Day 4: Other Stormwater Sampling Methods: Sediment Transport and Rainfall and Flow Monitoring

Mostly excerpted from:
Burton, G.A. Jr., and R. Pitt. *Stormwater Effects Handbook: A Tool Box for Watershed Managers, Scientists, and Engineers*. CRC Press, Inc., Boca Raton, FL . 2002. 911 pages
Freely available at:
http://unix.eng.ua.edu/~rpitt/Publications/BooksandReports/Stormwater%20Effects%20Handbook%20by%20%20Burton%20and%20Pitt%20book/MainEDFS_Book.html

Plus excerpts from various research projects

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

Other Stormwater Sampling Methods

- Sediment and trash transport in urban infrastructure
- Rainfall monitoring
- Flow monitoring
- Receiving water monitoring

Sediment and Trash Transport in Urban Infrastructure

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

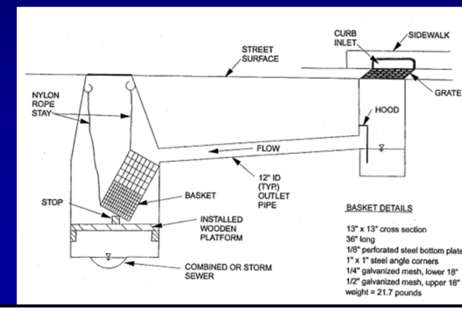
Coarse Floatable Control and Monitoring Important in Many Areas

5

Floatable Litter Sampling

- Litter discharges from stormwater inlets can be captured and measured using baskets that are inserted in manholes below catchbasins
- The baskets are made of mesh and were 13 inches square and 36 inches high. The lower half of the baskets were made of ¼ inch mesh, while the upper half were of ½ inch mesh.
- The baskets were positioned on a wooden platform just beneath the catchbasin outlet pipe and were held in place with ropes, allowing removal without requiring entry into the manholes.

The baskets need to be checked/reviewed frequently (after each storm) to prevent clogging and/or degradation of the debris by water flowing through the captured material.



6

Bed-Load Samplers

- Bed load is the material that travels in almost continuous contact with the stream bed.
- The simplest bed load samplers are box or basket samplers which are containers having open ends facing upstream.
- Bed load material bounces and rolls into the sampler and is trapped.
- Other types of bed load samplers consist of containers set into the sediment with slot openings about flush with the sediment surface.

7

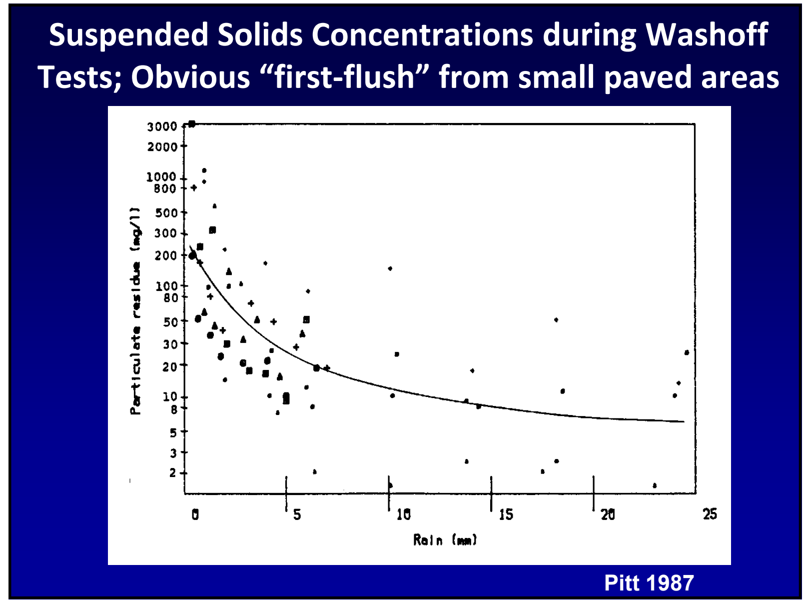
7

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

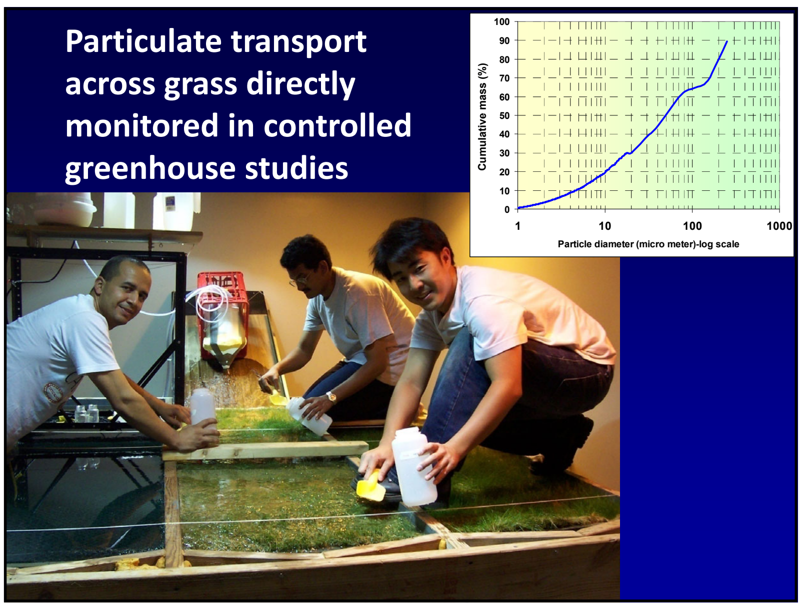
8


Street dirt washoff and runoff test plot, Toronto
Pitt 1987

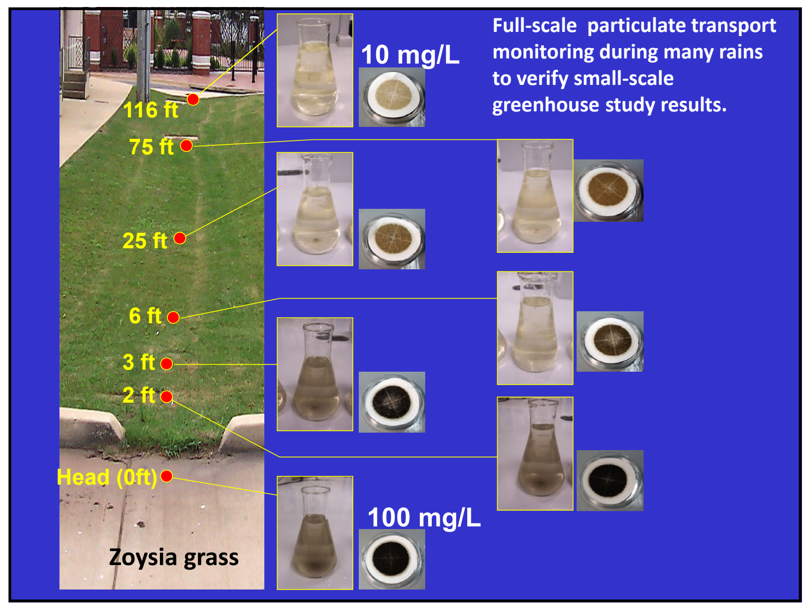
9


Suspended Solids Concentrations during Washoff Tests; Obvious “first-flush” from small paved areas
Particulate residue (mg/l)
Rain (mm)
0
5
10
15
20
25
Pitt 1987

