Sediment in the Urban Environment – A Historical Perspective

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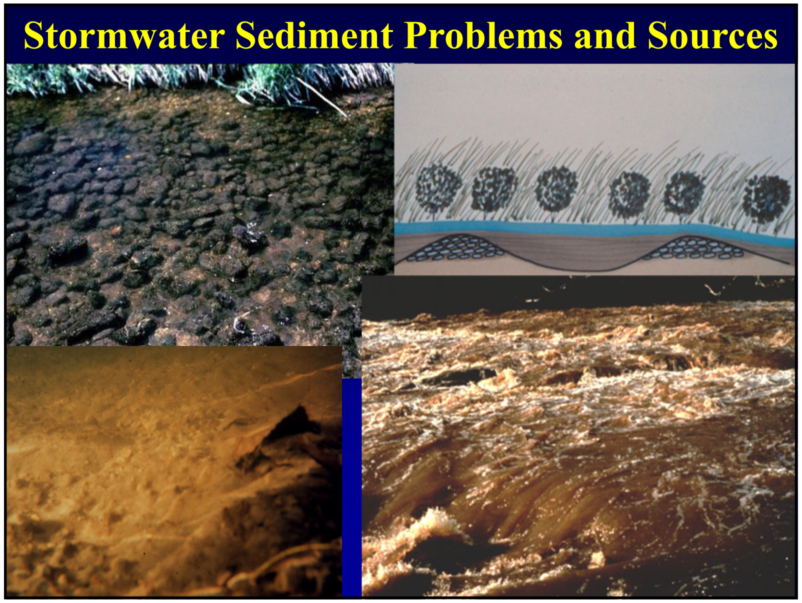
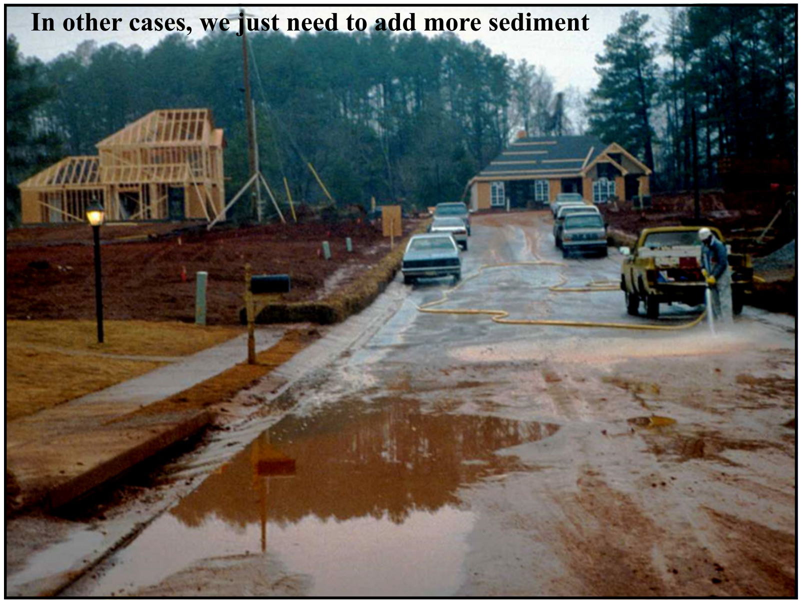


Stormwater Sediment Problems and Sources

Many sources of stormwater particulates are obvious; seasonal snowmelt debris, badly eroding slopes, etc.



In other cases, we just need to add more sediment

Many stormwater monitoring configurations used over the years

Loss of Large Particulates in Sampling Lines (100 cm/sec sample line velocity)

Percentage loss of particulates	Critical settling rate (cm/sec)	Size range (1.5 to 2.5 sp. gr.)
100	100	8,000 – 25,000
50	50	3,000 – 10,000
25	25	1,500 – 3,000
10	10	350 – 900
1	1	100 – 200

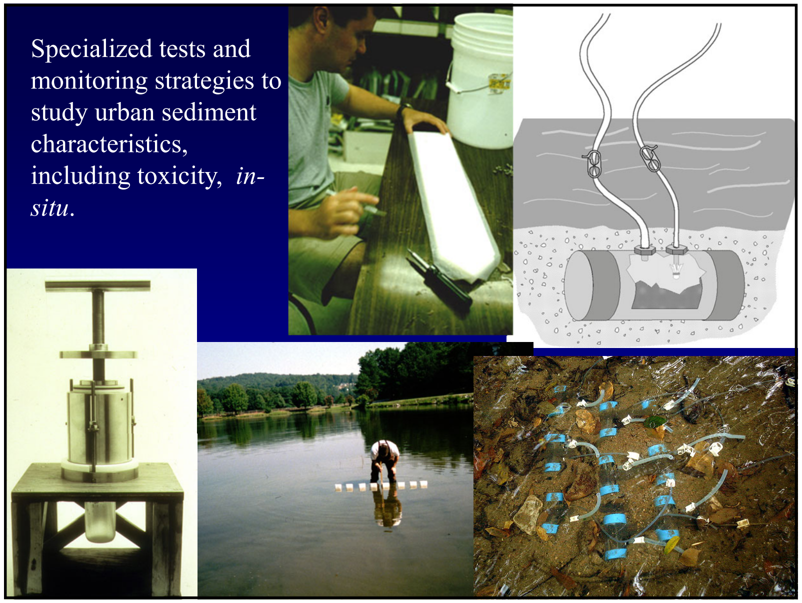
Problem isn't sample line velocity, but location of intake; need bedload sampler

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

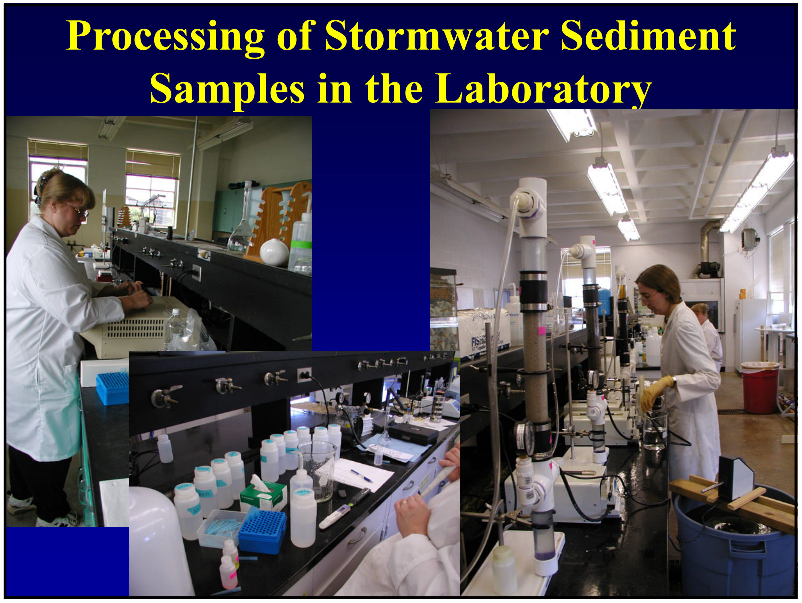
Results of Verification Monitoring of Stormceptor (Madison, WI)

Sampled solids load in	1623 kg
Sampled solids load out	1218 kg
Trapped (by difference)	405 kg (25% removal)
Actual trapped total sediment	536 kg (33% actual removal)
Total solids not captured by automatic samplers	131 kg out of 1623 kg missed (8%)

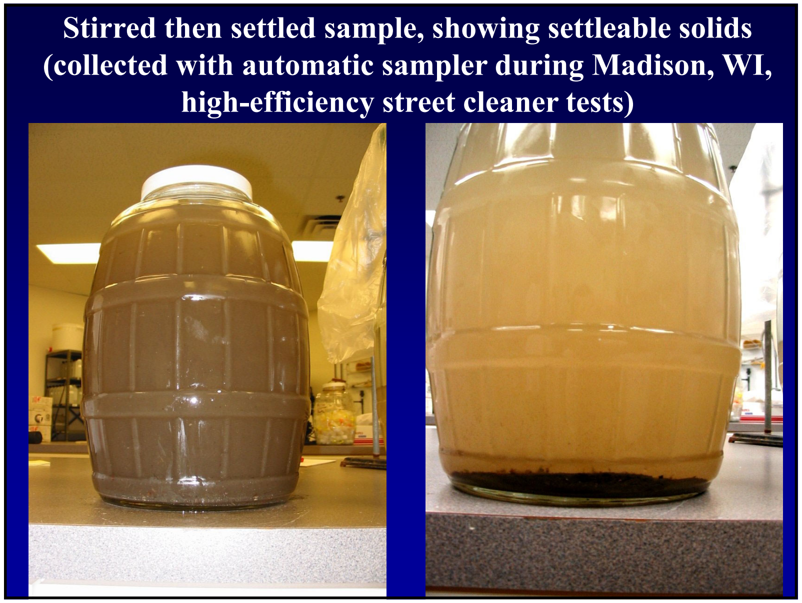
Need to conduct complete mass balance of sediments in urban areas, including receiving water sediment.



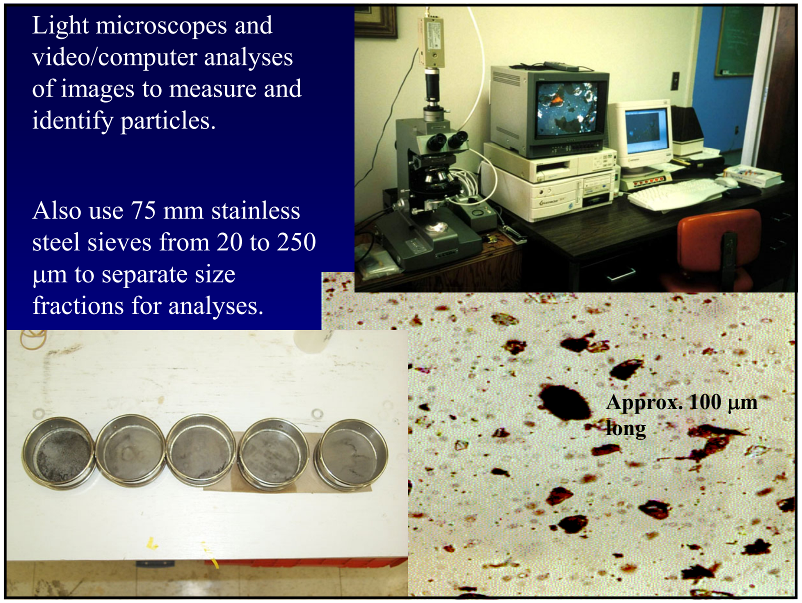
Specialized tests and monitoring strategies to study urban sediment characteristics, including toxicity, *in-situ*.



Processing of Stormwater Sediment Samples in the Laboratory



Stirred then settled sample, showing settleable solids (collected with automatic sampler during Madison, WI, high-efficiency street cleaner tests)



Light microscopes and video/computer analyses of images to measure and identify particles.

Also use 75 mm stainless steel sieves from 20 to 250 µm to separate size fractions for analyses.

