Monitoring Critical Source Area Stormwater Controls

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Issues Concerning Stormwater that May Need to be Addressed

- Rainfall patterns must be considered for area being studied, and accurate flow measurements are necessary as performance is commonly related to hydraulic conditions. Most flow instruments must be calibrated at the site.
- The variability of stormwater quality must be considered when designing a sampling program.
- Incorrectly reported data can have a very large effect on many statistical analyses
- Variability of stormwater quality does not always vary as anticipated ("first-flush" relatively rare, unless mostly paved areas and small drainage areas; little relationship with rain depth of event; high concentrations likely associated with periods of high rain intensities)
- Sources of flows and pollutants vary with land use and development characteristics

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Probability distribution of rains (by count) and runoff (by depth).

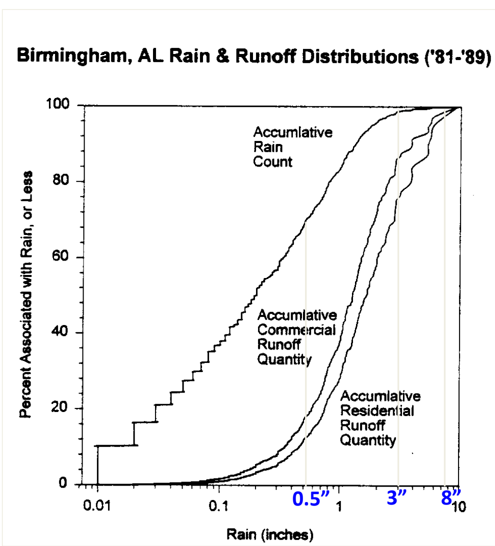
Central Alabama Rain Condition:

<0.5": 65% of rains (10% of runoff)

0.5 to 3": 30% of rains (75% of runoff) We therefore need to focus on these rains!

3 to 8": 4% of rains (13% of runoff)

>8": <0.1% of rains (2% of runoff)



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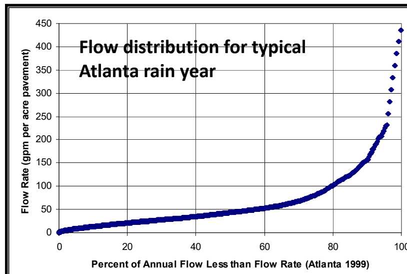

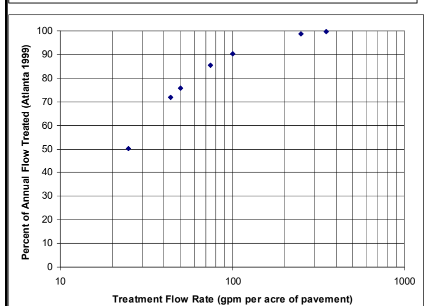

Continuous Simulation can be used to Determine Needed Treatment Flow Rates:

- 90% of the annual flow for SE US conditions is about 170 gpm/acre pavement (max about 450).

- treatment of 90% of annual runoff volume would require treatment rate of about 100 gpm/acre of pavement. More than three times the treatment flow rate needed for NW US.

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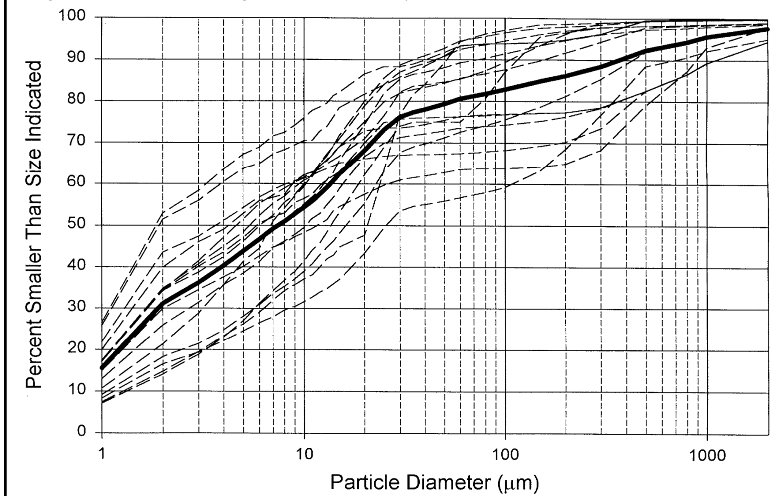
Measured Particle Sizes, Including Bed Load Component,
at Monroe St. Detention Pond, Madison, WI

Long term outfall monitoring (with bedload samplers) show bedload about 10% of annual mass



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

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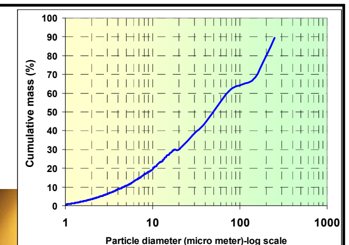
Particulate transport across grass directly monitored in controlled greenhouse studies



