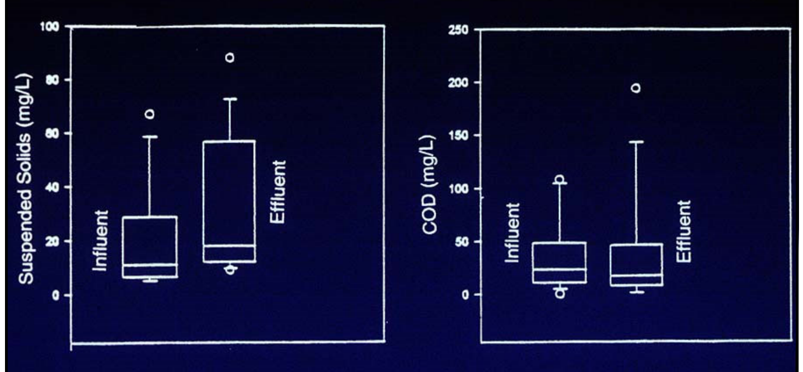
70

Coarse Screen Tested at Ocean County, NJ



71

Box Plots - Coarse Screen Unit



Stormwater forced through debris trapped on the screen results in increased concentrations of some pollutants (TSS and nutrients) in the effluent due to degradation of the organic material.

72

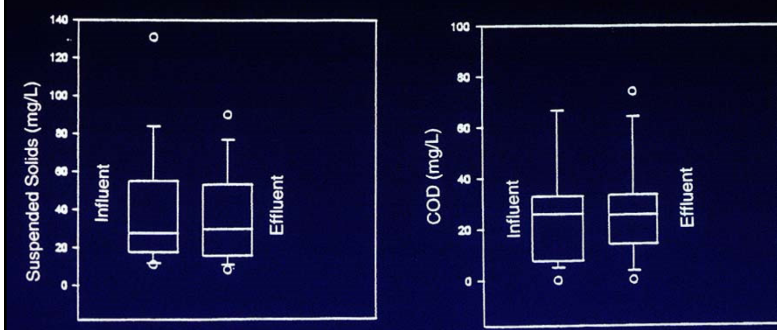
72

Filter Fabric Inlet Insert Tested at Ocean County, NJ

73

73

Box Plots - Filter Fabric Unit



No difference in influent and effluent concentrations as most of the stormwater bypasses the small filter fabric screens after they rapidly clog.

74

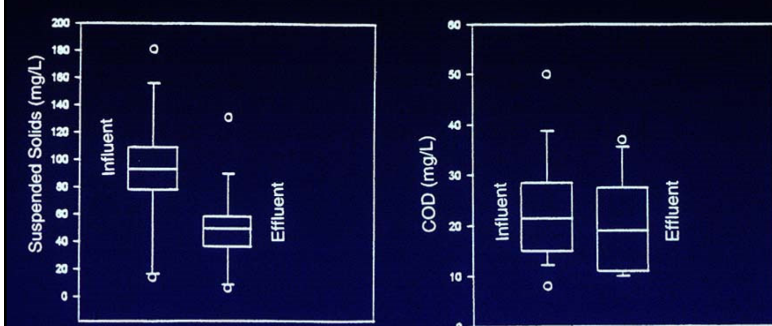
74

Retro-fitted Catchbasin with Sump Tested at Ocean County, NJ

75

75

Box Plots - Catchbasin with Sump



Similar results as noted elsewhere during catchbasin tests as material is captured in the sumps and not scoured. Inlets with no (or small sumps) provide very small benefits.

76

76

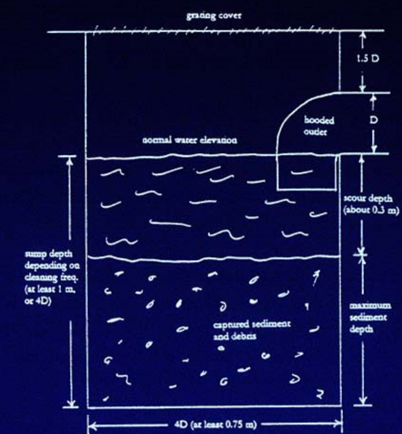
Goals of Storm Drainage Inlet Devices

- Do not cause flooding when clogged with debris
- Do not force stormwater through the captured material
- Do not have adverse hydraulic head loss properties
- Maximizes pollutant reductions
- Requires inexpensive and infrequent maintenance