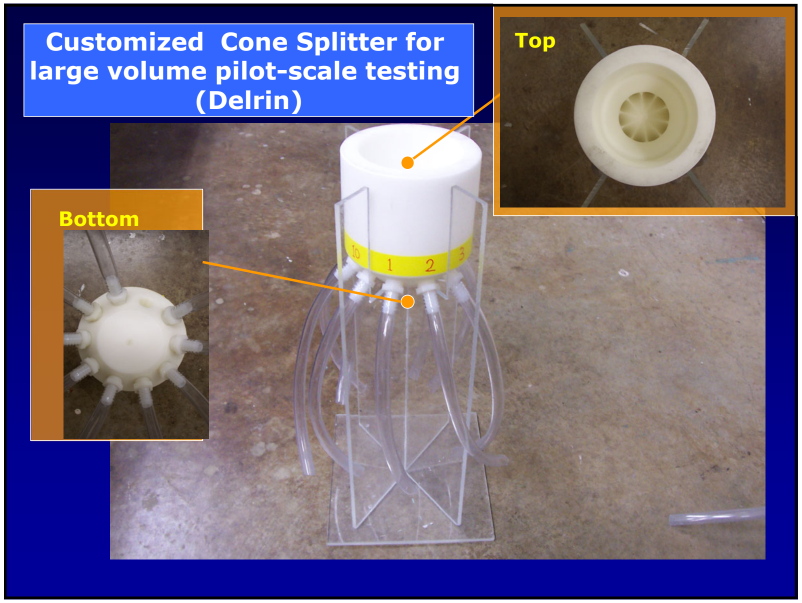
Approx. 100 µm long

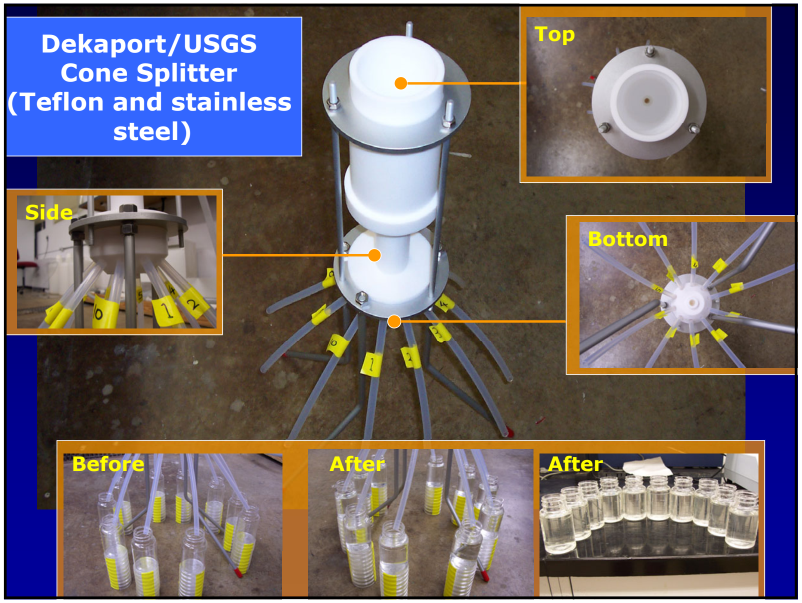
Sample Splitting for Volume and Sediment Accuracy

- USGS studies found that “shaking and pouring” (or worse, pipetting) 100 mL subsamples from sample bottles for TSS analyses frequently leads to unacceptable errors.
- The USGS found that if the sand fraction (>63 micrometers) comprised less than 25% of the total sample mass, then preferred cone or churn splitting methods were in reasonable agreement with pouring or pipetting methods.
- Since we are concerned with the complete range of particle sizes, and that some source area samples, or some seasonal outfall runoff samples, may exceed this amount of sand-sized particles, stormwater sample splitting needs to be done with churn, or preferably, cone splitters.

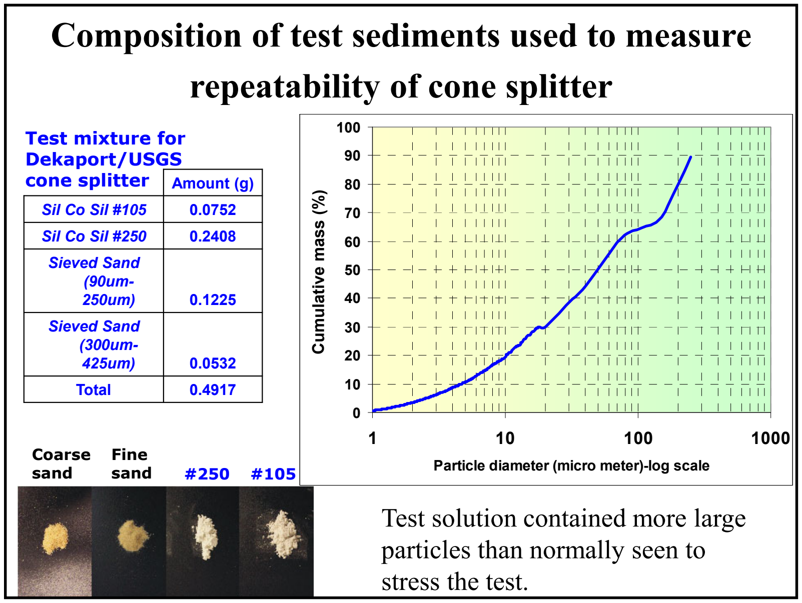
Churn Splitter

Customized Cone Splitter for large volume pilot-scale testing (Delrin)





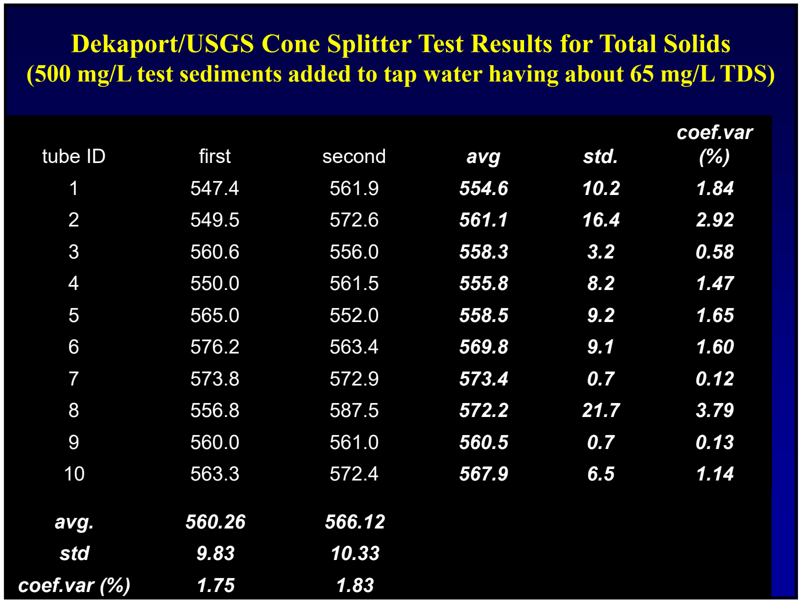
Dekaport/USGS Cone Splitter (Teflon and stainless steel)



Composition of test sediments used to measure repeatability of cone splitter

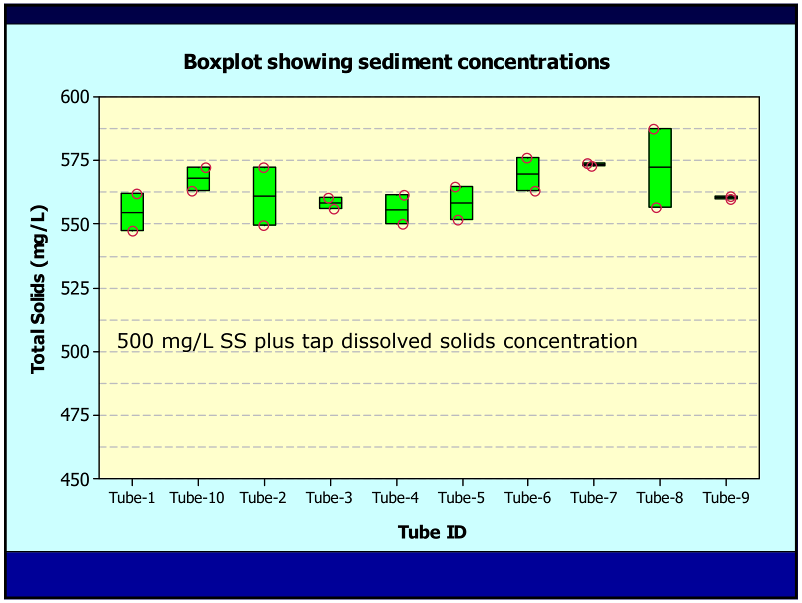
Test mixture for Dekaport/USGS cone splitter	**Amount (g)**
Sil Co Sil #105	0.0752
Sil Co Sil #250	0.2408
Sieved Sand (90um-250um)	0.1225
Sieved Sand (300um-425um)	0.0532
Total	0.4917

Test solution contained more large particles than normally seen to stress the test.



Dekaport/USGS Cone Splitter Test Results for Total Solids (500 mg/L test sediments added to tap water having about 65 mg/L TDS)

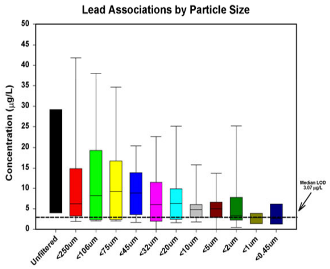
tube ID	first	second	*avg*	*std.*	*coef.var (%)*
1	547.4	561.9	***554.6***	***10.2***	***1.84***
2	549.5	572.6	***561.1***	***16.4***	***2.92***
3	560.6	556.0	***558.3***	***3.2***	***0.58***
4	550.0	561.5	***555.8***	***8.2***	***1.47***
5	565.0	552.0	***558.5***	***9.2***	***1.65***
6	576.2	563.4	***569.8***	***9.1***	***1.60***
7	573.8	572.9	***573.4***	***0.7***	***0.12***
8	556.8	587.5	***572.2***	***21.7***	***3.79***
9	560.0	561.0	***560.5***	***0.7***	***0.13***
10	563.3	572.4	***567.9***	***6.5***	***1.14***
avg.	***560.26***	***566.12***			
std	***9.83***	***10.33***			
coef.var (%)	***1.75***	***1.83***			



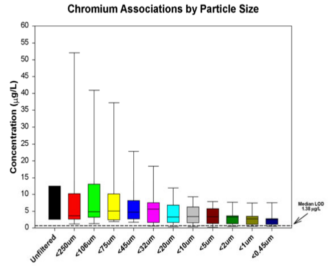
Boxplot showing sediment concentrations

Dekaport cone splitter used to separate sample into smaller volumes for different sieve analyses.

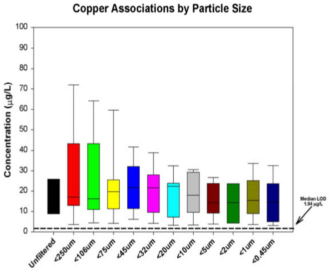
All-plastic vacuum filtering setups are used with a series of polycarbonate membrane filters (10, 5, 2, 1, 0.45 µm) to supplement sieves. Effluent after filtering analyzed for a wide variety of constituents.



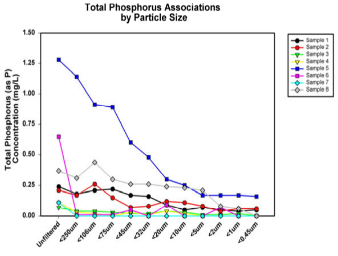
Lead Associations by Particle Size



Chromium Associations by Particle Size



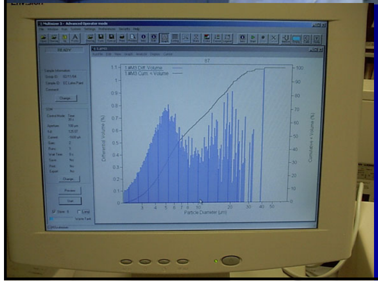
Copper Associations by Particle Size



Total Phosphorus Associations by Particle Size

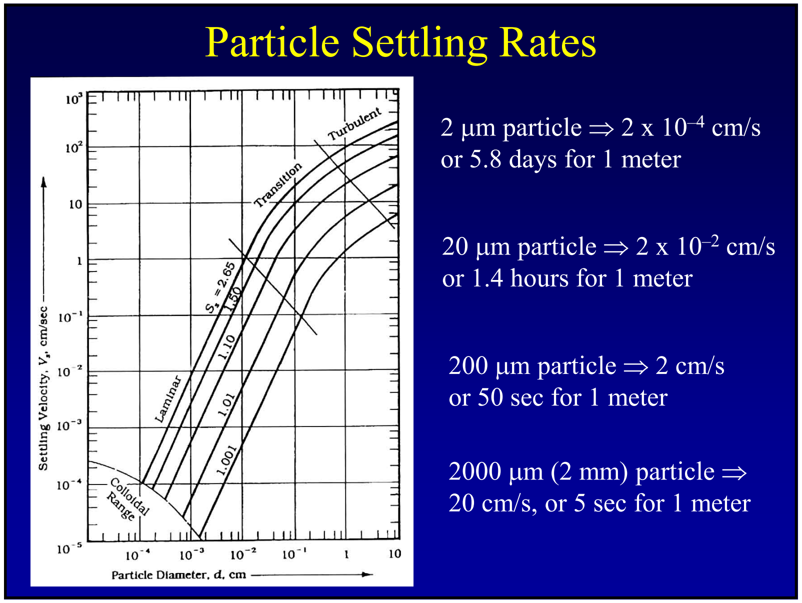
Sieving with a 106 µm sieve to remove large debris before Coulter counting. Similar sample analyzed for total solids.

Unfiltered sample after total solids analysis showing grass debris



Coulter Counter Multi-Sizer 3 used to measure particle size distribution of solids up to several hundred micrometers. Larger particles (up to several mm) are quantified using sieves.