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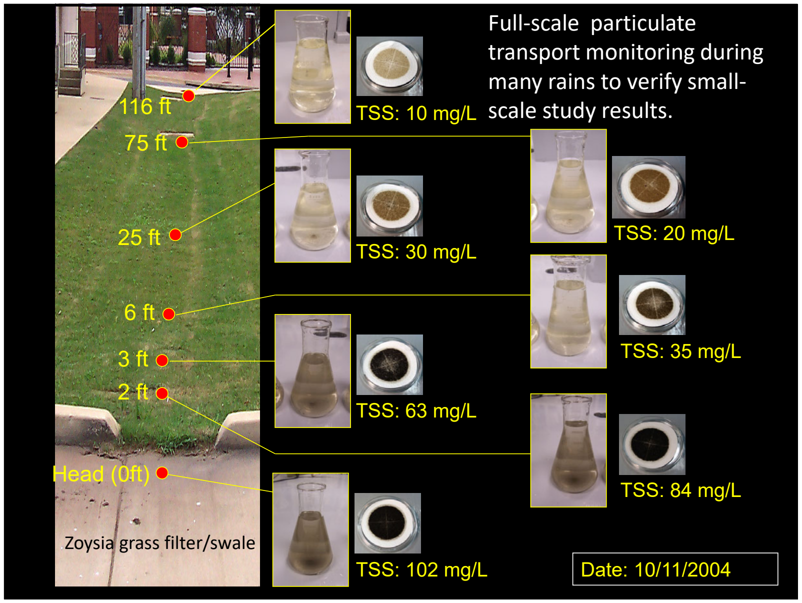

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Velocity and shear stress for different slopes and depths (2 ft pipe)

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 particles >100 µm to settle and form permanent deposits, while pipes with large slopes will likely have moving beds of larger material.

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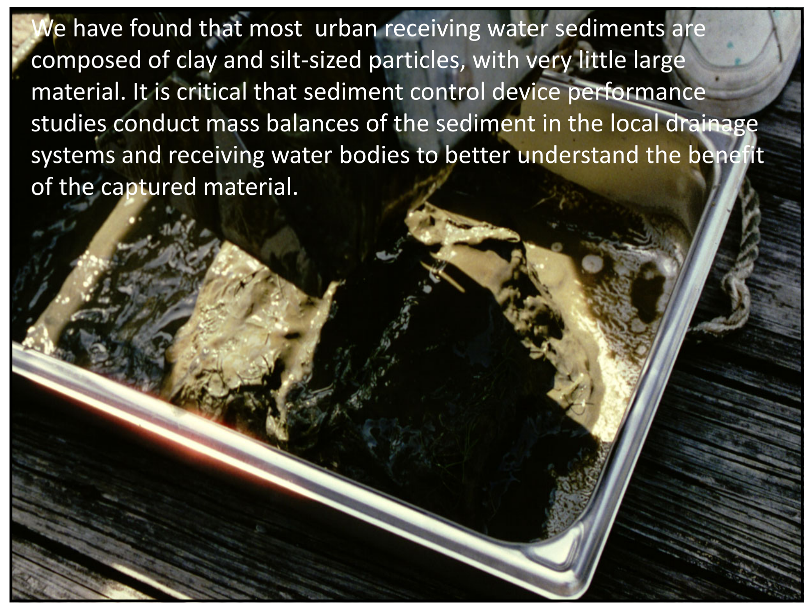

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Stormwater Sampling

- Important to monitor sources, transport, and fate of stormwater pollutants.
- Need to program automatic samplers to collect samples under a wide-range of flow conditions and to locate their intakes in a completely mixed turbulent flow (such as in a water cascade).
- Need to supplement automatic samplers with bed-load samples and/or conduct complete mass balance of captured material in a stormwater control device.

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Many types of runoff monitoring have been used to understand their transport and fate, from small source areas to outfalls.

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Many stormwater monitoring configurations used over the years, including permanent refrigerated units, discrete samplers, and composite samplers

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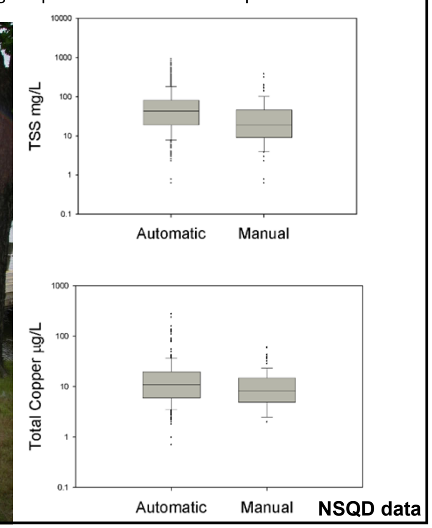
May have small biases with automatic vs. manual sampling, but automatic sampling allows unattended operation under a variety of conditions and captures complete event. Manual sampling can better represent complete range of particulate matter in sample.



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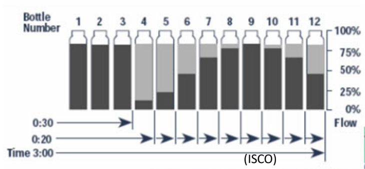
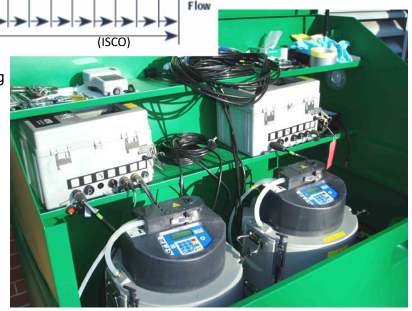
It is difficult to program an automatic sampler to collect flow-weighed samples over a wide range of flow conditions.



use a large sample base in order to accommodate a wide range of runoff events

use time-compositing instead of flow-weighted sampling and then manually composite the sample using the available flow data



use two samplers located at the same location, one optimized for small events, the other optimized for larger events

Special Sampling and Sample Handling Needs – solids handling and processing

- A wide range of sample characteristics need to be considered in a sampling program
- Automatic samplers are not effective in collecting large particles; recovery of particles >250 and <1200 µm is usually about 50%, while they are close to 100% effective for particles <100 µm.
- In most cases, the actual errors in annual mass discharges are <10%. However, complete mass balances need to be done as part of control practice monitoring to quantify the errors and to identify the large particle fraction.
- Particle size information is one of the most important stormwater characteristics affecting treatability, transport, and fate.
- Cone splitters need to be used to divide samples for analyses and SSC (suspended sediment concentration) should be used instead of TSS for the most repeatable results.
- Discrete particle size pollutant analyses on different particle sizes can also be important for treatability and fate analyses.