10


Particulate transport across grass directly monitored in controlled greenhouse studies
Cumulative mass (%)
Particle diameter (micro meter)-log scale

11


Full-scale particulate transport monitoring during many rains to verify small-scale greenhouse study results.
10 mg/L
116 ft
75 ft
25 ft
6 ft
3 ft
2 ft
Head (0ft)
100 mg/L
Zoysia grass

12

Other Sources of Sediment to Monroe St. Storm Sewer

13

Bank instability and habitat destruction due to increased flows

14

Scour of Captured Sediment in Storm Drain Catchbasin Inlets

- Three flow rates: 10, 5, and 2.5 LPS (160, 80, and 40 GPM)
- Velocity measurements (Vx, Vy, and Vz)
- Five overlying water depths above the sediment: 16, 36, 56, 76, and 96 cm

- 155 total points per test
- 30 velocity measurements at each point

15

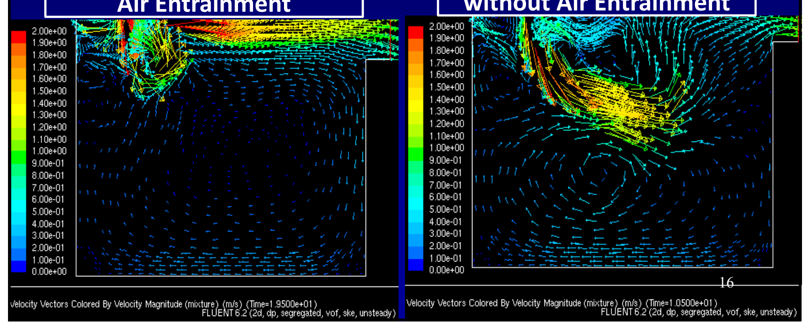
15

CFD Modeling to Calculate Scour/Design Variations

- Used CFD (Fluent 6.2 and Flow 3D) to determine scour from stormwater controls; results being used to expand WinSLAMM analyses after verification with full-scale physical model
- This is an example of the effects of the way that water enters a sump on the depth of the water jet and resulting scour

Calibrated CFD Model with Air Entrainment

Uncalibrated CFD Model without Air Entrainment

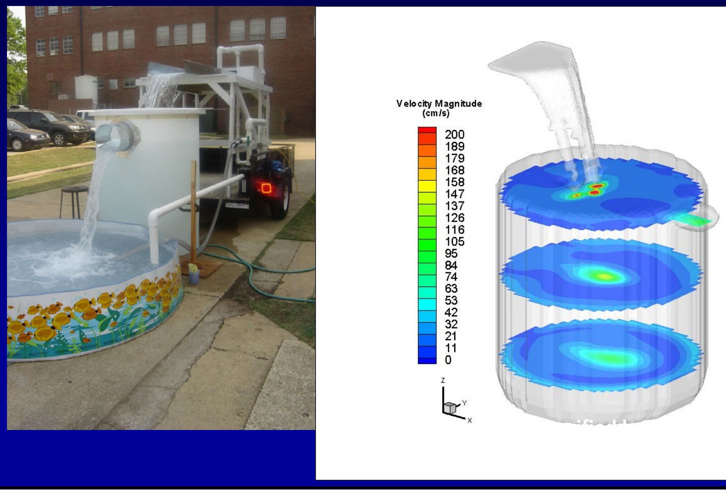


16

16

Physical and 3D-CFD Modeling

Scour tests of previously deposited sediment in sumps



17

Experimental Description: *Scour Tests*

Installation of blocks to set the false bottom

Measuring of depth below the outlet

Cone Splitter and Sample Bottles

False bottom sealed on the border

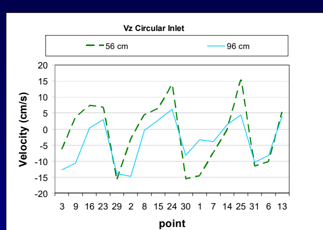
Performing scour test

Sediment bed after test

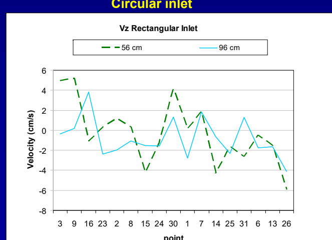
Leveling of sediment bed: 20 cm thick

18

Hydrodynamic Tests Results: *z-velocities at different elevations*

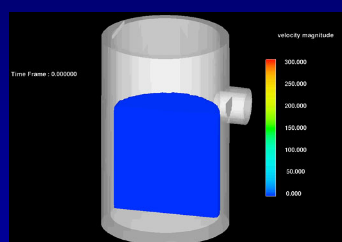


Circular inlet



Rectangular inlet

- The plunging water jet does not directly affect the flow at deeper locations.
- Velocity magnitudes are reduced in deeper water due to turbulent dispersion.
- Buoyancy generated in the impacting zone by the air entrainment also reduces the impacting effect.
- Secondary flows are responsible for the shear stress magnitudes in deeper water.

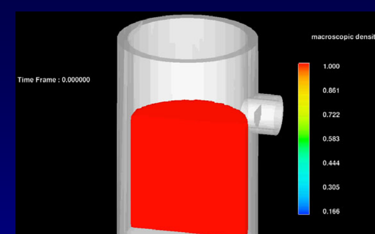


Simulation: Rectangular inlet, 10 LPS
Colors represents Velocity magnitude (On calibration process).

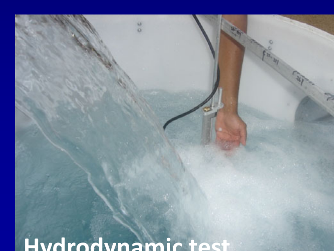
19

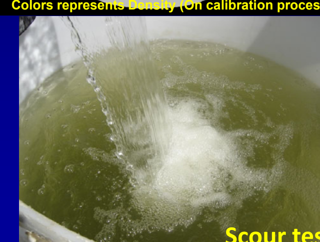
Hydrodynamic Tests Results: *Air entrainment effect*

- Observations during the test showed that the air entrainment reduces the impacting effect of the plunging water jet.
- Air bubbles creates an ascending velocity component due to buoyancy.
- Air entrainment must be included for calibration and simulation of sediment scour.



Simulation: Rectangular inlet, 10 LPS
Colors represents Density (On calibration process).