77

77

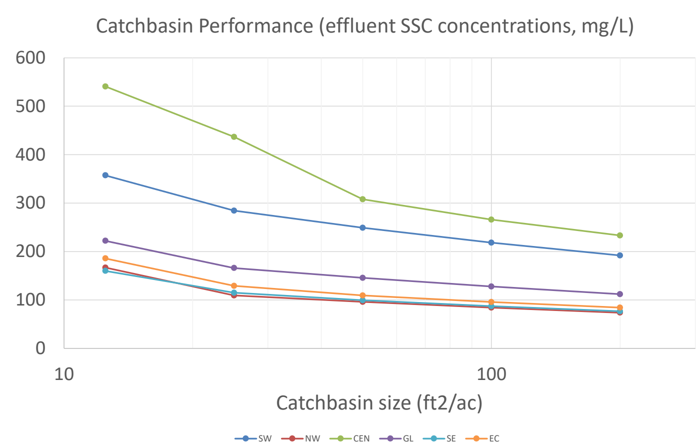
Dimensions of Optimally-Designed Catchbasin



78

78

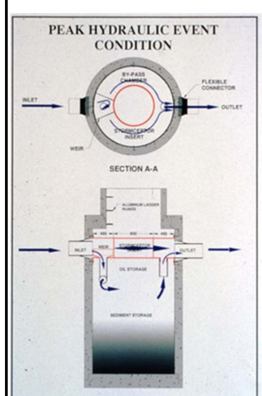
Calculated Catchbasin Performance



79

79

Hydrodynamic Devices



80

80

Research Results

- Clark (2006) evaluated the performance of inclined plate settlers for treating stormwater solids
- Greb, *et al.* (1998) evaluated the performance of a hydrodynamic device in a City of Madison maintenance yard.

81

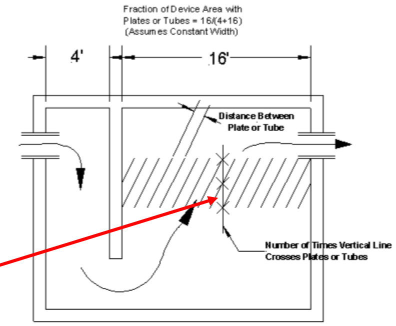
81

What are Lamella Plates?

Key Variables

- Fraction of device area with plates or tubes
- Average tube diameter or distance between plates
- Number of plates or tubes in a vertical line

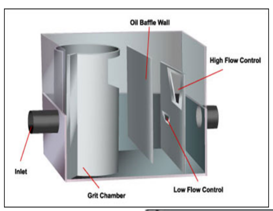
Increase the effective surface area of the device by the number of times a vertical line crosses a plate or tube



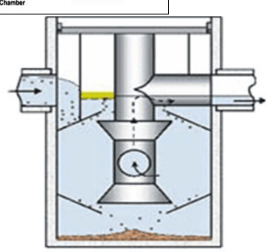
82

82

Field Testing and Modeling Results for Proprietary Hydrodynamic Separators.



Vortechs



DownStream Defender

Stormceptor

83

83

Vortechs Monitoring Site at Milwaukee Freeway Site

84

TSS Load Reduction Results Used for Model Verification

- Sum of Loads; *TSS Loads, kg*

	Influent	Effluent
Vortechs (18 events, no bypass)	**63**	**51**
Stormceptor (15 events, bypass)	**939**	**895**

85

85

USGS and WI DNR Monitoring Facility for Stormceptor Tests, Madison, WI

86

Mass Balance Monitoring of Hydrodynamic Separator (Madison, WI)

Sampled solids load in + additional in sump	1,623 kg +131 kg = 1,754 kg
Sampled solids load out	1,218 kg
Trapped by difference	405 kg (25% removal, based on sampled amount)
Actual trapped total sediment	536 kg (31% actual removal)
Fraction total solids not captured by automatic samplers	7.5%

87

Detailed Tests of Scour Potential in Catchbasin Sumps by Avila (2008) during his PhD Research at the University of Alabama

- Sediment-retaining performance in a catchbasin depends on the size and geometry of the device, the flow rate, sediment size, and specific gravity of the sediment.
- Scour phenomenon includes all those parameters previously mentioned, in addition to the depth of the water protection layer and the consolidation of the sediment bed due to aging.
- An experimental design was developed and analyzed with four parameters: flow rate, sediment size, overlying water protection depth, and specific gravity of the sediment. A 2-dimensional Computational Fluid Dynamic (CFD) model was implemented in Fluent 6.2.
- Shear stresses at different sediment depths were also calculated for different flow rates and inlet geometries. These shear stress values were compared to the critical shear stress of different particle sizes.