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

USGS and WI DNR Monitoring Facility for Hydrodynamic Separator Tests, Madison, WI

Results of Verification Monitoring of Hydrodynamic Separator (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 by measuring captured material	536 kg (33% actual removal)
Total solids not captured by automatic samplers	131 kg out of 1623 kg missed (8%)

USGS data

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Comparison of three TSS/SSC analytical methods

	EPA TSS (160.2) ISO 11923	*Standard Methods* TSS (2540D)	USGS SSC (ASTM D3977-97(B))
Filter Nominal Pore Size	Not specified	< 2.0 µm	1.5 µm
Sample Mixing	Shake vigorously	Stir plate	Decant super-natant & flush bottle with DI
Aliquot Size	Not specified (normal 100 mL)	Not specified (normal 100 mL)	Entire sample
Method of Aliquot Collection	Pour aliquot into graduated cylinder	Pipet: mid-depth in bottle & mid-way between wall and vortex	Pour from original bottle

Tested differences between methods using samples from 0 – 500 mg/L particulate matter having two different particle size distributions (PSDs), d_{50} of 90 and 260 µm.

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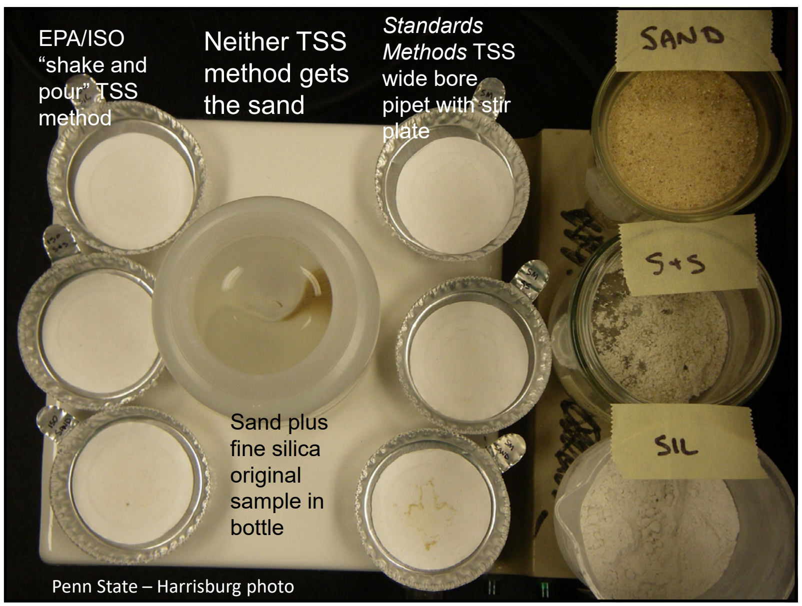

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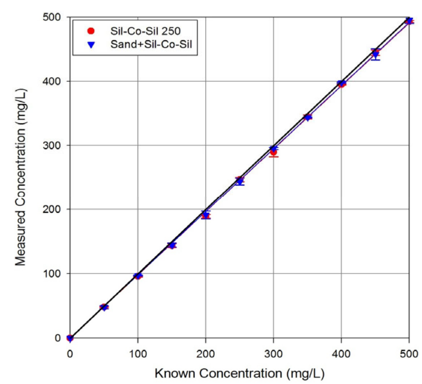
Suspended Sediment Concentrations Compared to Known Laboratory Additions



- SSC methodology closely matches known concentrations, regardless of sample concentrations or PSD.

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Sample Preparation before Particle Size Association Tests

- These tests are used to obtain concentration and particle samples associated with different particle sizes.
- Samples are first split using a cone splitter, and the individual samples are individually separated using a variety of filters and sieves.
- The filtered portion for each separated subsample is then individually analyzed and the associations are determined by difference. Sediment samples can also be examined by examining the filters, or by removing some of the captured debris from the sieves.

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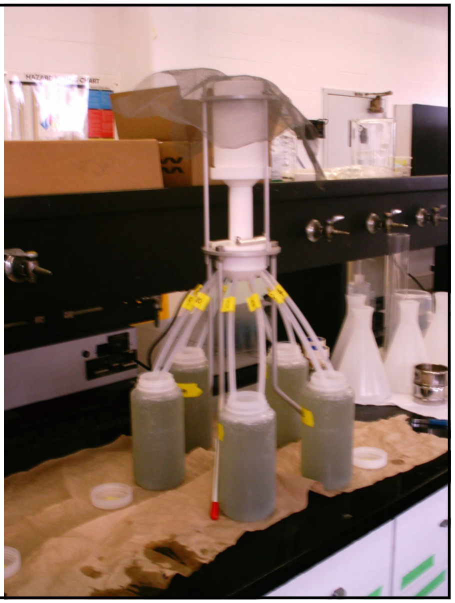
Large sample volume (about 5 L) separated into subsamples using cone splitter. The sample is first poured through a 1,200 µm screen to remove leaves and grass clippings, and coarse sediment that would clog the splitter. This captured material is also analyzed.