Stormwater Sediment Characteristics in Urban Areas



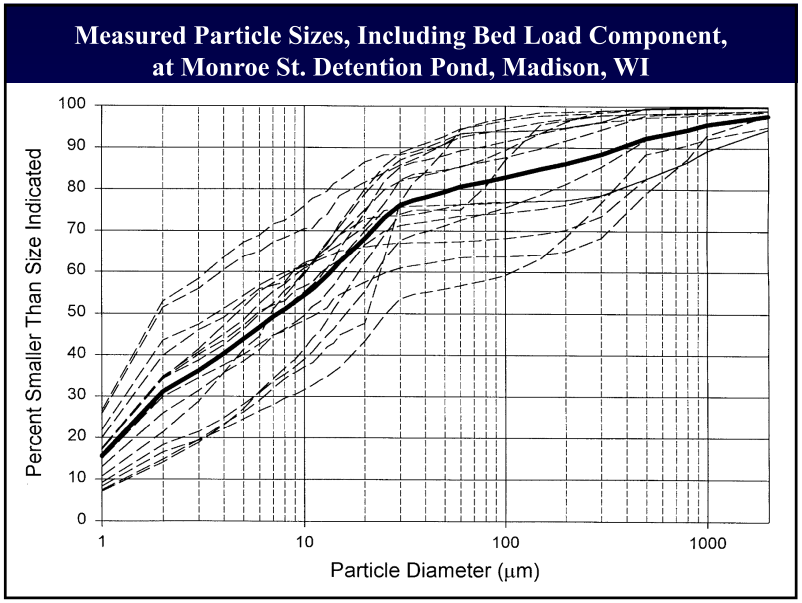
Particle Settling Rates

2 μm particle ⇒ 2 x 10^{-4} cm/s or 5.8 days for 1 meter

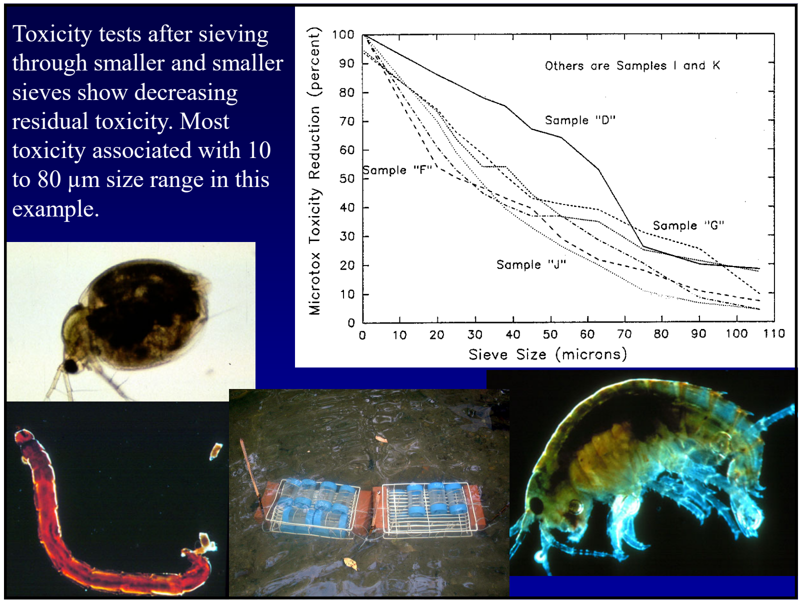
20 μm particle ⇒ 2 x 10^{-2} cm/s or 1.4 hours for 1 meter

200 μm particle ⇒ 2 cm/s or 50 sec for 1 meter

2000 μm (2 mm) particle ⇒ 20 cm/s, or 5 sec for 1 meter



Measured Particle Sizes, Including Bed Load Component, at Monroe St. Detention Pond, Madison, WI



Toxicity tests after sieving through smaller and smaller sieves show decreasing residual toxicity. Most toxicity associated with 10 to 80 μm size range in this example.

Stormwater control improves as smaller particles are removed. Five micrometer objective works well for detention ponds.

	Percent Pollutant Reduction after Removing all Particulates Greater than Size Shown			
	20 µm	5 µm	1 µm	0.45 µm
Total Solids	40%	43%	52%	53%
Suspended Solids	76	81	98	100
Turbidity	43	55	92	96
Total-P	68	82	89	92
Total-N	30	41	35	23
Nitrate	0	0	12	17
Phosphate	71	78	81	88
COD	48	52	52	47
Ammonia	35	46	54	58
Cadmium	20	22	22	22
Chromium	69	81	82	84
Copper	26	34	34	37
Iron	52	63	95	97
Lead	41	62	76	82
Zinc	64	70	70	72

Accumulation and Washoff of Street Dirt

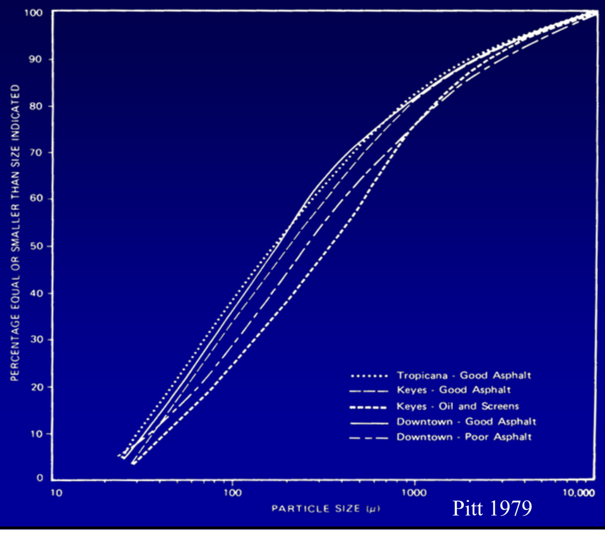
Street Dirt Chemical Quality (mg/kg)

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

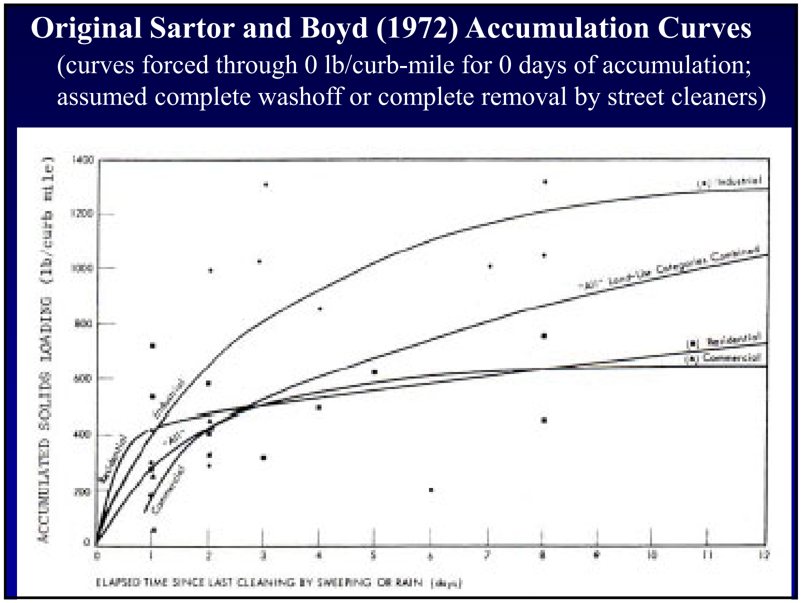
Phosphorus (P)	400 – 1500
Total Kjeldahl Nitrogen	290 – 4300
Chemical Oxygen Demand	65,000 – 340,000
Copper (Cu)	110 – 420
Lead (Pb)	530 – 7500
Zinc (Zn)	260 – 1200
Cadmium (Cd)	<3 – 5
Chromium (Cr)	31 – 180

Pitt, Bannerman, and others

Particle Size Distribution of Street Dirt

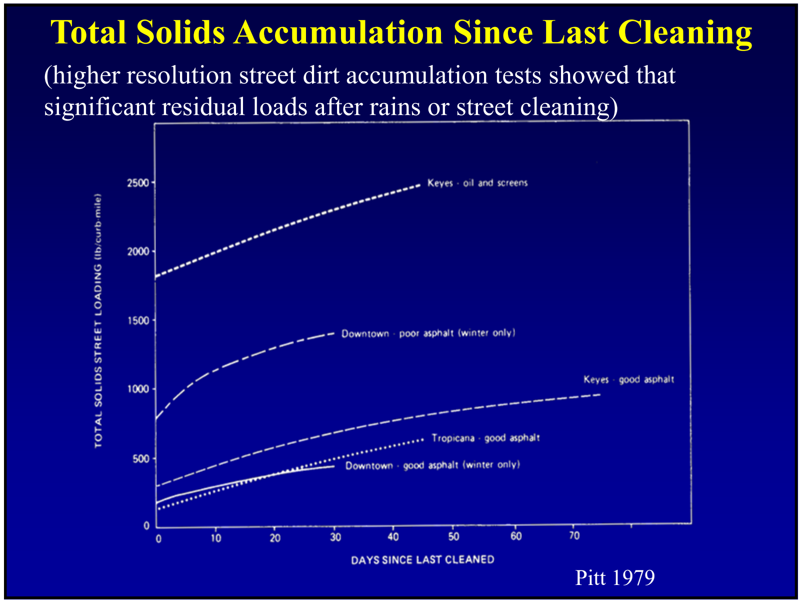


Pitt 1979



Original Sartor and Boyd (1972) Accumulation Curves

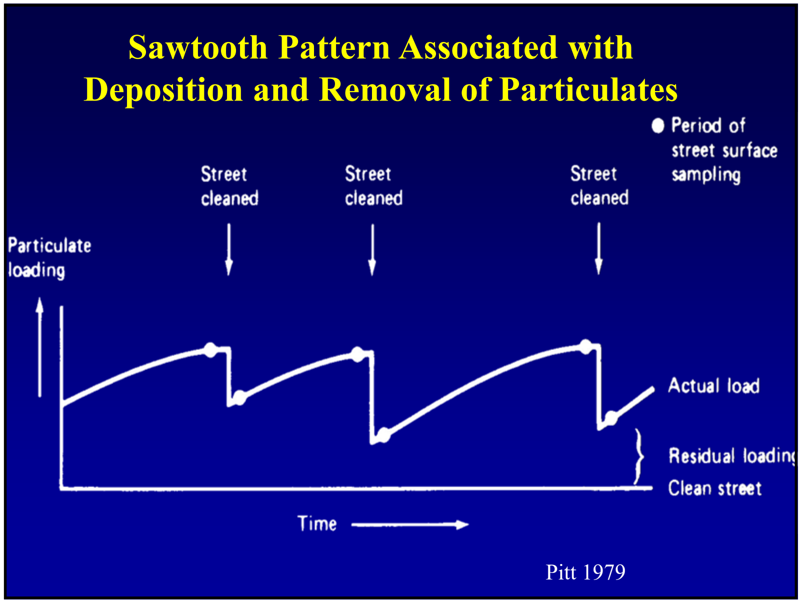
(curves forced through 0 lb/curb-mile for 0 days of accumulation; assumed complete washoff or complete removal by street cleaners)



Total Solids Accumulation Since Last Cleaning

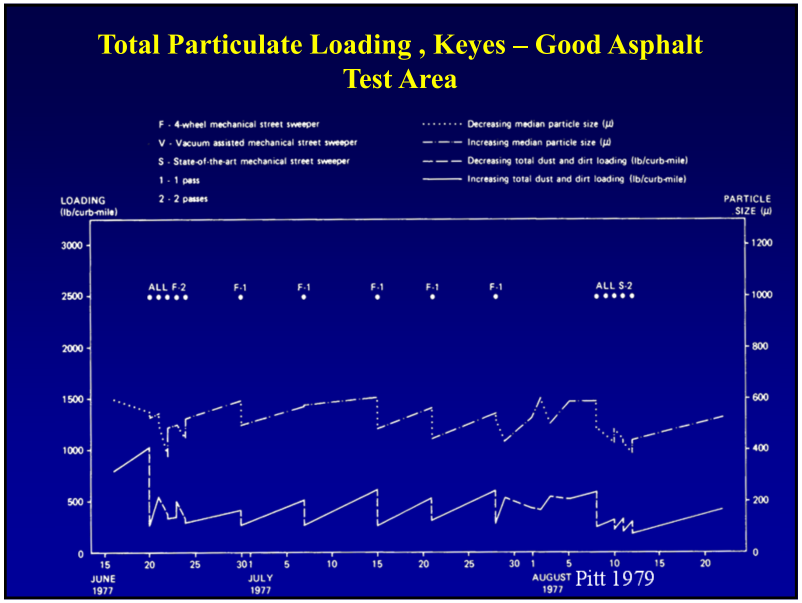
(higher resolution street dirt accumulation tests showed that significant residual loads after rains or street cleaning)