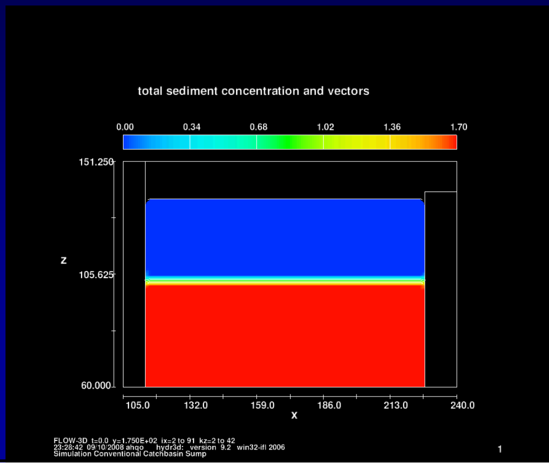




20

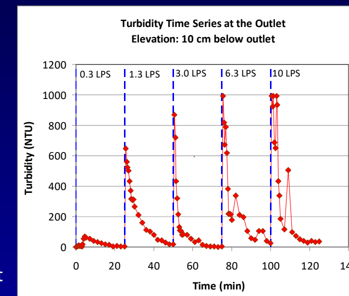
CFD-Customized Scour Model Validation

Colors represent sediment concentration (g/cm³)



Scour Tests Results: *Turbidity Time Series – Sequential Flow rate*

- A decreasing exponential pattern was found in the turbidity time series for each flow rate at steady conditions.
- The initial impact of the plunging water jet disturbs the sediment bed exposing all the particle sizes.
- The impacting zone is stabilized by dispersion, and buoyancy (air entrainment). Steady state is reached.
- Small particles are suspended and washed out creating a hole and leaving the large particles on the sediment bed surface.
- The large particles create an armoring on the sediment surface bed which protects the small particles below from being scoured.



- This Turbulent Time Series shows that the armoring is created exponentially over time.

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

Rainfall and Flow Monitoring

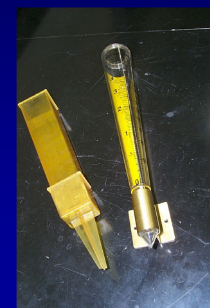
- **It is essential that there be an accurate description of the system's hydrodynamics when assessing the effects of stormwater runoff on receiving waters.**
- **Flow represents the pollutant loading mechanism and its power and frequency of occurrence can degrade the physical habitat.**
- **One of the principal reasons there is a relatively poor understanding of stormwater runoff effects is due to the difficult logistics involved in measuring short-term, high flow events quickly and accurately.**

Rainfall and flow monitoring critical components of receiving water study

25

Rainfall Monitoring

- Rainfall data is very important when monitoring receiving water quality and quantity.
- Basic hydrology texts all contain excellent summaries of rainfall aspects of importance in runoff studies.



26

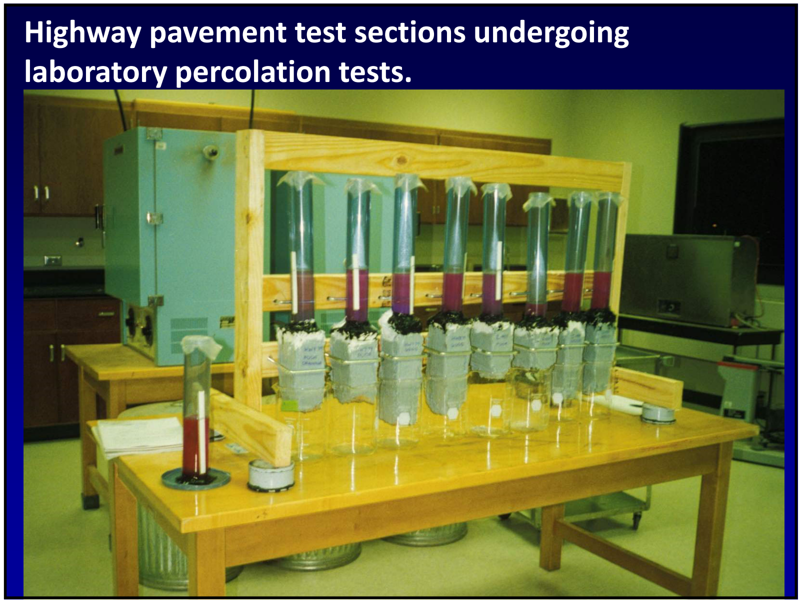
Rainfall Monitoring

Rainfall Monitoring Method	Advantages	Disadvantages
Tipping bucket rain gages	Most commonly used and available gage. Obtains high resolution rainfall intensity data. Relatively inexpensive for current versions of recording models.	Must be frequently calibrated and located adjacent to a standard rain gage (not usually done). Usually insufficient numbers of recording gages in most local networks.
Standard rain gages	Standard rain gage and most accurate. Can be heated and used for monitoring snowfall.	Does not obtain rain intensity information. Must be manually read at least once a day.
"Garden store" rain gages	Inexpensive and can be placed throughout a study area. Best use to supplement standard and tipping bucket rain gages.	Does not obtain rain intensity information. Must be manually read.
Radar rainfall measurements (such as NEXRAD)	High resolution data over a large area. Real-time measurements.	Most indicative of severe weather conditions. Can be very inaccurate and requires substantial calibration from standard rain gages. Only suitable for areas relatively close to a radar installation.

27

Special Hydrology Tests in Urban Areas:
Pavement infiltration tests along interstate highway, Alabama. Test sites also had moisture sensors under the pavement and tipping-bucket rain gages (and extensive road safety!).

28


Highway pavement test sections undergoing laboratory percolation tests.

29


Test plot
infiltration
measurements

30


Compaction Measurements
Soil Density Measurements

31


Natural forces and management attempts to increase infiltration in compacted soils. Nature much better at this than we are.

32


Source Area Flow Monitoring
33

33


Kansas City, MO, EPA Green Infrastructure and Combined Sewers demonstration project
34

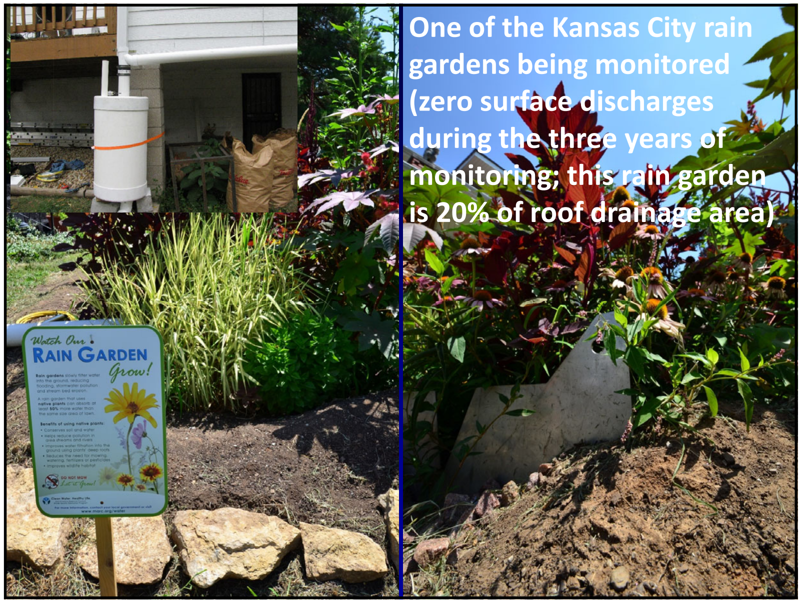
34


Curb extension rain garden
Other Stormwater Controls in Test Area

35


1324 76th St. monitoring location, biofilter and adjacent porous concrete sidewalk
36

36


One of the Kansas City rain gardens being monitored (zero surface discharges during the three years of monitoring; this rain garden is 20% of roof drainage area)
Watch Our RAIN GARDEN Grow!