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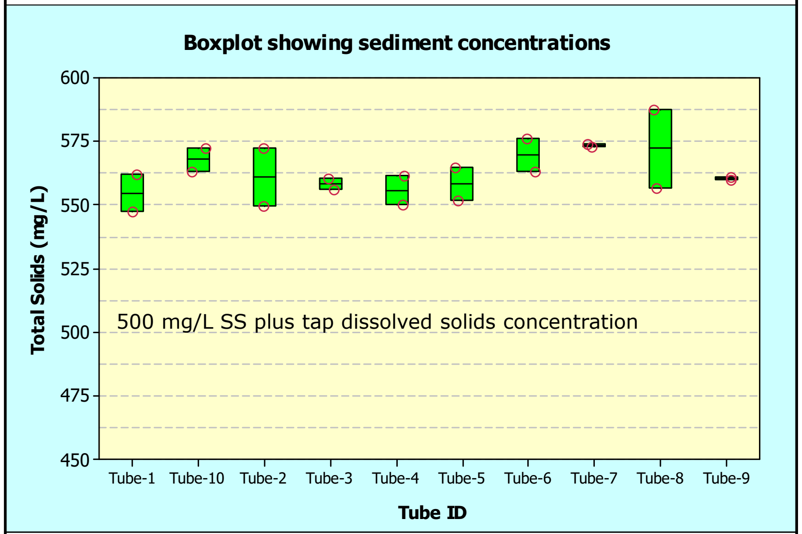

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A series of small stainless steel sieves (250, 106, 75, 45, and 20 µm) are used for the large particle fractions (filtrate is normally analyzed).

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Sample Processing before Coulter Counter Analyses

- The Coulter Counter Multi-Sizer 3 is most suitable for particles in the range of about 1 to 200 µm.
- Larger particles (especially those of about 500 µm and larger) settle to the bottom of the measurement vessel and are not kept suspended and drawn through the analytical aperture.
- Coulter recommends increasing the viscosity of the analytical solution (such as by using Karo syrup) to keep particles as large as 1,200 µm suspended. We were never pleased with this option.

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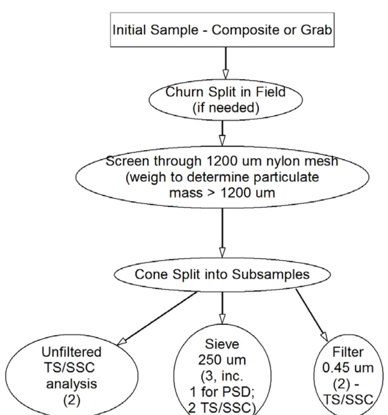
Lessons Learned: Sample Pre-Processing Protocol for Particle Size Fractionation of Samples



- With the solids analyses described above, particulate masses in the following size ranges are measured: <0.45 µm, 0.45 to 250 µm, 250 to 1200 µm, and >1200 µm.
- Replicate analysis allow for evaluation of variability in sample preparation.
- Coulter Counter uses several aperture tubes and data overlapped for very high resolution psd information.

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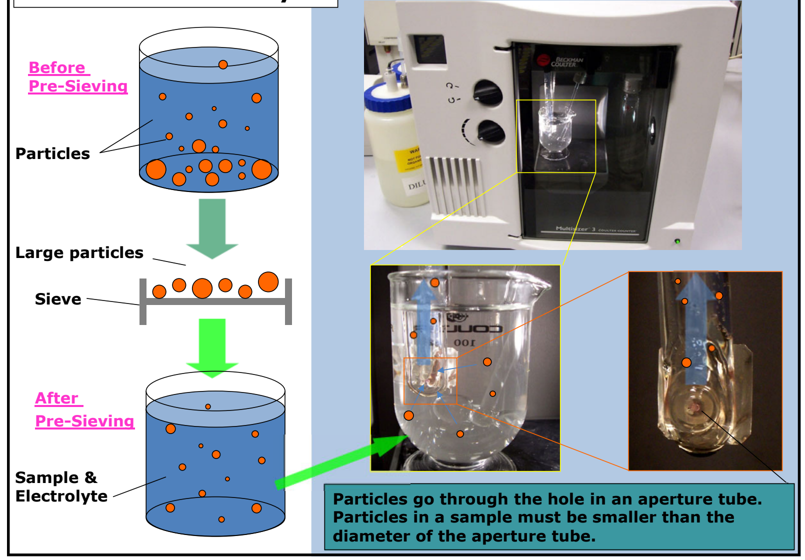
Coulter Counter analysis



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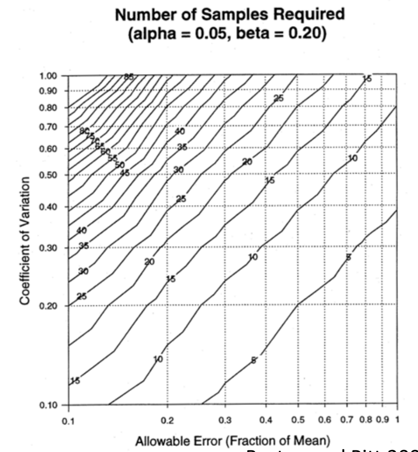
Experimental Design – monitoring to consider variability and objectives

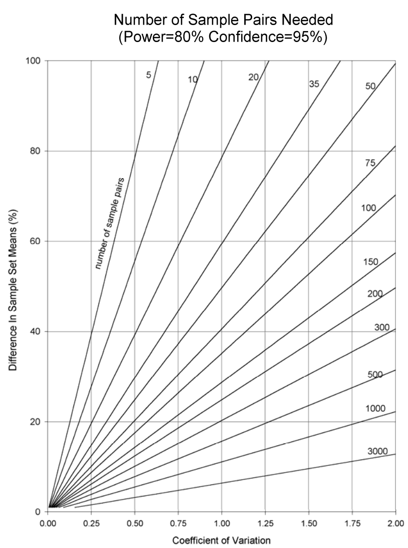
- The large variability of stormwater quality requires a major sampling effort to obtain useful data
- Experimental design equations can be used to estimate the number of samples needed to meet the data quality objectives (power analysis)

Experimental Design - Number of Samples Needed

The number of samples needed to characterize stormwater conditions for a specific site is dependent on the COV and allowable error. For most constituents and conditions, about 20 to 30 samples may be sufficient for most objectives. Most MS4 Stormwater Permit Phase 1 monitoring sites only have about 10 events, but each stratification category (land use for region of the country) usually has much more.