Pitt 1979



Sawtooth Pattern Associated with Deposition and Removal of Particulates

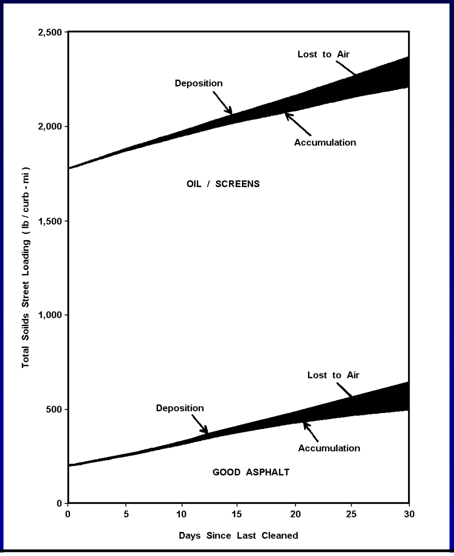
Pitt 1979



Total Particulate Loading , Keyes – Good Asphalt Test Area

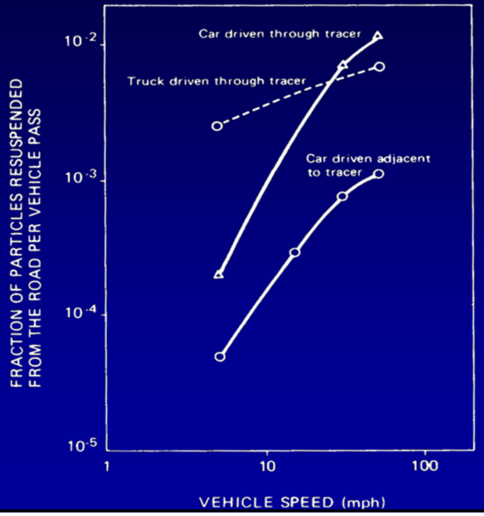
Pitt 1979

Deposition and Accumulation of Street Dirt



Pitt 1979

Particle Resuspension Rates Caused by Vehicle Passage on an Asphalt Road



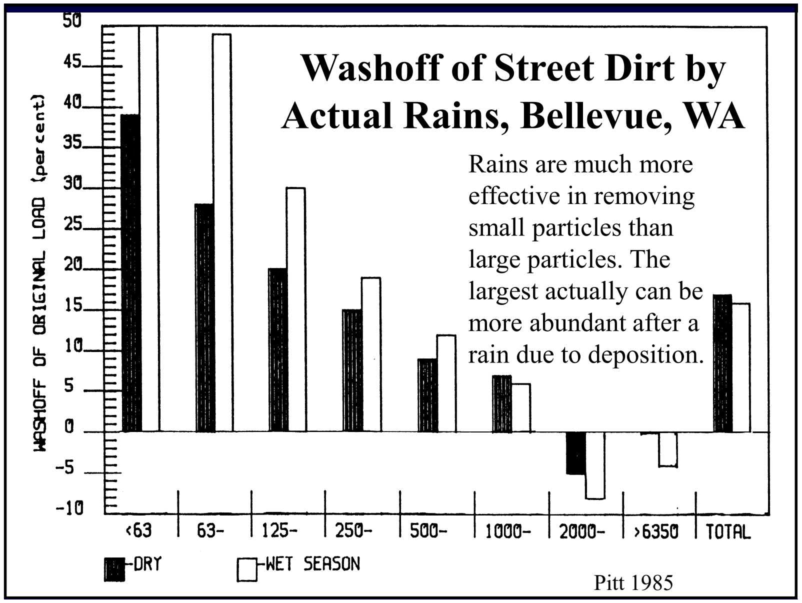
Measured Fugitive Dust Losses from Streets, San Jose, CA

Keyes, good asphalt	6 lb/curb-mi/day	0.33 grams/vehicle-mi
Keyes, oil and screens asphalt	4 lb/curb-mi/day	18 grams/vehicle-mi
Tropicana, good asphalt	6 lb/curb-mi/day	2.5 grams/vehicle-mi

Pitt 1979

Example Deposition and Accumulation Rates (many studies)

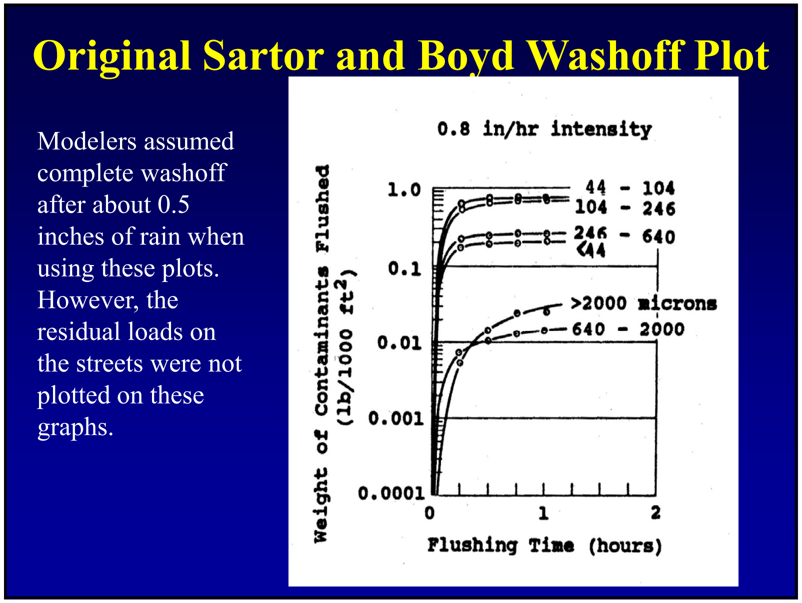
	Initial load (g/m)	Depos. Rate (g/m-d)	Days to max. load
Reno, NV, smooth and good condition	80	1	5
San Jose, CA, good condition	35	4	>50
Castro Valley, CA, mod. condition	85	10	70
Ottawa, Ontario, mod. condition, indus.	60	40	>10
Toronto, Ontario, mod. condition, resid.	40	32	>10
Bellevue, WA, smooth, heavy traffic	60	1	30
San Jose, CA, oil and screens overlay	510	6	>50
Ottawa, Ontario, rough	200	20	>10



Washoff of Street Dirt by Actual Rains, Bellevue, WA

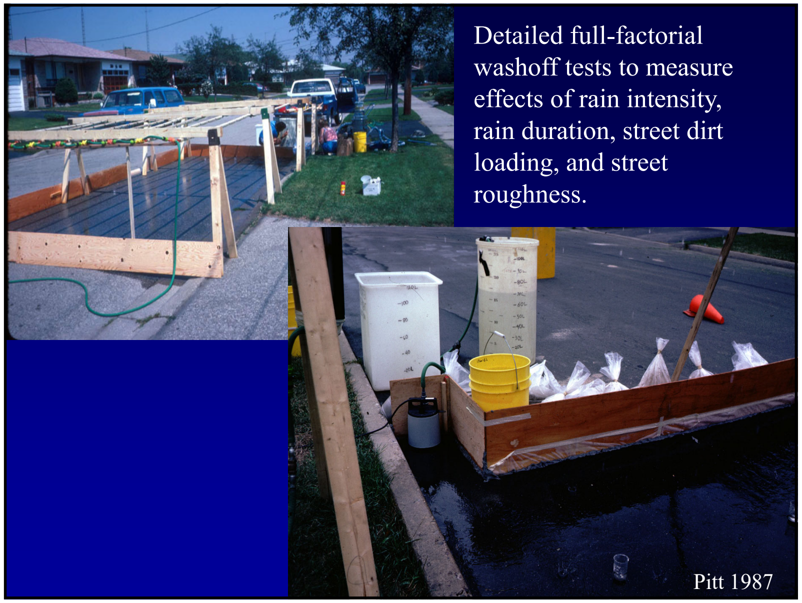
Rains are much more effective in removing small particles than large particles. The largest actually can be more abundant after a rain due to deposition.

Pitt 1985



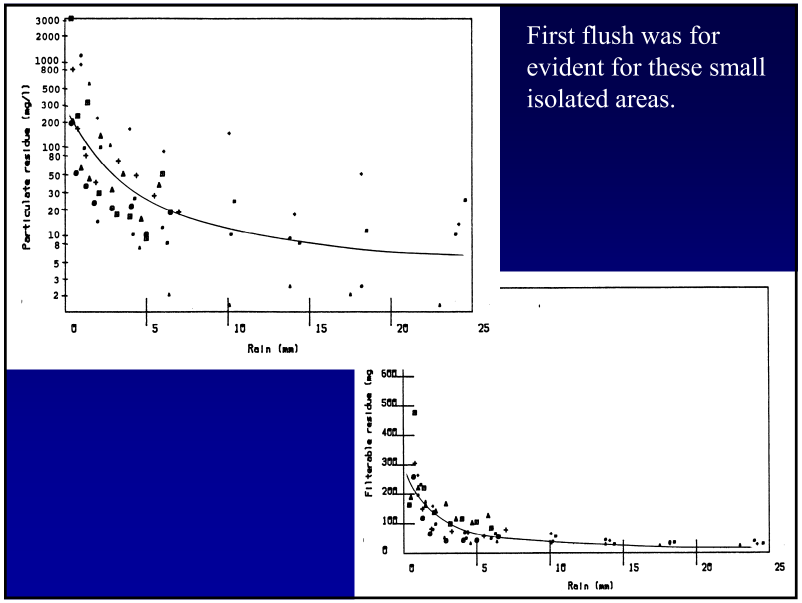
Original Sartor and Boyd Washoff Plot

Modelers assumed complete washoff after about 0.5 inches of rain when using these plots. However, the residual loads on the streets were not plotted on these graphs.



Detailed full-factorial washoff tests to measure effects of rain intensity, rain duration, street dirt loading, and street roughness.

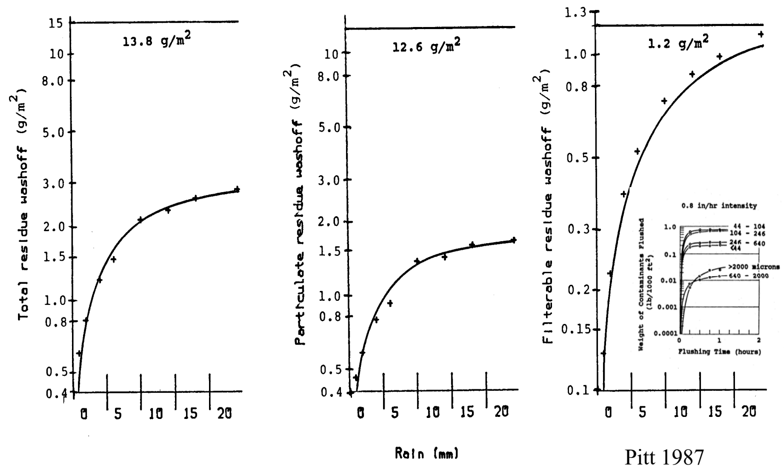
Pitt 1987



First flush was for evident for these small isolated areas.

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

(only a small fraction of the particulate solids washed off)



Pitt 1987

Ratio of Available SS to Total SS Street Dirt Loadings

$$I = 0.08 \pm 0.04$$
$$T = -0.08 \pm 0.05$$

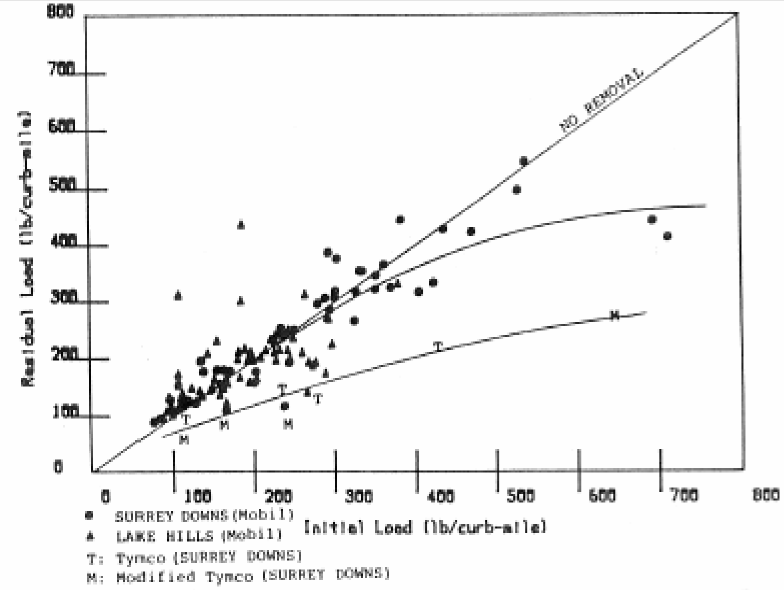
$$\hat{Y} = 0.097 + 0.04(I) - 0.04(T)$$

I+T+ (high and rough) : $\hat{Y} = 0.10$
I+T- (high and smooth): $\hat{Y} = 0.18$
I-T+ (low and rough) : $\hat{Y} = 0.02$
I-T- (low and smooth) : $\hat{Y} = 0.10$

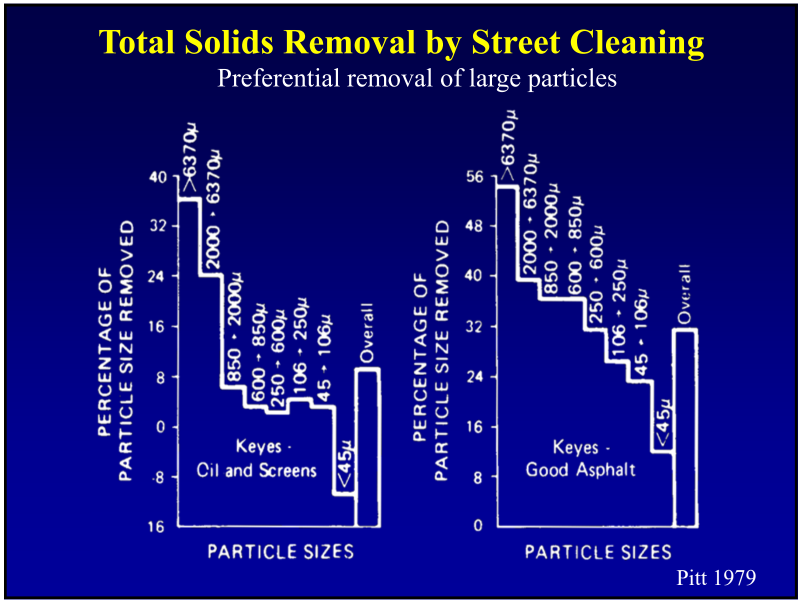
Pitt 1987

Low rain intensities on rough streets only remove about 2% of the initial street dirt loading, while high rain intensities on smooth streets remove about 18% of the initial street dirt load.