37


Area-Velocity Sensors and Automatic Water Samplers
750

38


Installation of pipe flume insert, flow sensor, and water sample intake into small diameter pipe.
39

39

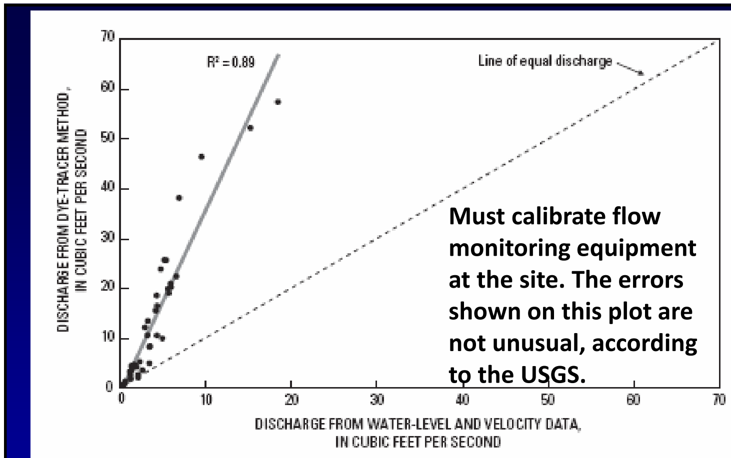

Installation of flow-velocity sensor (and sample intake) into large diameter pipe, and equipment box.
40

40

Outfall and Pipe Flow Monitoring

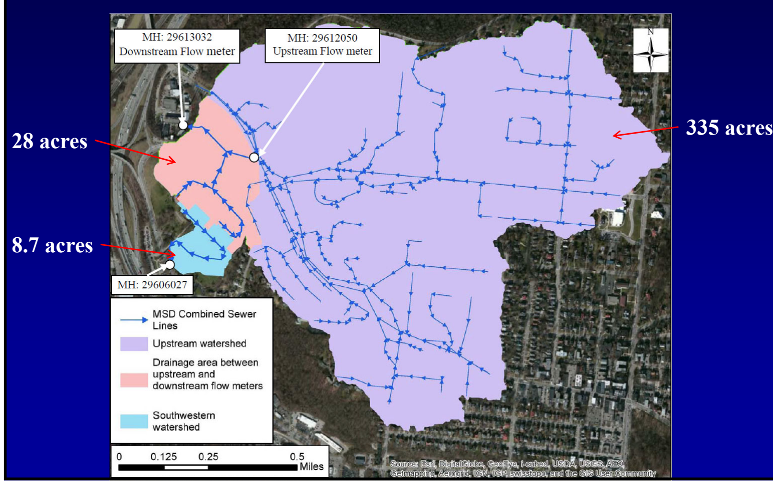
- In most cases, flow monitoring equipment available from the same vendor that supplied the automatic water samplers is selected.
- The best location is to use a special pre-fabricated manhole that contains a flume.
- Many flow measurement equipment vendors now offer simultaneous stage and velocity sensors. The velocity sensors directly measure the flow rate of the water.

41



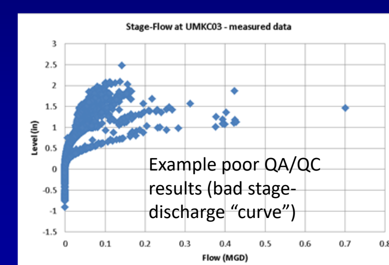
Relation between actual discharges determined using a rhodamine dye tracer and measured discharges, computed by water-level and velocity data, during free-flow conditions and actual runoff events (Selbig and Bannerman 2008)

Cincinnati CSO Green Infrastructure Watershed Analysis

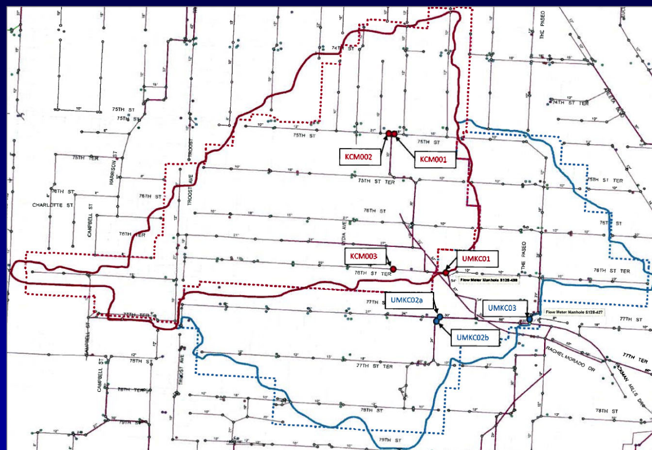


- The Cincinnati State college study area includes three drainage areas. The largest sub-watershed (in purple) is 335.5 acres which drains towards the *Upstream Flow Meter* with manhole. The additional drainage area between the *Downstream Flow Meter* and the *Upstream Flow Meter* is about 8% of the drainage area into the *Upstream Flow Meter*. Subtracting the upstream flows from the downstream flows to measure the flows from the campus area is very uncertain. The downstream monitoring flow was frequently less than the upstream flow due to poor installation location and inability to recalibrate, so these data were not able to be used.

Problems due to large diameter pipe at monitoring location and shallow flows having excessive depth measurement errors, in addition to close sources of other flows.