Burton and Pitt 2002



Experimental Design - Number of Samples Needed can be Large

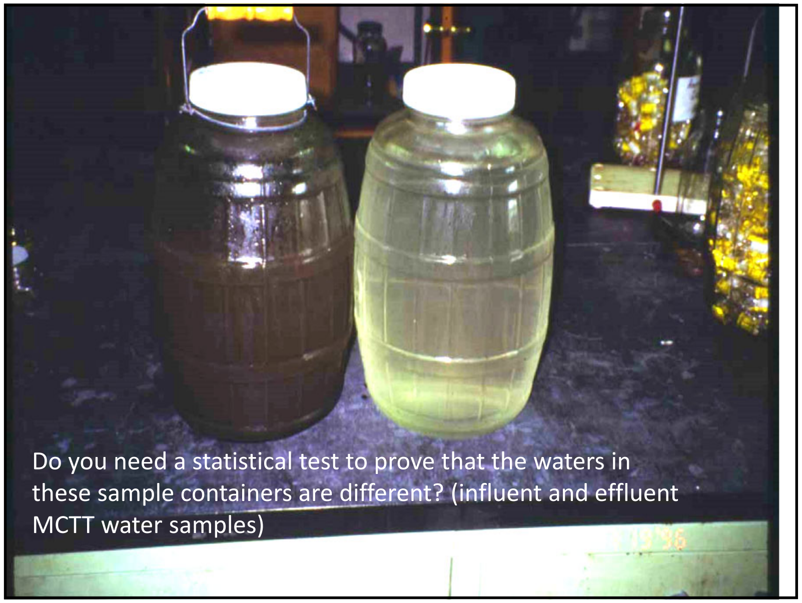
Much information will be needed to confirm performance of stormwater controls for most constituents.

Obviously, easier to confirm removals when the differences between influent and effluent are greatest. Data sets having few samples cannot detect small and moderate differences. A power analysis before the monitoring program needs to be conducted to determine the level of control that can be detected with significance and to ensure that value meets the data quality objectives for the project.

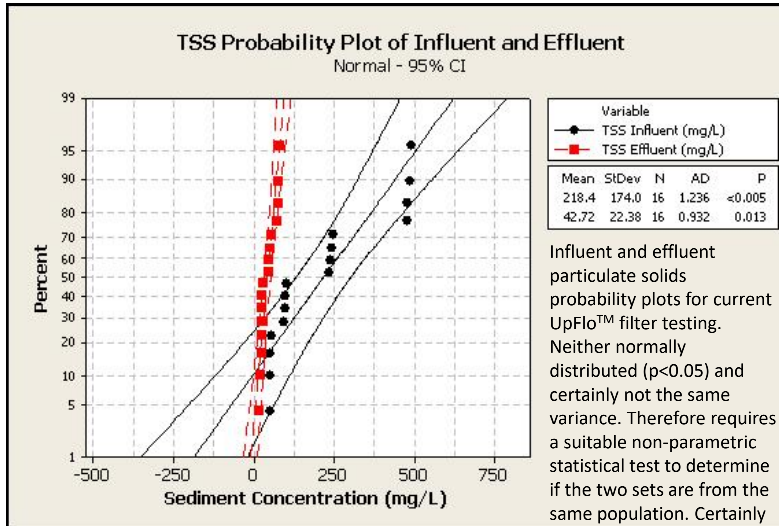
Burton and Pitt 2002

Basic Data Analyses

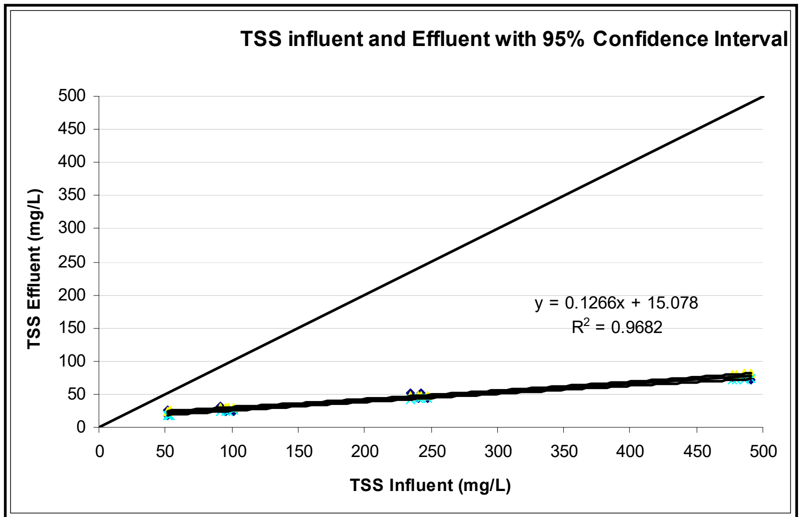
- The most common statistical data analyses for stormwater are comparisons (influent vs. effluent), characterization (for different conditions), and model building (relating effluent to influent conditions).
- Simple exploratory data analysis plots are very helpful (scatter plots, line graphs, histograms).
- Probability analyses are very important to compare the data sets directly and to help select the best and correct statistical tests
- ANOVA and residual analyses must be conducted with regression analyses to verify that the test assumptions have been met.