Street Cleaning to Reduce Stormwater Sediments



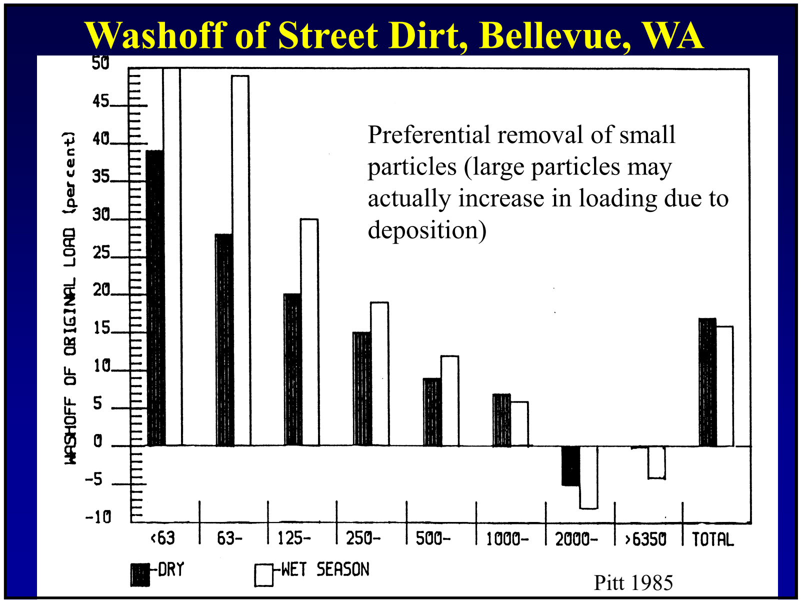
Redistribution of Street Dirt During Street Cleaning



Total Solids Removal by Street Cleaning

Preferential removal of large particles

Pitt 1979

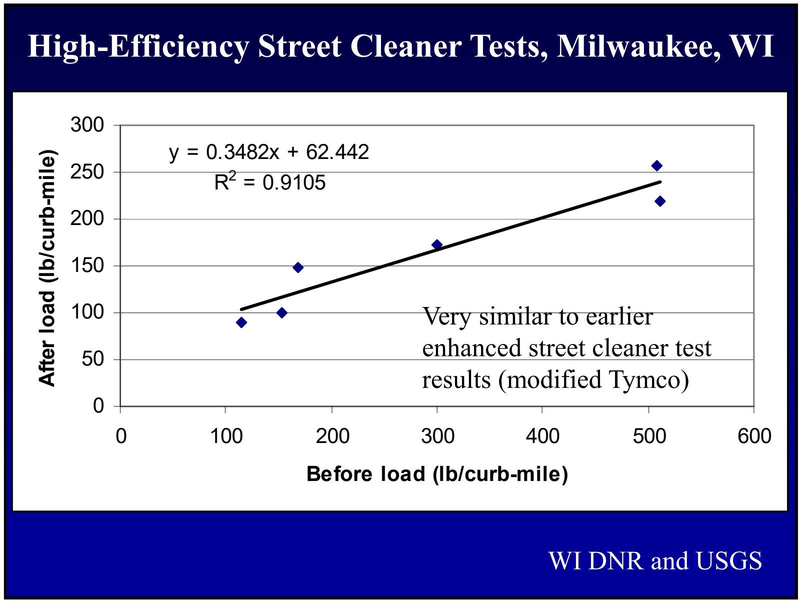


Washoff of Street Dirt, Bellevue, WA

Preferential removal of small particles (large particles may actually increase in loading due to deposition)

Pitt 1985

High-efficiency street cleaning tests conducted by WI DNR and USGS in Milwaukee, WI



High-Efficiency Street Cleaner Tests, Milwaukee, WI

Very similar to earlier enhanced street cleaner test results (modified Tymco)

WI DNR and USGS

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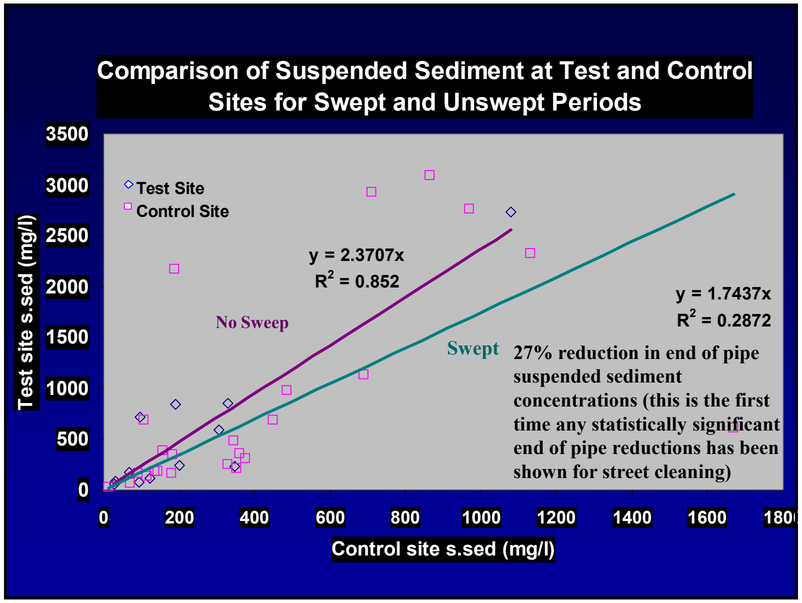

Comparison of Suspended Sediment at Test and Control Sites for Swept and Unswept Periods

27% reduction in end of pipe suspended sediment concentrations (this is the first time any statistically significant end of pipe reductions has been shown for street cleaning)

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Coarse Floatable Control

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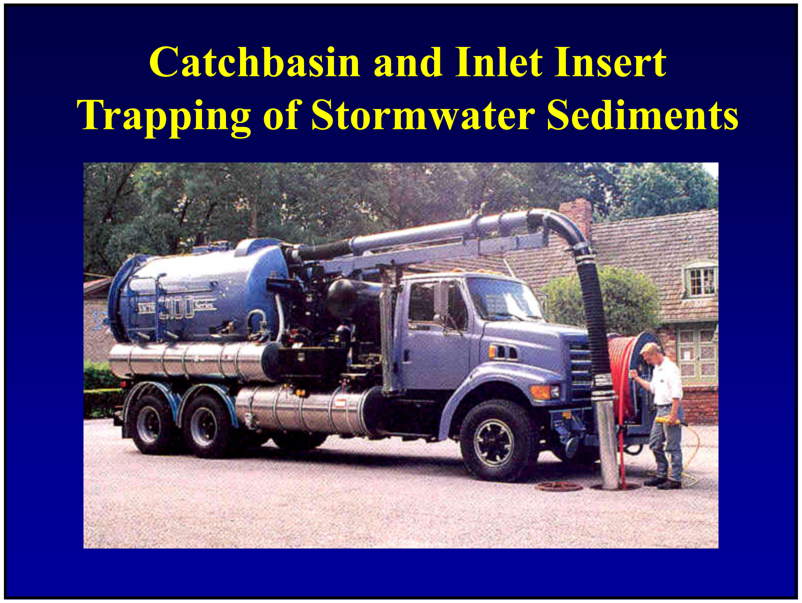


Catchbasin and Inlet Insert Trapping of Stormwater Sediments

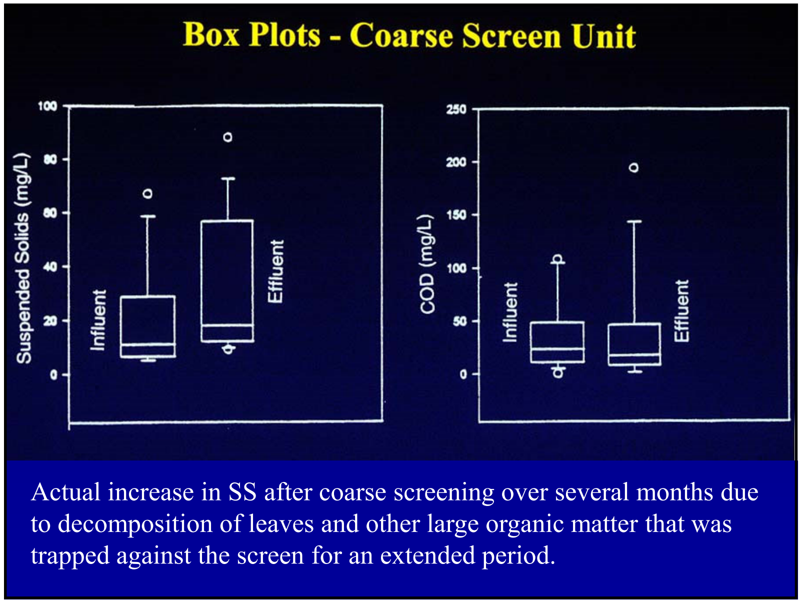
Pollutant Accumulations in 200+ Bellevue, WA, Residential/Commercial Area Catchbasins (kg/ha/yr) (Pitt 1985)

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

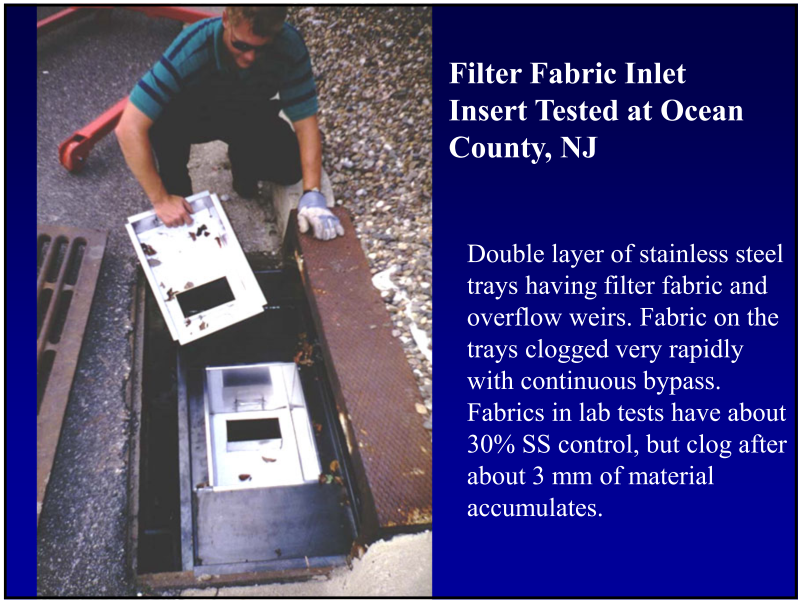
A lot of material resides in catchbasins compared to discharged amounts.