Large-scale performance monitoring at Kansas City, MO



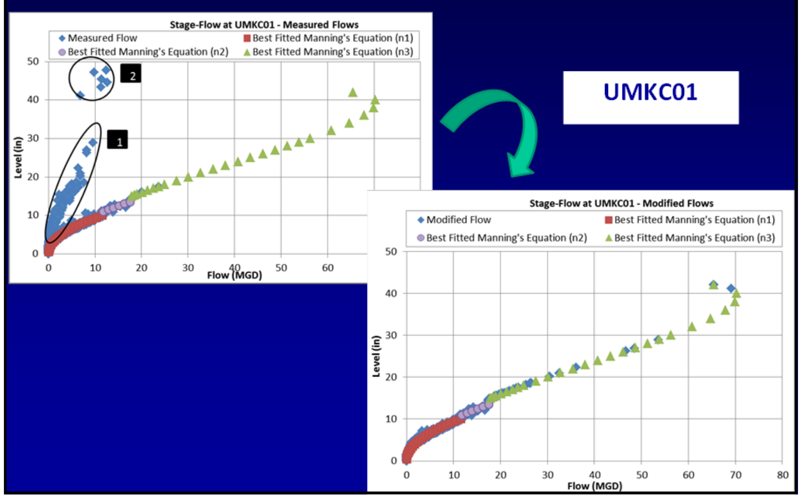
45

- Runoff monitoring was conducted in the combined sewer system at several locations in the test and control watersheds. The detailed land development and land use information for the test and control watersheds enabled the verification of the water quantity portion of WinSLAMM using the site rainfall and runoff data. The figure shows the test and control watershed boundaries and the locations of the flow monitoring stations. Monitoring station S128-427 measures the flows portions of the control watershed; station S128-498 measures the flows from the test (pilot) watershed alone.

46

46

Quality Assurance and Quality Control Examinations of Monitored Runoff and Rainfall Data



47

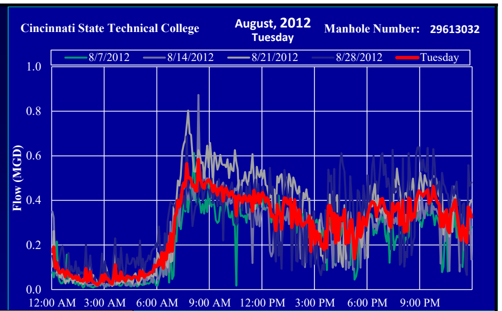
- The monitored stage-discharge relationship in the combined sewer was plotted and compared to basic plots based on Manning's equation as part of the QA/QC process. These data were obtained from an area-velocity sensor that reports the discharge (flow) directly, using a calculated flow cross-sectional area based on the stage value multiplied by the measured velocity value. Figure 4.35 shows the stage-discharge at UMKC01 (downstream of the 100 ac pilot study area). This figure was plotted using the separately recorded stage and flow data. As shown on this figure, changing Manning's roughness coefficient "n" values were used to account for the varying n values with depth and the observed stage-discharge relationship (basic Camp's curve relationships) (0.0082 to 0.012). This plot shows three regions of data observations. The "main sequence" includes almost all of the data and was fitted using reasonable n roughness values that slightly varied with depth. Most of the data group 1 were observed during the "before construction" period. The reduced discharge values for these stage observations were therefore deemed incorrect for unknown reasons. The stage values for group 2 represent surcharged conditions, being greater than the 42'' pipe diameter. These six surcharged pressure recorded stage values were therefore re-adjusted to 42". The stage observations in group 2 were therefore changed to 42" and full-flowing discharge values were assigned for these data. The stage values for the observations in group 1 were also applied to the Manning's equation with the calibrated n roughness values. In all, only about 3% of the measured flows were modified at UMKC01. Figure 4.36 shows the final set of stage-discharge values for all observations at this monitoring location.

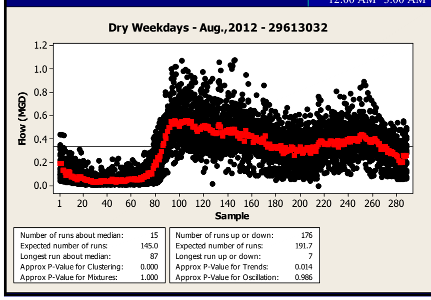
48

48

Flow Measurements in combined sewers, after QA/QC

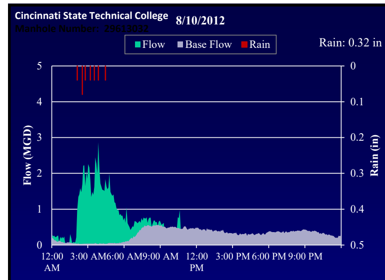
- Determine the base flow and the dry and wet weather flow components from the flow time series in sewer lines

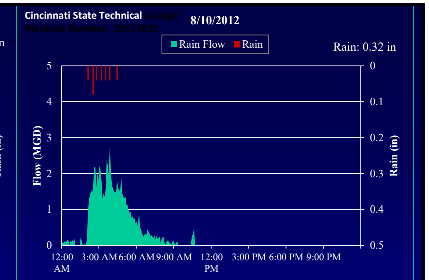




Trend Analysis

49





Prepare individual storm event data summaries that are coordinated with the rain data for each monitoring point, including:

- start/end time of rain,
- rain duration,
- antecedent dry days,
- total rain,
- peak and average rain intensity,
- pipe-flow start/end time,
- total pipe-flow discharge volume,
- total runoff,
- peak and average flow discharge rates,
- R_v (the ratio of runoff to rainfall depth).

50

Urban Area Hydrograph Characteristics

- Observed Urban Area Hydrographs
- Modeling Hydrographs in Urban Areas
- Calculated WinTR-55 Hydrographs
- Hydrograph Characteristics used in WinSLAMM
- Analyses of Observed Urban Hydrograph Shapes for Stormwater Quality Analyses

51

Observed Urban Hydrographs

Evaluated about 550 different urban area hydrographs from 8 watersheds (1, 1a, 2, and 3 rain distributions and B soils to pavement)

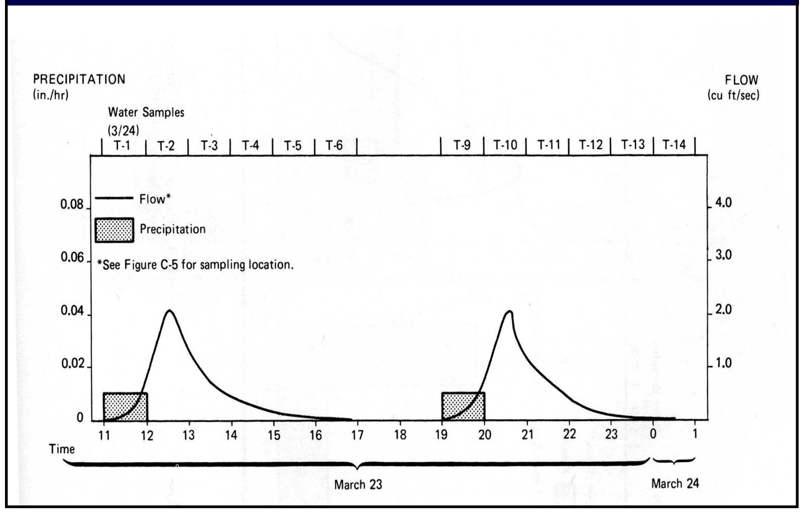
Location	Land use	area (acres)	directly connected impervious	# of events monitored
Bellevue, WA				
Surrey Downs	Resid, med. den.	95	17 %	196
Lake Hills	Resid, med. den.	102	17	201
San Jose, CA				
Keyes	Resid, med. den.	92	30	6
Tropicana	Resid, med. den.	195	25	8
Toronto, Ontario				
Thistledowns	Resid, med. den.	96	21	35
Emery	Industrial	381	42	60
Tuscaloosa, AL				
City Hall	Institutional/com	0.9	100	31
BamaBelle	Commercial	0.9	68	17