Do you need a statistical test to prove that the waters in these sample containers are different? (influent and effluent MCTT water samples)



Influent and effluent particulate solids probability plots for current UpFlo™ filter testing. Neither normally distributed ($p<0.05$) and certainly not the same variance. Therefore requires a suitable non-parametric statistical test to determine if the two sets are from the same population. Certainly doesn't look it, but need the numbers!



Scatter plot with calculated regression line and 95% confidence interval (very narrow 95% confidence interval because of consistent performance of the UpFlo™ filter, sufficient numbers of samples, and repeatable sampling and analytical methods).

ANOVA to verify that the equation coefficients are significant (if not, then must remove the offending coefficient and re-analyze) and to ensure that the total equation is significant. In this case, both coefficients and the equation are all highly significant, with each $p<0.001$)

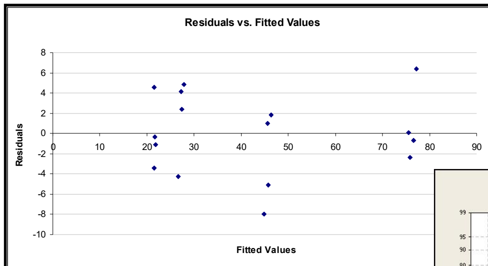
SUMMARY OUTPUT

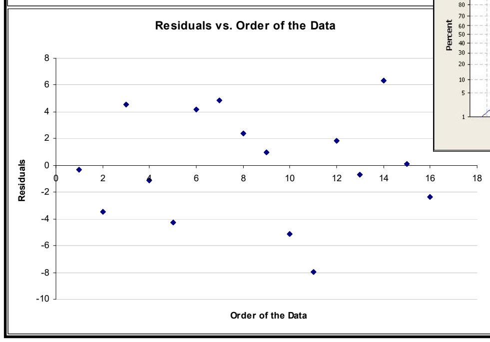
Regression Statistics	
Multiple R	0.984
R Square	0.968
Adjusted R Square	0.966
Standard Error	4.132
Observations	16

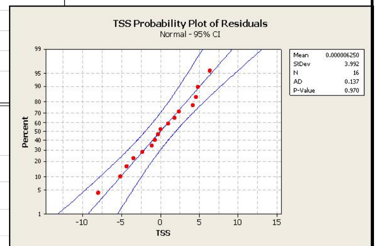
ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	7275.225	7275.225	426.021	0.000
Residual	14	239.080	17.077		
Total	15	7514.305			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 90.0%*	*Upper 90.0%*
Intercept	15.078	1.691	8.914	0.000	11.450	18.706	12.099	18.057
X Variable 1	0.127	0.006	20.640	0.000	0.113	0.140	0.116	0.137







Must check residual behavior to verify that they are random against the fitted values and the order of the data collection, and that they are normally distributed.

The Anderson-Darling test shows that the residuals are normally distributed (p>0.05), and the scatterplots of the residuals appear to be random.

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Development of the Up-Flo™ Filter

- Filter and soil amendment research at the University of Alabama (with the help of many graduate students), funded by the EPA in the early 1990s, examined many alternative media and systems, and found that clogging by particulates and debris greatly hindered long-term performance. Anaerobic conditions in the media was also found to cause serious operational problems. Different media can be used to target specific groups of pollutants and can be effectively used in conjunction with other treatment operations.
- Further stormwater treatability research funded by the EPA resulted in the Multi-Chambered Treatment Train (MCTT) (in the public domain) which provides excellent treatment of stormwater and was intended for pretreatment of stormwater from critical source areas before infiltration.
- EPA Small Business Innovative Research (SBIR) funding was obtained in the early 2000s to develop and commercialize an advanced stormwater treatment device that would provide acceptable levels of treatment at a high-rate of stormwater flow. As part of this SBIR series of projects, Pitt and colleagues developed and patented the Up-Flow filter and Hydro International developed a commercial product.

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Basic Monitoring Strategy

- Scale-up of monitoring from pilot to full-scale control devices
- Need flexibility of small units and control to test many variables under large variety of conditions
- Need to verify with full-scale units to check performance under real-world conditions

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Different Pilot-Scale Treatment Setups

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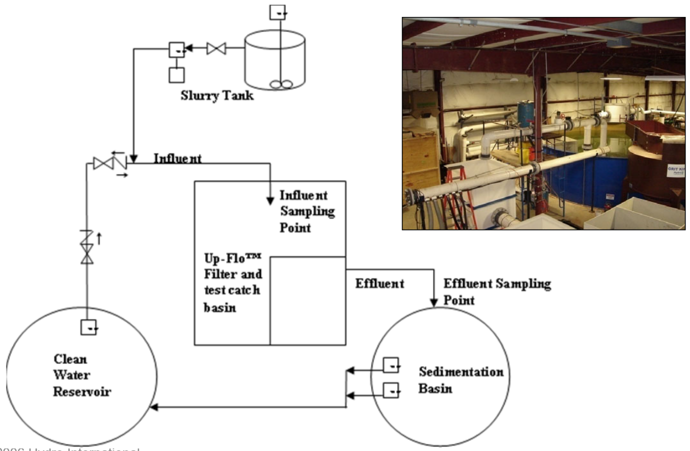
Hydro International, Full-Scale Laboratory Testing Set-Up, Portland, Maine



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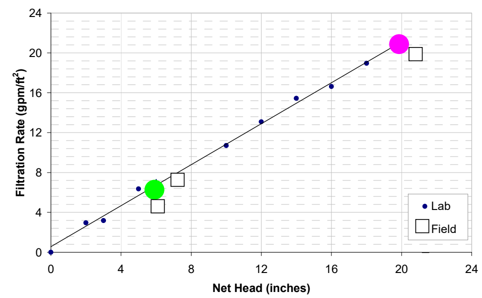
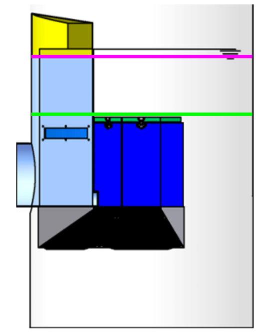
Comparison of Laboratory and Field Flow Measurements (CPZ Mix™ Filter Media)