88

88

Pitt (1979) conducted mass balance measurements in the drainage system and at the outfall used to determine the fate and transport of the urban particulates. Much of the larger particulates that are not washed off are lost from the paved surfaces by fugitive dust by winds and traffic turbulence.

Measured fugitive dust losses from traffic (San Jose, Pitt 1979)

Keyes, good asphalt	0.33 grams/vehicle-mi
Keyes, oil and screens asphalt	18 grams/vehicle-mi
Tropicana, good asphalt	2.5 grams/vehicle-mi

89

89

Pollutant Accumulations in 200+ Bellevue, WA, Residential/Commercial Area Catchbasins (kg/ha/yr) (Pitt 1985)

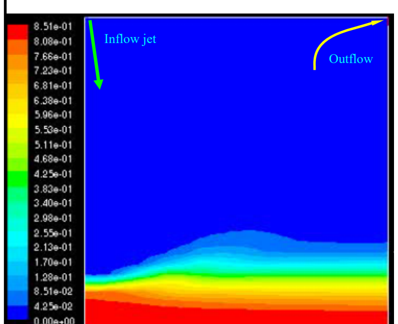
Total Solids	COD	TKN	TP	Lead	Zinc
100 – 147	7.5 – 37	0.07 – 0.17	0.07 – 0.25	0.07 – 0.49	0.02 – 0.10

Baseflow total solids discharge: 110 kg/ha/yr
Stormwater: 210 kg/ha/yr

Therefore, material residing in catchbasin sumps are a large fraction of the total stormwater discharges for an area, if they can become mobilized.

90

Description of the CFD Scour Model



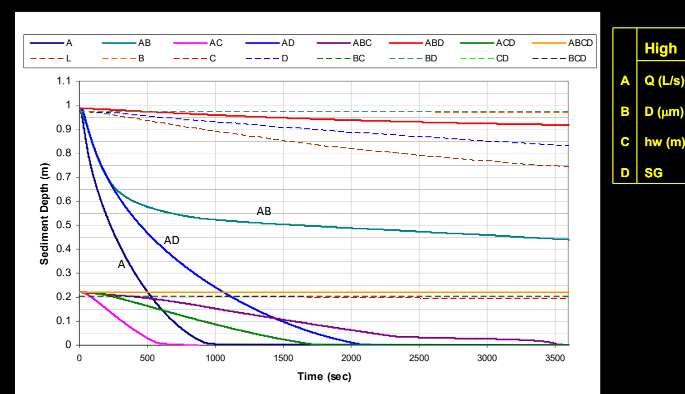
General representation of a simulation. Inflow, and outflow directions are indicated by arrows. Upper layer of water in blue, and sediment layer in color scale.

- A 2D-Computational Fluid Dynamic Model was implemented in FLUENT 6.2, applying the Eulerian multiphase model, considering a dense fluidized bed.
- The sediment bed was exposed to a continuous flow from a vertical-submergible water jet during a 3600 sec (60 min) period.
- The water jet was modeled to represent gutter flows and an in-line pipe.

91

91

Reduction of sediment depth over time



Runs A, AD, and AB show how the specific gravity and the diameter affect the response, reducing the loss of sediment over time.
Particle size has more effect on the loss of sediment than specific gravity.

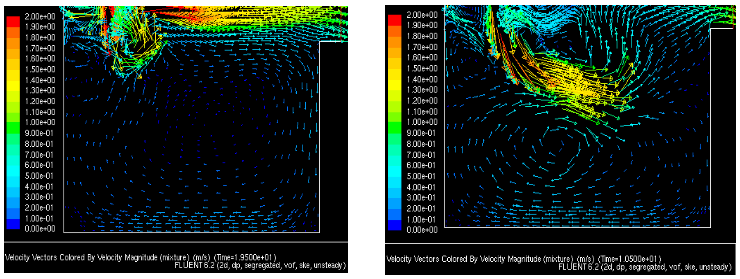
92

92

Comparison of Hydrodynamic Effect: *Water Impact*

- The impact force of the waterfall coming from the pipe inlet is considerably higher than when the inlet is rectangular gutter flow.