Coarse Screen Tested at Ocean County, NJ



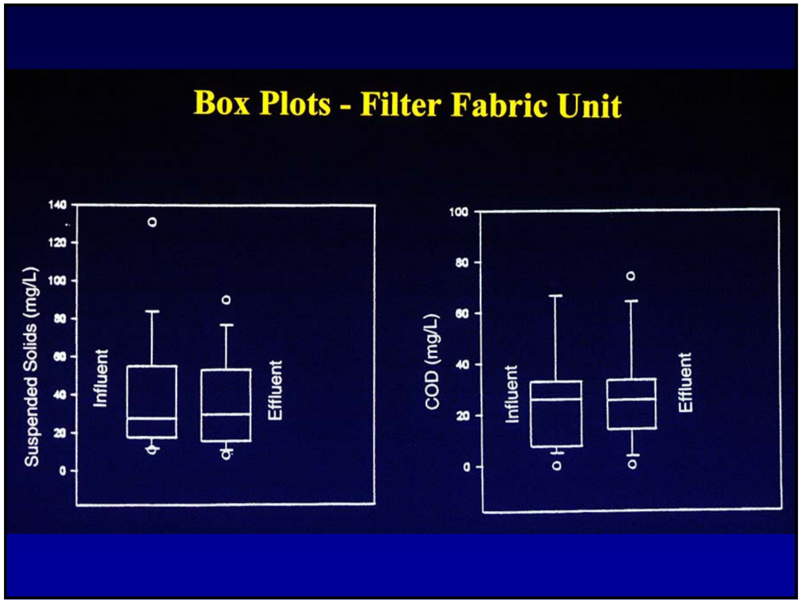
Box Plots - Coarse Screen Unit

Actual increase in SS after coarse screening over several months due to decomposition of leaves and other large organic matter that was trapped against the screen for an extended period.

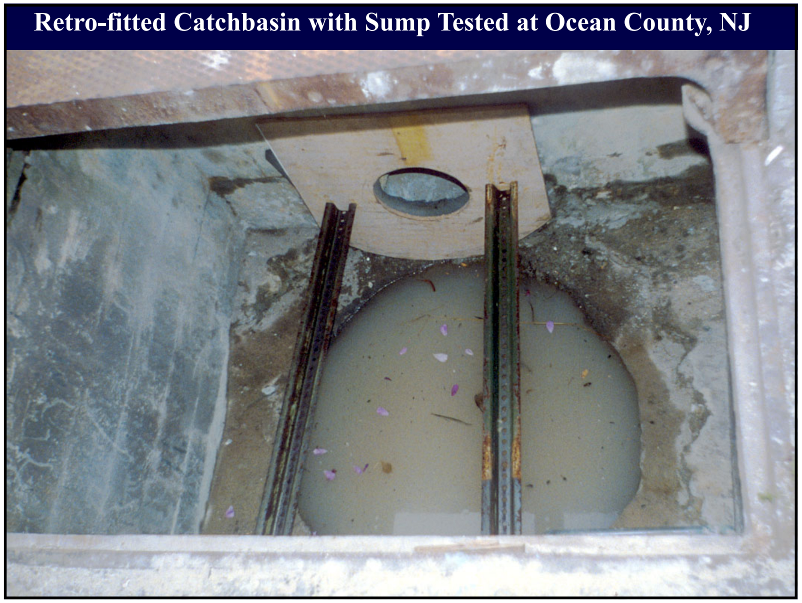


Filter Fabric Inlet Insert Tested at Ocean County, NJ

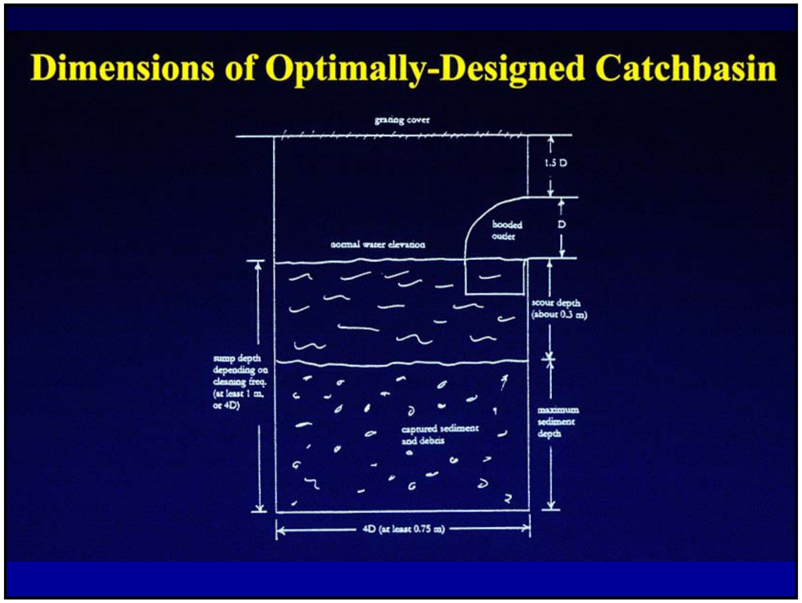
Double layer of stainless steel trays having filter fabric and overflow weirs. Fabric on the trays clogged very rapidly with continuous bypass. Fabrics in lab tests have about 30% SS control, but clog after about 3 mm of material accumulates.



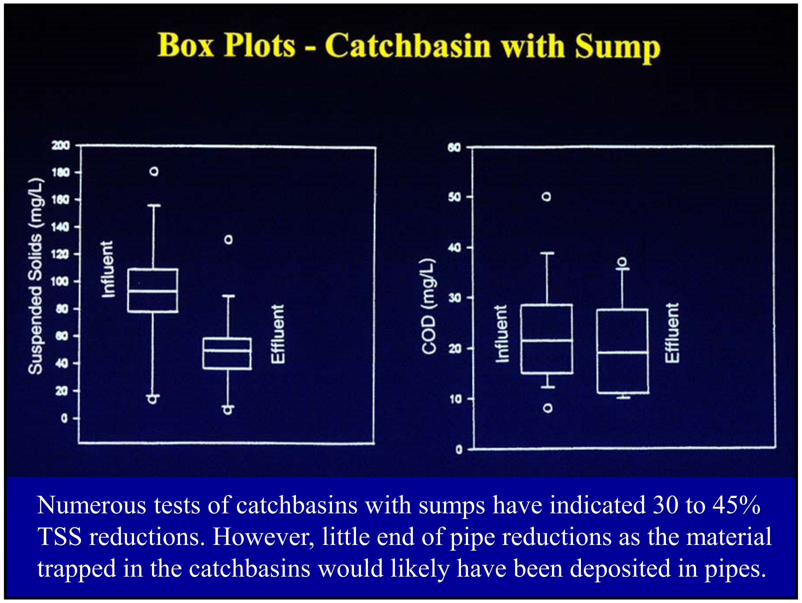
Box Plots - Filter Fabric Unit



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



Dimensions of Optimally-Designed Catchbasin



Box Plots - Catchbasin with Sump

Numerous tests of catchbasins with sumps have indicated 30 to 45% TSS reductions. However, little end of pipe reductions as the material trapped in the catchbasins would likely have been deposited in pipes.

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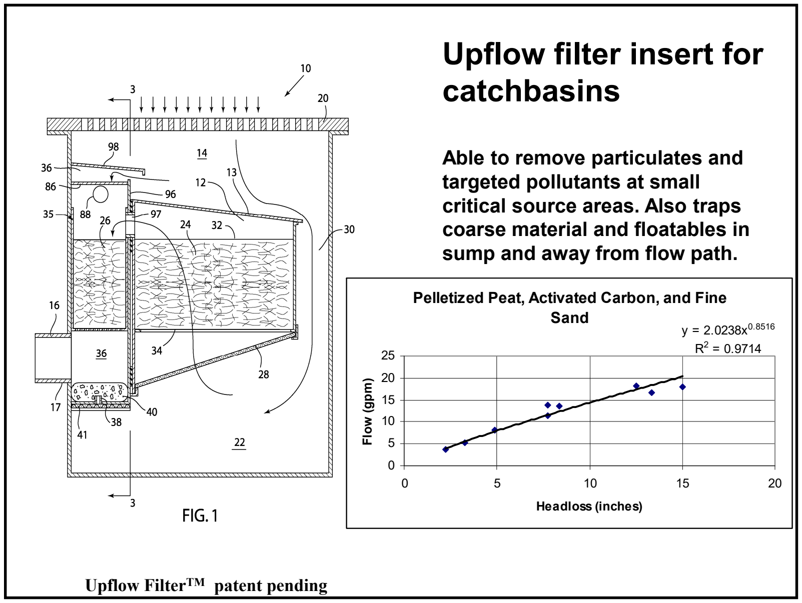


Upflow filter insert for catchbasins

Able to remove particulates and targeted pollutants at small critical source areas. Also traps coarse material and floatables in sump and away from flow path.

Upflow Filter™ patent pending

66

Sediment Movement in Storm Drainage

Typical urban receiving water sediment: Where are the large particles?

67

Bedload in corrugated stormdrain and mound of settleable material at discharge into wet detention pond after many years of operation at ski resort at Snowmass, CO (drain from several acre resort parking area having sand applications for traction control).

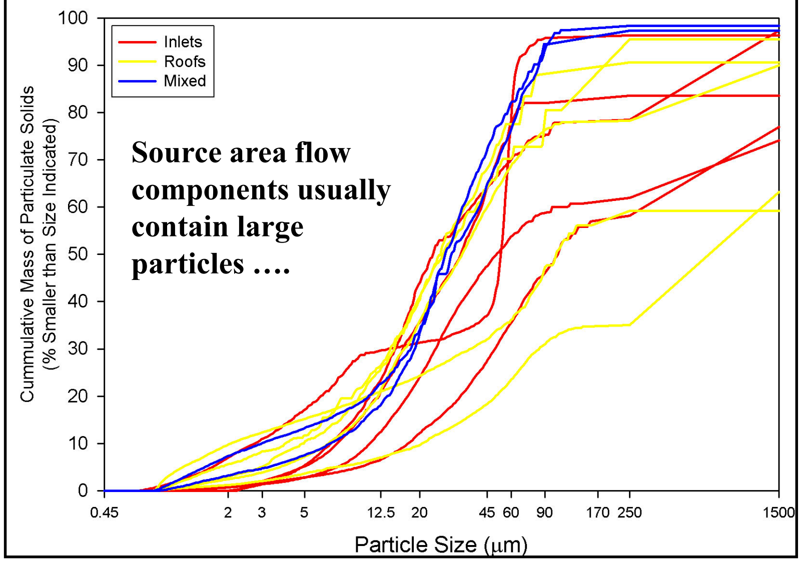
68

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

Depth/ Diameter ratio	Velocity (ft/sec) 0.1% slope	Shear stress (lb/ft^2) 0.1% slope	Velocity (ft/sec) 2% slope	Shear stress (lb/ft^2) 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

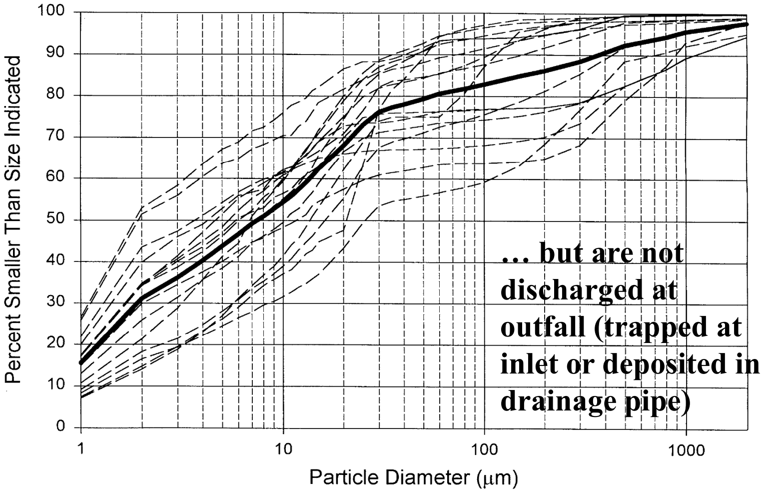
Pipes having small slopes allow large particles to settle and form permanent deposits, while pipes with large slopes will likely have moving beds of larger material.

Velocity (ft/sec)	Fluid Shear Stress (lb/ft^2)	Example conditions for 10 ft rough concrete pipe (full-flowing pumped system) (recent 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%)



Source area flow components usually contain large particles ….