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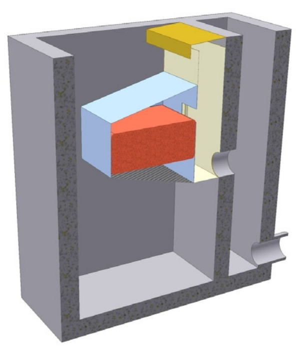
Important Attributes of Upflow Filtration Systems

- Should have features of multiple unit processes in a treatment train
  - Screening, Settling, Filtration, Absorption/ion-exchange , etc.
- Incorporate a Sump
- Should use non-leaching media
- Media should be restrained
- Should prevent anaerobic conditions in media (i.e., drain down between events)
- Should be readily accessible for maintenance
- Should have overflow bypass capacity to prevent upstream flooding
- Have retrofit capabilities



Schematic of pilot-scale unit

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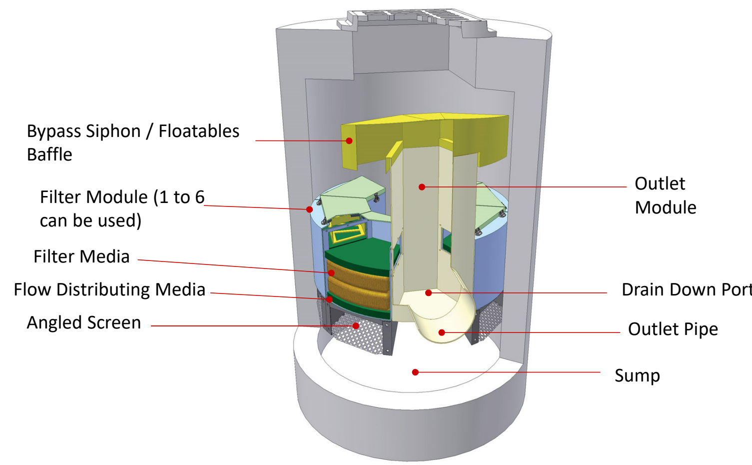
Full-Scale Up-Flo™ Filter Chamber Components



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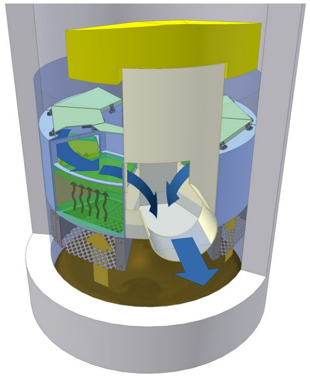
Multiple Treatment Methodologies

- **Chamber** – Retains floatables and trash
- **Angled Screens** – Deflects neutrally buoyant material from media interface
- **Sump** – Stores coarse grit and gross debris
- **Filter media – high rate of flow due to partial bed expansion of contained media:**
  - Fine sediment
  - Hydrocarbons
  - Metals
  - Organics (pesticides, herbicides)
  - Nutrients (particulate phosphorus)



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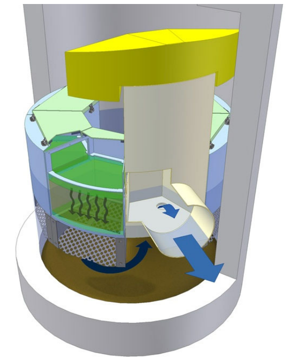
Back Flush and Drain Down

- Siphon drain down lowers the standing water level to the height of the outlet invert between runoff events
- Ensures that filter media sits above the standing water level between storm events, minimizing anaerobic conditions
- Minimizes media deterioration
- Guards against bacterial growth and pollutant re-release
- Debris “falls away” from the media and screen



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Pilot-Scale Field Monitoring

- Data collected through extensive field testing by the University of Alabama
- No chemical exhaustion of media after 12 months of field testing
- Greater than 70% removal of particulate metals & nutrients and fine SSC in filter and another 10% capture of SSC in the sump
- SSC removal down to 1 micron particles

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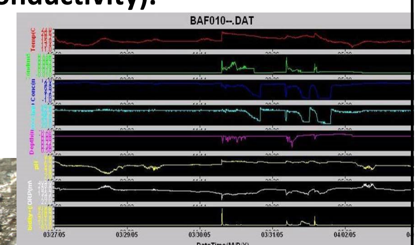
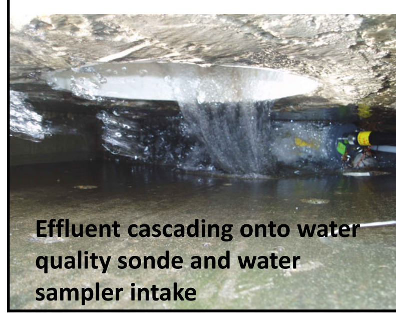
The use of continuous water quality sondes can supplement other sampling programs by providing high resolution data for a variety of constituents (turbidity, temperature, DO, ORP, and conductivity).