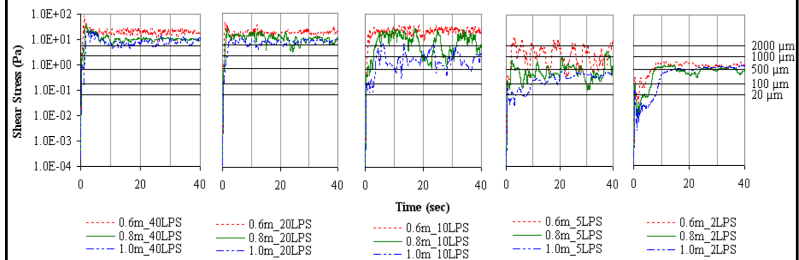
- In the case of the rectangular inlet (left) the jet (with velocity magnitudes of about 1.2 m/s) only reaches about 0.15 m below the outlet; in contrast, the jet reaches about 0.5 m below the outlet when the inlet is circular.



Steady-state velocity vectors ranged between 0 and 2.0 m/s. Flow rate: 20 L/s, Sediment level below the outlet: 0.8 m.

93

Shear Stress: 300 mm-diameter Pipe Inlet



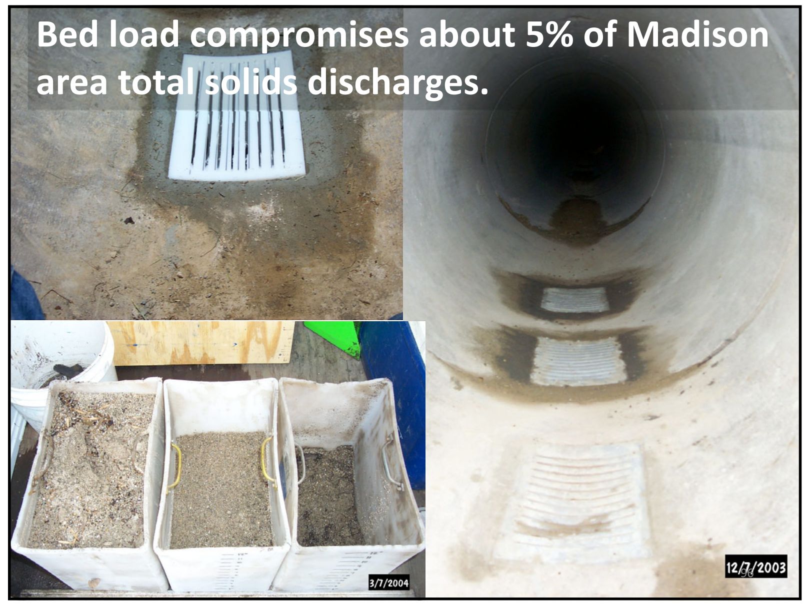
Shear stress on the sediment layer at different elevations in a conventional manhole with circular inlet of 300-mm diameter, and initial suspension threshold for different particle sizes. Series of graph classified by flow rate: 40, 20, 10, 5, and 2 LPS

94

Large Sediment Can be Seen Near Outfalls:

95

Bed load compromises about 5% of Madison area total solids discharges.



96

Velocities and shear stress for different slopes and depths (2 ft pipe)

Depth/ Diameter ratio	Velocity (ft/sec) 0.1% slope	Shear stress (lb/ft²) 0.1% slope	Velocity (ft/sec) 2% slope	Shear stress (lb/ft²) 2% slope
0.1	0.91	0.0081	4.1	0.16
0.5	2.3	0.031	10	0.62
1.0	2.3	0.031	10	0.62

Pipes having small slopes allow large particles to settle and form permanent deposits, while pipes with large slopes will likely have moving beds of larger material.

97

Velocity (ft/sec)	Fluid Shear Stress (lb/ft²)	Example conditions for 10 ft rough concrete pipe (full-flowing pumped system) (EPA wet-weather group report)
1.2	0.0056	Severe deposition
2.0	0.015	Mild to moderate deposition
3.5	0.038	None to slight erosion top layer
4.0	0.059	Slight to mild erosion of consolidated beds (2-5%)
5.9	0.13	Moderate erosion of consolidated beds (15-25%)
7.9	0.24	Substantial erosion (35-50%)

98

Initial Motion and Initial Suspension Criteria

- The sediment bed shifting will not necessarily represent migration out of the device because the sediment does not necessarily reach the elevated outlet. Only suspended sediment is assumed to leave the chamber.