Measured Particle Sizes, Including Bed Load Component, at Monroe St. Detention Pond, Madison, WI

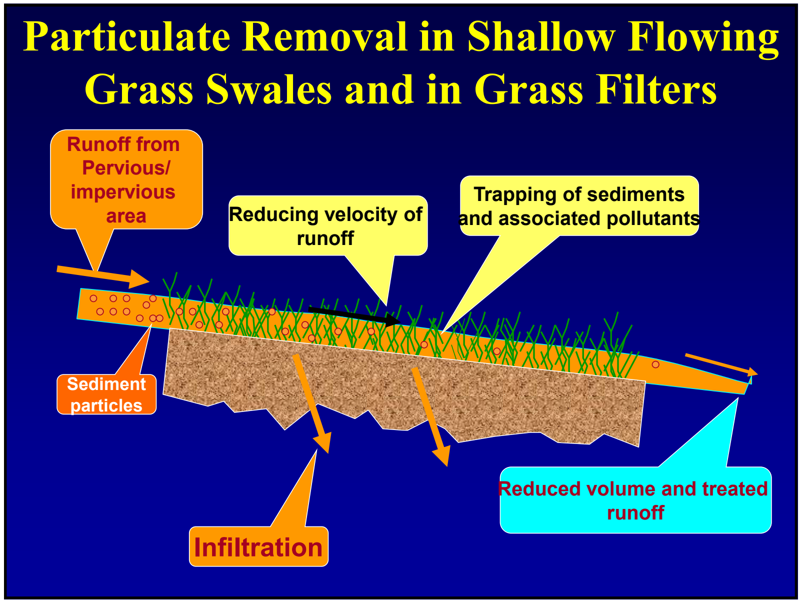


… but are not discharged at outfall (trapped at inlet or deposited in drainage pipe)

Bed load in storm drainage compromises about 4% of Madison area total solids discharges (WI DNR and USGS monitoring).

Grass Filtering of Stormwater Sediment

Typical stable grass swales (wide and shallow)



Particulate Removal in Shallow Flowing Grass Swales and in Grass Filters

Runoff from Pervious/ impervious area

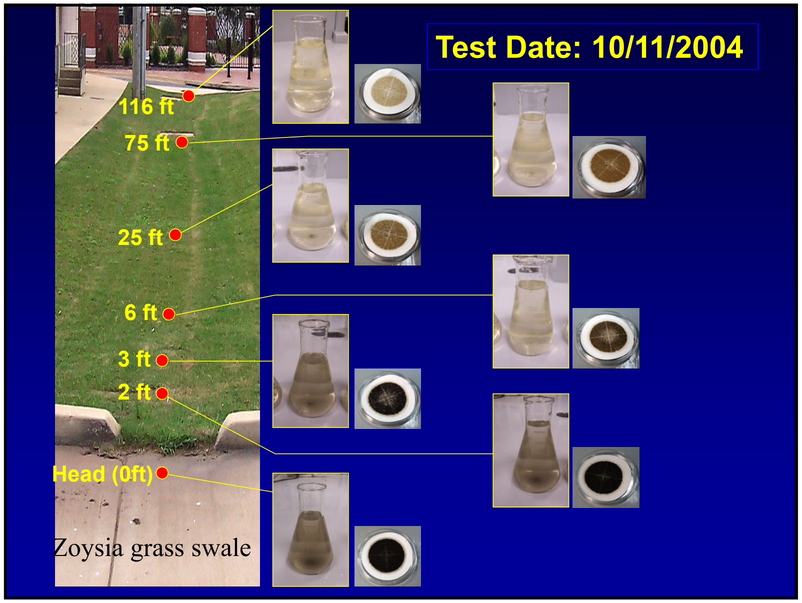
Reducing velocity of runoff

Trapping of sediments and associated pollutants

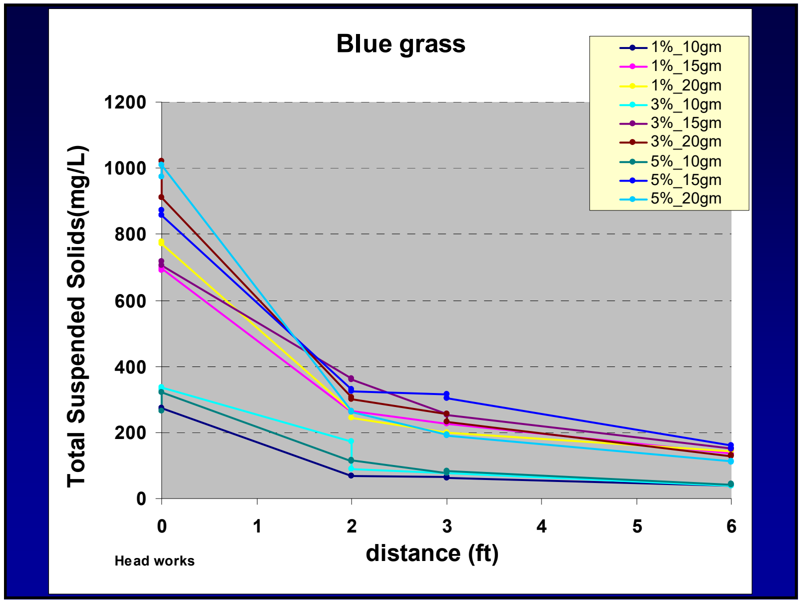
Sediment particles

Infiltration

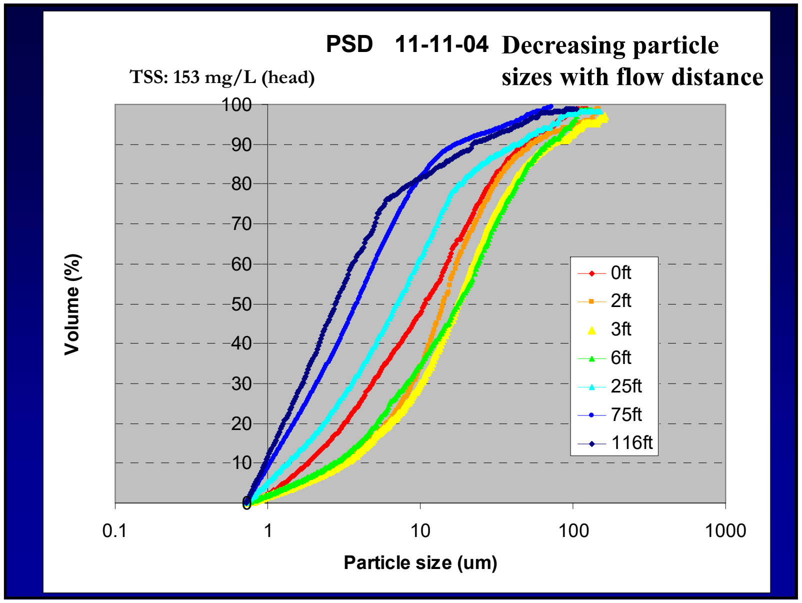
Reduced volume and treated runoff



Test Date: 10/11/2004



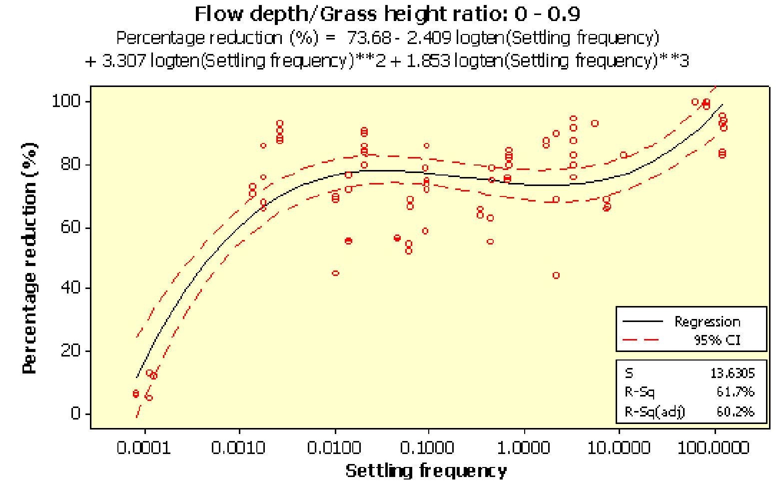
Blue grass



PSD 11-11-04 Decreasing particle sizes with flow distance

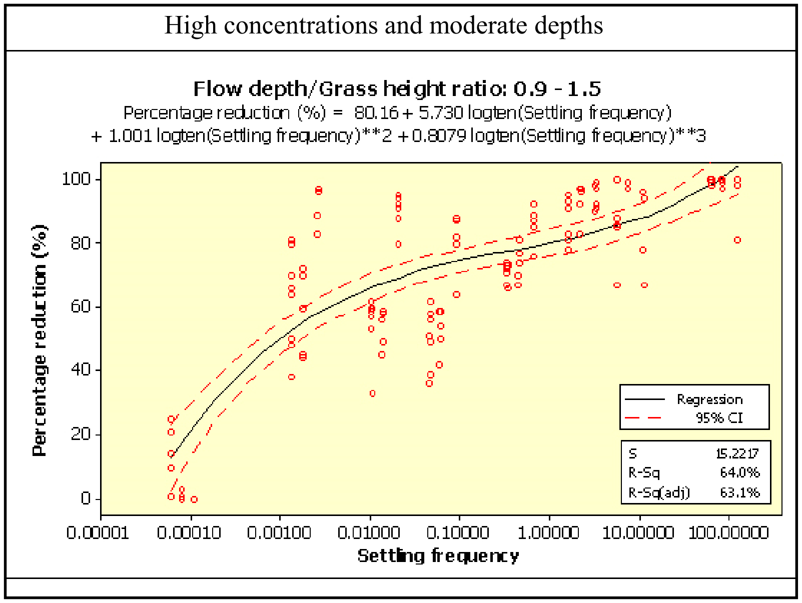
TSS: 153 mg/L (head)

Particulate trapping in grass filters (high initial concentrations and shallow flows)



Flow depth/Grass height ratio: 0 - 0.9

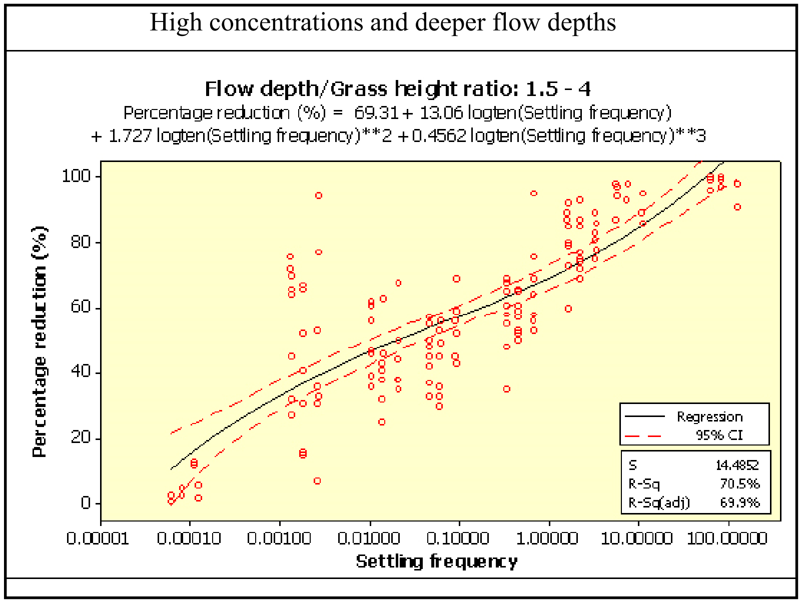
Percentage reduction (%) = 73.68 - 2.409 logten(Settling frequency) + 3.307 logten(Settling frequency)**2 + 1.853 logten(Settling frequency)**3



High concentrations and moderate depths

Flow depth/Grass height ratio: 0.9 - 1.5

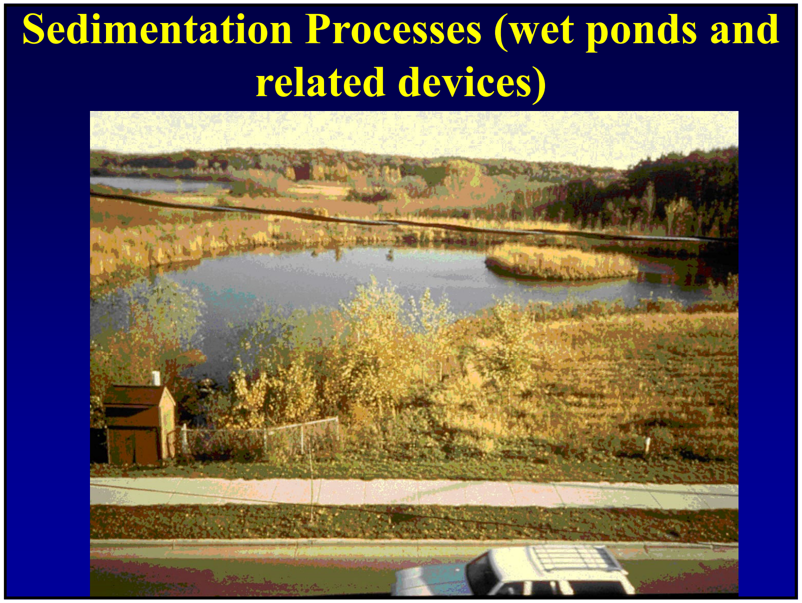
Percentage reduction (%) = 80.16 + 5.730 logten(Settling frequency)
+ 1.001 logten(Settling frequency)**2 + 0.8079 logten(Settling frequency)**3