52

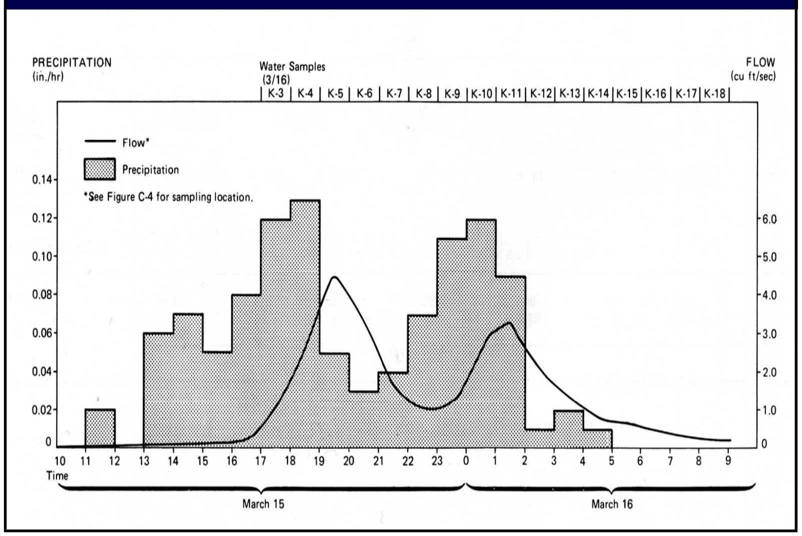
Observed Runoff Characteristics

	Monitored rains (in, range)	Observed Rv (avg)	Observed CN (range)	peak/avg flow ratio (avg)
Bellevue, WA				
Surrey Downs	0.03 - 4.38	0.18	64 - 100	4.4
Lake Hills	0.02 - 3.69	0.21	73 - 100	5.4
San Jose, CA				
Keyes	0.01 - 1.06	0.10	88 - 100	3.2
Tropicana	0.01 - 1.08	0.59	95 - 100	3.8
Toronto, Ontario				
Thistledowns	0.03 - 1.01	0.17	84 - 99	4.0
Emery	0.03 - 1.0	0.23	87 - 99	3.1
Tuscaloosa, AL				
City Hall	0.02 - 3.2	0.60	95 - 99	4.2
BamaBelle	0.1 - 1.9	0.80	94 - 100	5.5

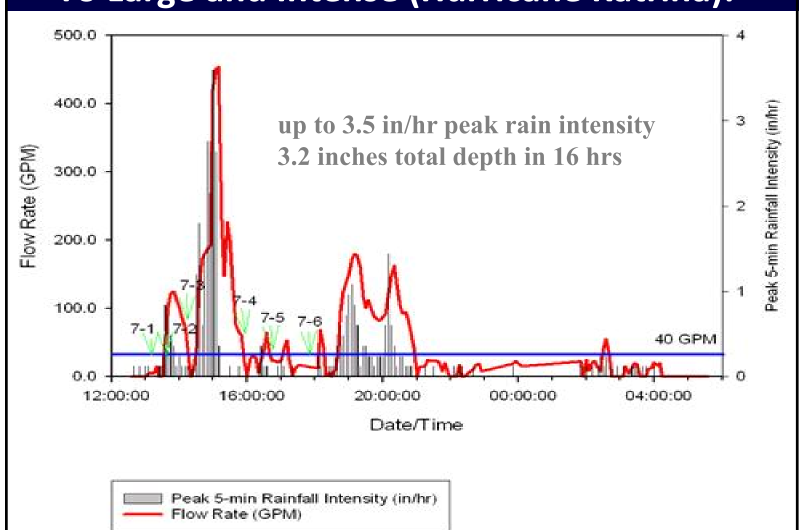
Rains Ranged from Small and Simple:



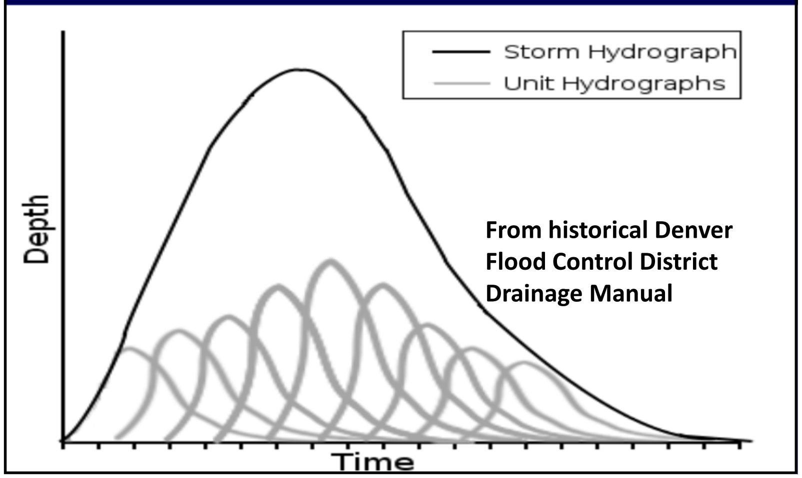
To Complex:



To Large and Intense (Hurricane Katrina):



Combine Unit Hydrographs to Produce Storm Hydrograph:



From historical Denver Flood Control District Drainage Manual

57

SWMM 5 Unit hydrographs and aggregate storm hydrograph (Bend, OR, 2008)

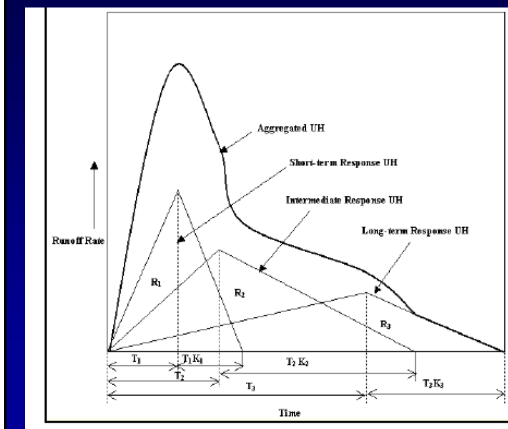
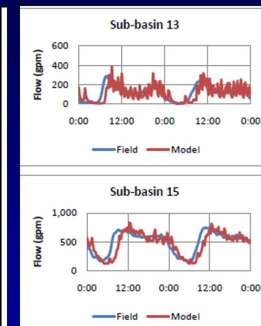