Effluent cascading onto water quality sonde and water sampler intake

Sonde data analysis screen showing ten days of high-resolution (every 15 minute) water quality measurements

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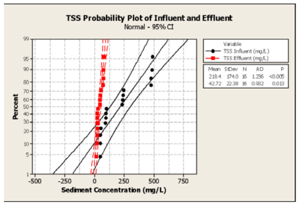
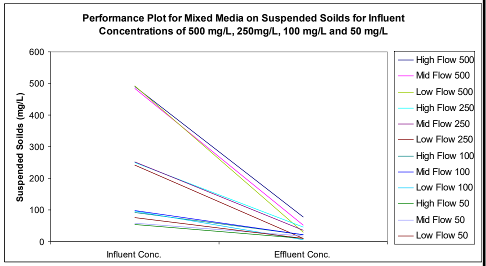
Pilot-Scale Tests, Controlled and 10 Months of Actual Runoff Events

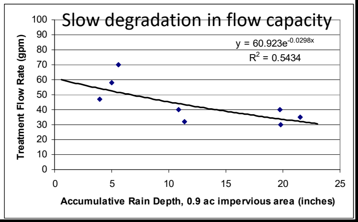
Flow rate has very little effect on effluent quality. Effluent quality is relatively constant over broad range of influent concentrations and flows.





Performance during actual rains over a 10 month monitoring period:

particle size range (µm)	SS influent mass (kg)	SS effluent mass (kg)	SS removed (kg)	% reduction
0.45-3	9.3	2.8	6.6	71
3-12	18.7	6.4	12.3	66
12-30	22.4	7.7	14.7	66
30-60	26.7	6.8	19.9	75
60-120	4.6	1.8	2.9	63
120-250	19.8	4.3	15.5	78
250-425	11.5	0.0	11.5	100
425-850	17.1	0.0	17.1	100
850-2,000	10.5	0.0	10.5	100
2,000-4,750	4.8	0.0	4.8	100
>4,750	3.5	0.0	3.5	100
sum	148.9	29.8	119.2	80



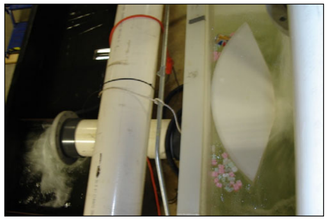
Performance Verification

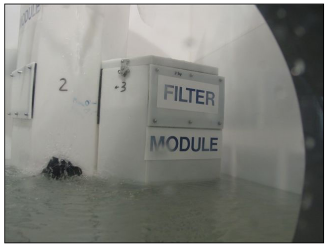
- Field testing of Full-Scale Up-Flo™ prototype
- CFD Verification
- Lab testing at Hydro International
- Verification under the EPA's ETV Program

Conclusions of the Laboratory Verification:

- Laboratory hydraulic measurements compare well with in-field hydraulic measurements
- Filtration rate of 12 to 25 gpm per Filter Module (75 to 150 gpm per 4-ft manhole system)
  - Upflow filtration is a higher-rate filtration alternative to surface filtration such as down-flow and radial-flow
- >85% removal Sil-Co-Sil 106 at 25 gpm per Filter Module
  - ~90% removal of all particles > 20 microns

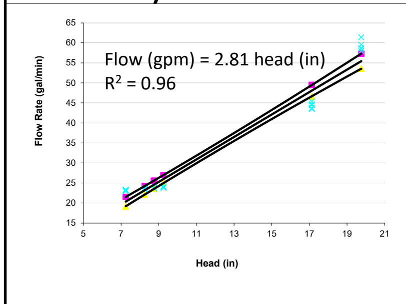
During our EPA tests, we have found that upflow filtration provides a high degree of SSC removal at high filtration rates due to partial bed expansion and retains a high flow rate capacity due to draindown between events.

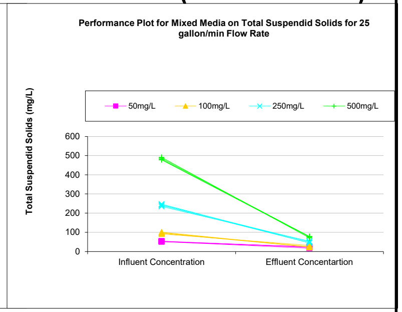




Current Full-Scale Setup in Tuscaloosa, AL

Preliminary Results of Full-Scale Field Installation (controlled tests)





25 gallon/min Flow Rate and 100 mg/L Conc.

Particle Size (µm)	Influent Conc. (mg/L)	Effluent Conc. (mg/L)	Reduction (%)
< 0.45	220	160	27
0.45 to 3	5.2	1.1	78
3 to 12	19	11	38
12 to 30	26	8.3	68
30 to 120	16	1.3	92
120 to 1180	28	0.18	99
> 1180	5.7	0	100
sum >0.45 µm	99	21.9	78

25 gallon/min Flow Rate and 500 mg/L Conc.

Particle Size (µm)	Influent Conc. (mg/L)	Effluent Conc. (mg/L)	Reduction (%)
< 0.45	240	120	49
0.45 to 3	26	3.2	88
3 to 12	92	32	65
12 to 30	130	28	79
30 to 120	81	3.9	95
120 to 1180	142	0.55	100
> 1180	30	0	100
sum >0.45 µm	500	67.7	86

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Conclusions

- The UpFlo™ filter has been tested in the laboratory and in the field, both in pilot-scale and full-scale situations.
- Performance tests under the different scales and conditions have been found to be quite repeatable.
- The use of multiple and complementary unit processes results in good removal in a small foot-print.

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Conclusions (cont.)

- There have been many stormwater monitoring strategies used over the years and we have learned a great deal about stormwater characteristics. It is possible to select a suitable approach based on the monitoring objectives, and to understand the limitations of the method.
- Automatic samplers are highly efficient for particles up to about 100 µm (and need to be located in well-mixed location, such as cascading water), while their recovery of larger particles may be about 50% (up to 1200 µm). Automatic samplers need to be supplemented with bed load samplers and/or mass balance analyses to quantify the large particle fraction in the water.
- Basic data analyses are easy to perform, but care must be taken to ensure that the methods used are appropriate.

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