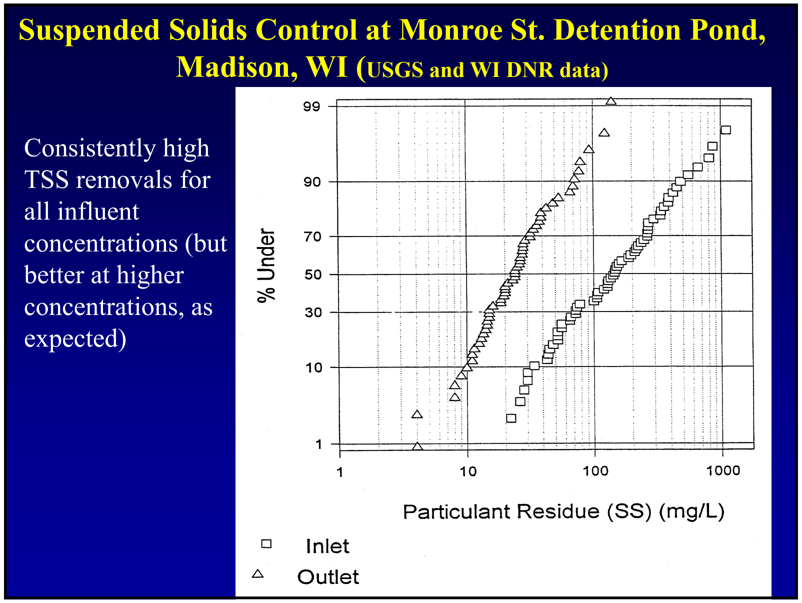
High concentrations and deeper flow depths

Flow depth/Grass height ratio: 1.5 - 4

Percentage reduction (%) = 69.31 + 13.06 logten(Settling frequency)
+ 1.727 logten(Settling frequency)**2 + 0.4562 logten(Settling frequency)**3



Sedimentation Processes (wet ponds and related devices)

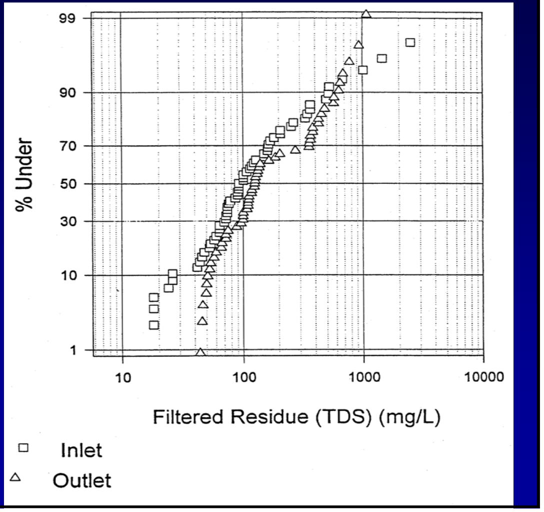


Suspended Solids Control at Monroe St. Detention Pond, Madison, WI (USGS and WI DNR data)

Consistently high TSS removals for all influent concentrations (but better at higher concentrations, as expected)

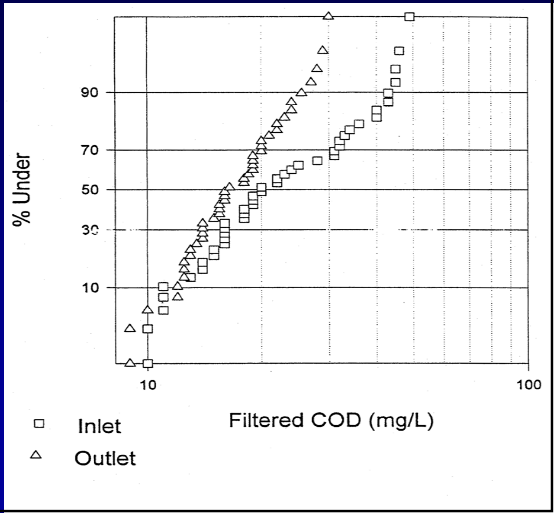
Total Dissolved Solids Control at Monroe St. Detention Pond, Madison, WI (USGS and WI DNR data)

Poor TDS removals under all conditions, as expected. Some TDS export associated with earlier snowmelt influences (high effluent TDS up to four months after snowmelt)



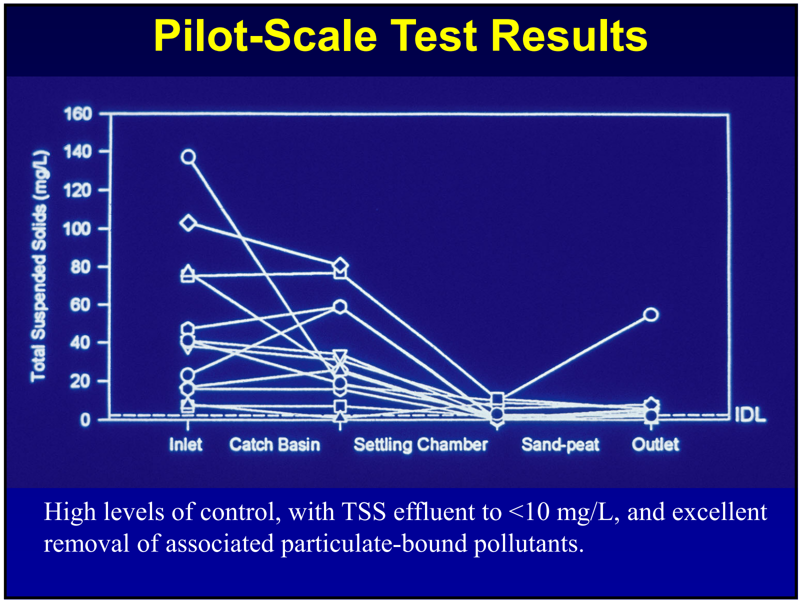
Dissolved COD Control at Monroe St. Detention Pond, Madison, WI (USGS and WI DNR data)

Unexpected dissolved organic matter removal in pond, especially if high influent concentrations. This reflects bio/chemical processes also occurring in pond to supplement physical settling processes.



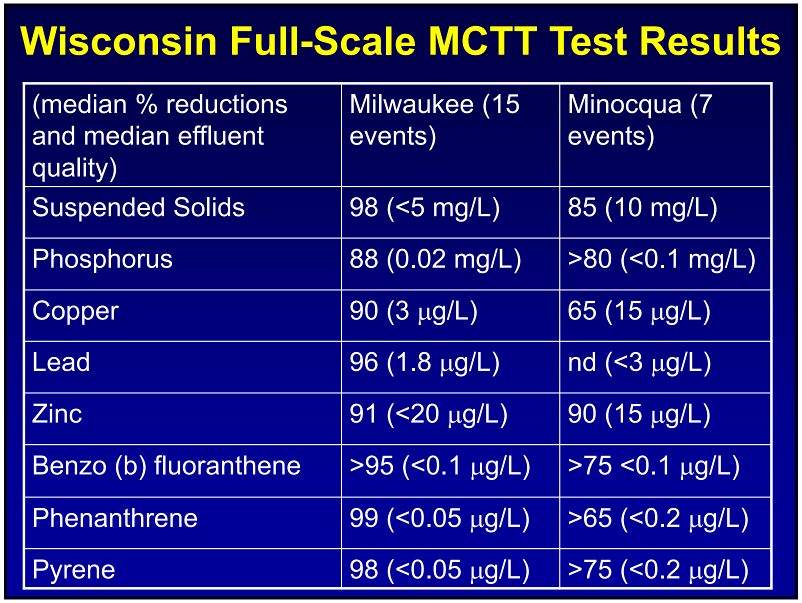
MCTT (Multi-chambered treatment train) incorporates many complementary removal processes, besides sedimentation (grit removal, fine sediment removal, gross floatable trapping, free oil sorption, ion exchange, etc.) This underground MCTT in Minocqua, WI.

MCTT Main Settling Chamber at Minocqua, WI



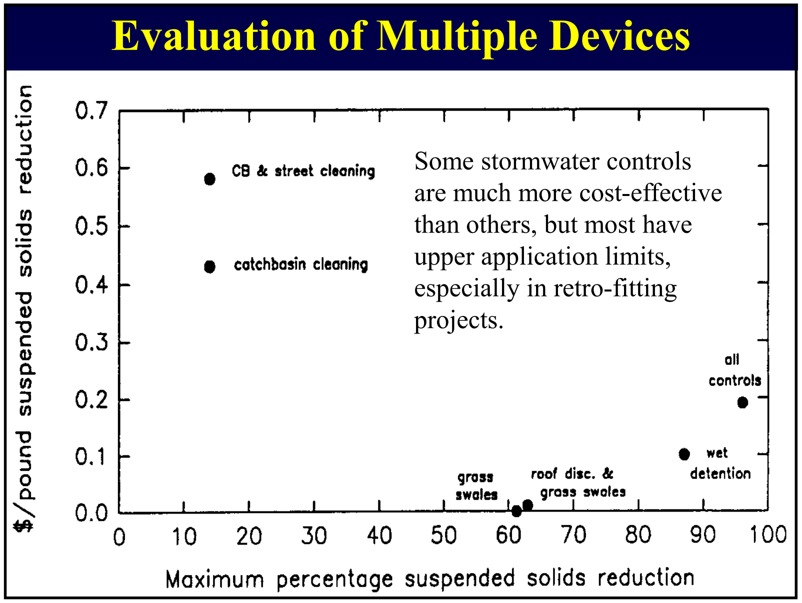
Pilot-Scale Test Results

High levels of control, with TSS effluent to <10 mg/L, and excellent removal of associated particulate-bound pollutants.



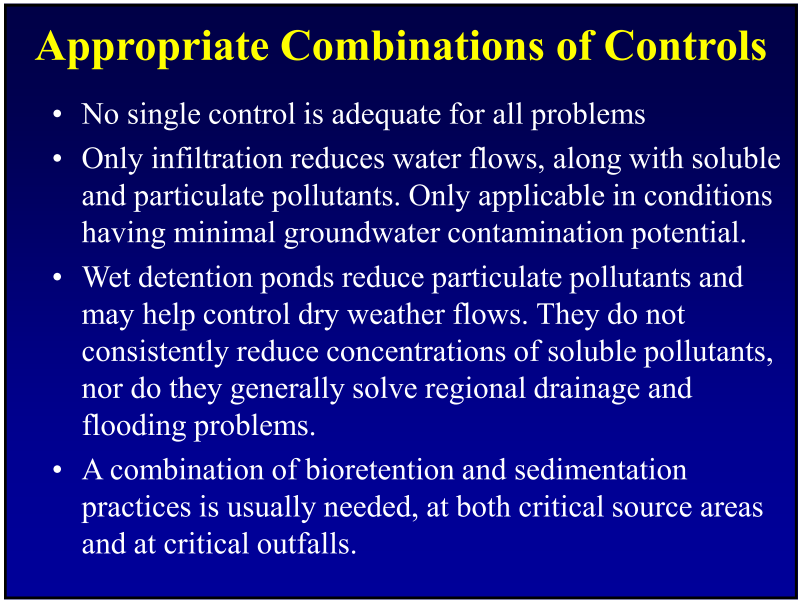
Wisconsin Full-Scale MCTT Test Results

(median % reductions and median effluent quality)	Milwaukee (15 events)	Minocqua (7 events)
Suspended Solids	98 (<5 mg/L)	85 (10 mg/L)
Phosphorus	88 (0.02 mg/L)	>80 (<0.1 mg/L)
Copper	90 (3 μg/L)	65 (15 μg/L)
Lead	96 (1.8 μg/L)	nd (<3 μg/L)
Zinc	91 (<20 μg/L)	90 (15 μg/L)
Benzo (b) fluoranthene	>95 (<0.1 μg/L)	>75 <0.1 μg/L)
Phenanthrene	99 (<0.05 μg/L)	>65 (<0.2 μg/L)
Pyrene	98 (<0.05 μg/L)	>75 (<0.2 μg/L)



Evaluation of Multiple Devices

Some stormwater controls are much more cost-effective than others, but most have upper application limits, especially in retro-fitting projects.



Appropriate Combinations of Controls

- No single control is adequate for all problems
- Only infiltration reduces water flows, along with soluble and particulate pollutants. Only applicable in conditions having minimal groundwater contamination potential.
- Wet detention ponds reduce particulate pollutants and may help control dry weather flows. They do not consistently reduce concentrations of soluble pollutants, nor do they generally solve regional drainage and flooding problems.
- A combination of bioretention and sedimentation practices is usually needed, at both critical source areas and at critical outfalls.

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 and are optimistic in control effectiveness.