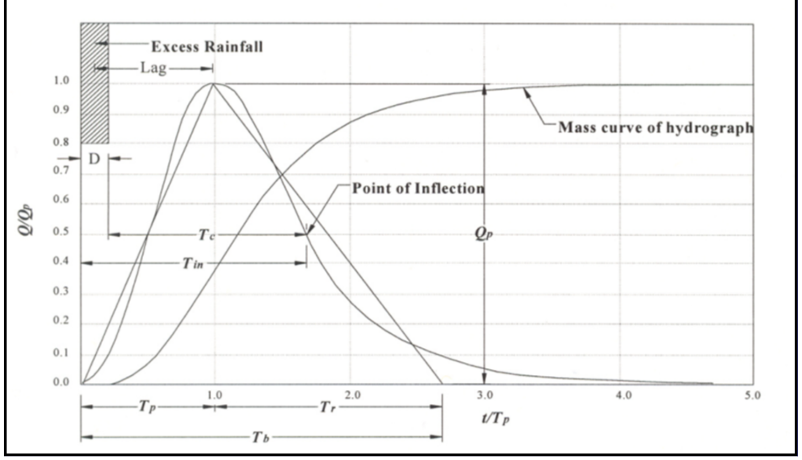
Figure 4. SWMM Unit Hydrograph Description



Examples of excellent calibrations with local data

58

NRCS Dimensionless Unit Hydrograph and Triangular Hydrograph



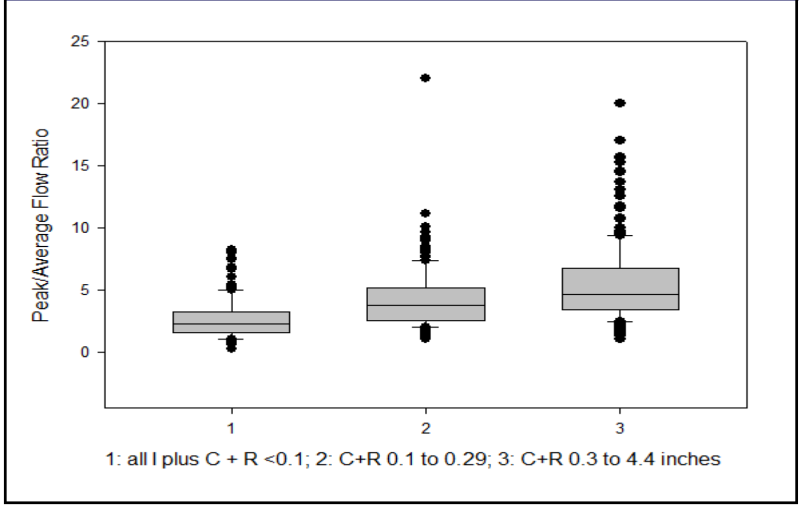
59

WinTR-55 Calculated Hydrographs

	WinTR55 using actual CN value and 1 inch rain	
	peak/avg flow rate ratio	runoff/rain duration ratio
Bellevue, WA		
Surrey Downs	1.7	0.71
Lake Hills	2.5	0.75
San Jose, CA		
Keyes	5.8	0.67
Tropicana	8.3	0.92
Toronto, Ontario		
Thistledowns	9.7	0.58
Emery	9.5	0.58
Tuscaloosa, AL		
City Hall	6.4	0.09
BamaBelle	4.9	0.09

60

Observed Peak to Average Flow Ratios
(non-parametric Kruskal-Wallis one way ANOVA on ranks)



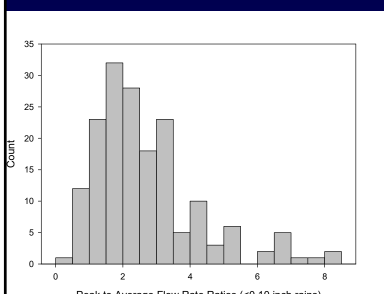
61

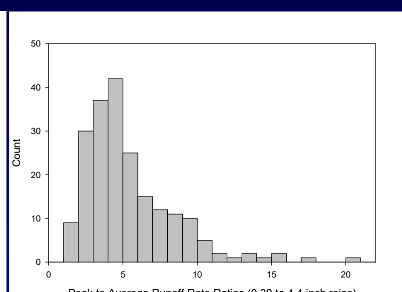
Peak to Average Flow Rate Ratios

	<0.10 in (<2.5 mm) rains	0.10 to 0.29 in (2.5 to 7.4 mm) rains	0.30 to 4.4 in (7.5 to 120 mm) rains
Number of Observations	172	172	206
Minimum	1.0	1.0	1.1
Maximum	8.3	22	20
Average	2.7	4.2	5.4
COV	0.55	0.65	0.66

62

Peak to Average Runoff Rate Ratios

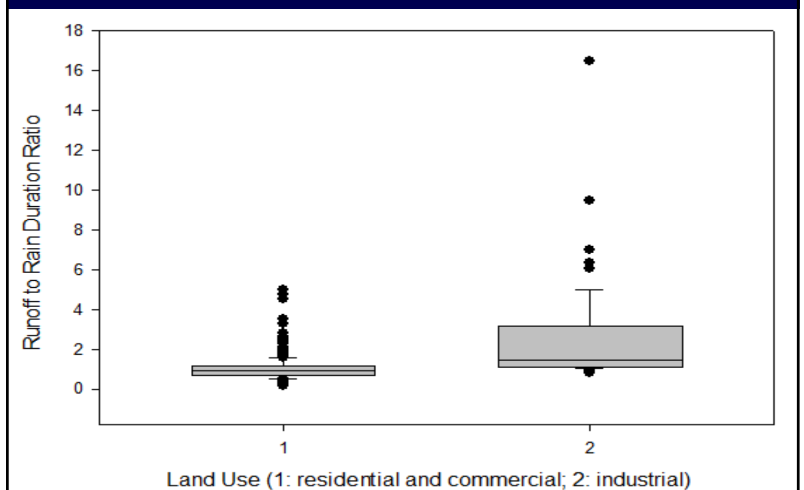




The variation in each rain/land use group can be described using a Monte Carlo stochastic modeling approach for long-tem continuous simulations.

63

Observed Runoff to Rain Duration Ratios
(non-parametric Kruskal-Wallis one way ANOVA on ranks)



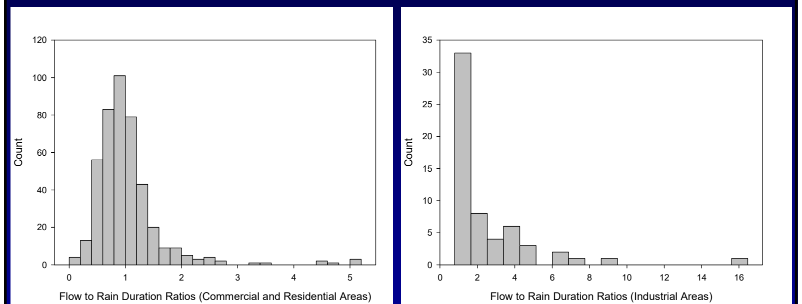
64

Runoff to Rain Duration Ratios

	Residential and Commercial Areas	Industrial Areas
Number of observations	447	60
Minimum	0.16	0.78
Maximum	5.0	16
Average	1.0	2.5
COV	0.63	1.0

65

Runoff to Rain Duration Ratios



Again, the variation in each land use group can be described using a Monte Carlo stochastic modeling approach for long-tem continuous simulations.