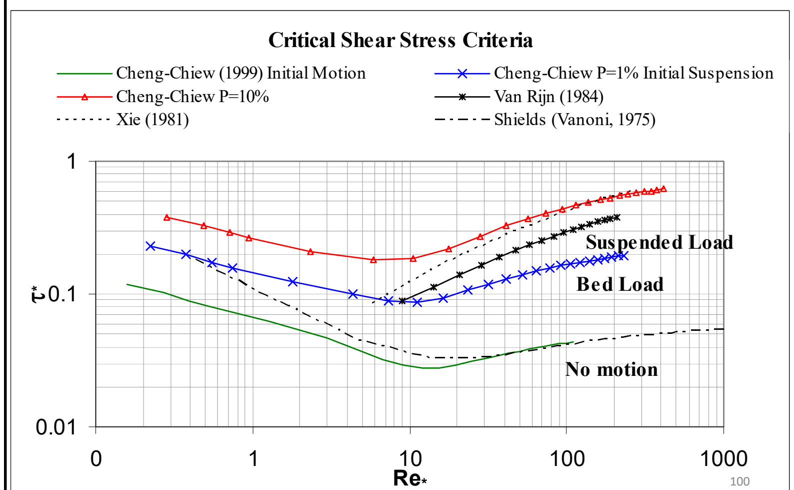
- The Cheng-Chiew criterion (1999), which involves both initial motion and initial suspension, was evaluated. This criterion relates the critical shear stress with the probability that sediment with a particular specific gravity, diameter, and settling velocity, becomes bed load or gets suspended.

- This shear stress was compared to initial-motion and initial-suspension critical shear stresses associated with a specific particle size. A total of 30 different scenarios were evaluated during pilot-scale tests to confirm.

99

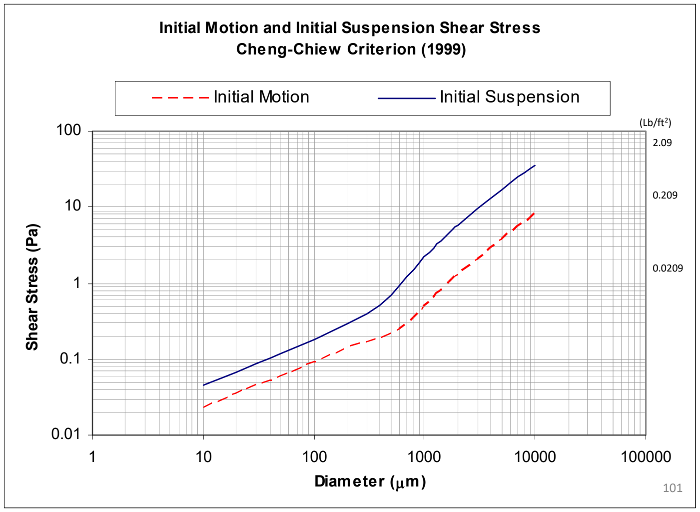
99

Initial Motion and Initial Suspension Criteria



100

Initial Motion and Initial Suspension Criteria



101

101

Conclusions

- Sediment in urban streams is a serious problem.
- Rains only remove a small fraction of the total particulate load from paved surfaces, mostly the smallest particles.
- Street cleaning only removes a small fraction of the street dirt loading, mostly the larger particles.
- The accumulation rate is much less than expected due to residual load.
- Particle size distributions at outfalls are mostly made up of small particles (larger particles that wash off accumulate in sewerage)
- Particle size distributions of source area sheetflows have large particles, but many of these aren't effectively transported to outfalls.
- Most models are out of balance on source area contributions.

102

102

- Catchbasins with sumps remove up to 35% suspended solids from inlet flowing water.
- This has minimal water quality benefit at outfalls, but protects storm sewerage from large debris.
- Most inserts have very limited capacity to retain material.
- Possible to modify inlets and catchbasins to provide significant floatable control (especially using hoods at catchbasin outlets).

103

103

- Flow rate, particle size, overlying water depth, and their interactions are significant factors that affect the scour of sediment in a conventional catchbasin sump.

- The inlet geometry has a significant effect on the scour potential of sediments captured in conventional catchbasin sumps. The impact force will be greater when the waterfall is concentrated in the smaller area associated with a pipe inlet.

- The overlying water layer depth above the sediment has an important function in protecting the sediment layer from scour. High shear stresses caused by the impacting water jet will not easily reach the sediment surface if the water is deep.

104

104

- Flows smaller than 2.0 L/s (30 GPM), typical for stormwater catchbasins, do not expose particles greater than 50 μm to suspension in manholes with rectangular inlets wider than 0.8 m. This suggests that the sediment would not be exposed to scour most of the time. This represents the typical smallest particle size found in catchbasin sumps.

- CFD modeling to include 3D analyses (using Flow-3D software), and detailed laboratory tests using a full-scale manhole were used to verify the computational results. Finally, the results will be implemented in the WinSLAMM stormwater model to better consider sediment scour from small hydrodynamic devices.

105

105