66

Urban Hydrology Conclusions

- Uncalibrated, or partially calibrated runoff models (such as only for annual runoff volume) likely greatly distort the actual hydrograph shapes in urban areas, especially for small to moderate-sized events.
- Smaller events are under-represented and larger events are over-predicted to balance long-term flows.
- Greatly affects flow-duration analyses for habitat assessment.

67

Urban Hydrology Conclusions (cont.)

- Simple models cannot match the hydrograph shape and commonly use the same mechanisms for all rains.
- More complex models can be appropriately calibrated to represent a wide range of rains and watershed conditions.
- However, if uncalibrated (and use “traditional” model parameters representative of drainage design), even these better models will distort the flow-duration relationship (usually by greatly over-predicting the peak to average runoff ratio, especially for the smaller rains).

68

Receiving Water Monitoring

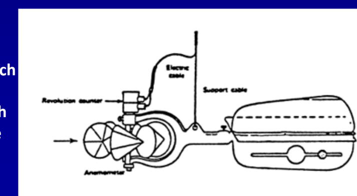
69

69

Stream Flow Monitoring Methods

- The drift method is simply watching and timing debris floating down the stream. This velocity is then multiplied by the estimated or measured stream cross-sectional area to obtain the stream discharge rate. Of course, this method is usually the least accurate of available flow estimation methods. The accuracy can be improved by choosing drift material that floats barely under the stream surface (such as an orange).
- The most traditional method of flow measurements is by using a mechanical current meter. This method requires a current meter and simple surveying equipment. The stream discharge is measured at a selected cross section, usually selected along a relatively straight stretch (about 10 stream widths downstream from any major bends).

Current meter flow monitoring requires that the stream be divided into several sections. About 10 sections that are from 1 to several feet wide are usually adequate, depending on overall stream width. The depth of the stream is measured at each section edge, and the water current velocity is measured in a vertical profile in the center of each section. The average velocities in each section are multiplied by the section areas to obtain the discharge rates for each section. These are then summed to obtain the total stream discharge.



70

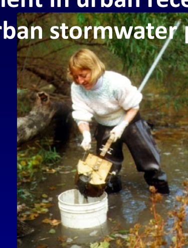
Stream and Pipe Flow Monitoring Using Tracers

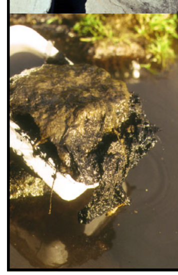
- The most precise method of stream current measurements is through the use of tracers.
- This method is especially important when measuring flows in areas having karst conditions where surface waters frequently lose and/or gain substantial flows to and from underground flows.
- A single upstream dye injection location and multiple downstream sampling stations through the study area are used in this situation.
- Tracers are also needed if there is an obviously large fraction of inter-bed flow, or if the stream flow is very turbulent.
- The flow in very shallow streams, especially when the stream is cobble-lined, is also very difficult to monitor with current meters, requiring the use of tracers.
- Another common use of tracers is when measuring the transport and diffusion of a discharge into a receiving water.



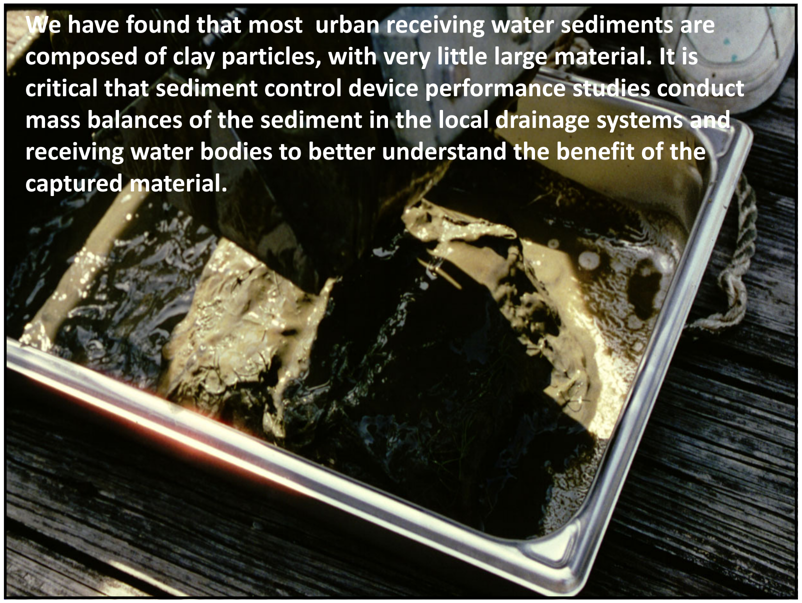
71

We have monitored sediment transport in storm drainage systems and accumulated sediment in urban receiving waters to quantify the fate and transport of urban stormwater particulates.



72

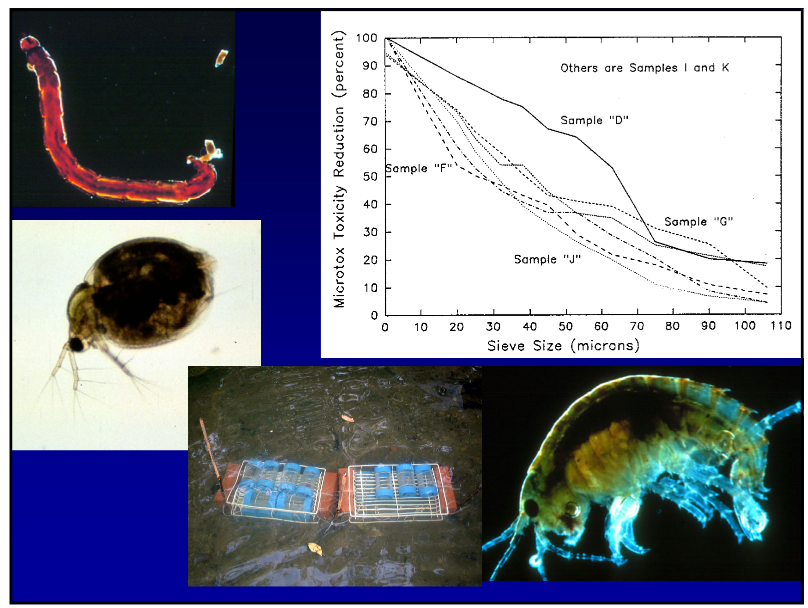

We have found that most urban receiving water sediments are composed of clay particles, with very little large material. It is critical that sediment control device performance studies conduct mass balances of the sediment in the local drainage systems and receiving water bodies to better understand the benefit of the captured material.

73

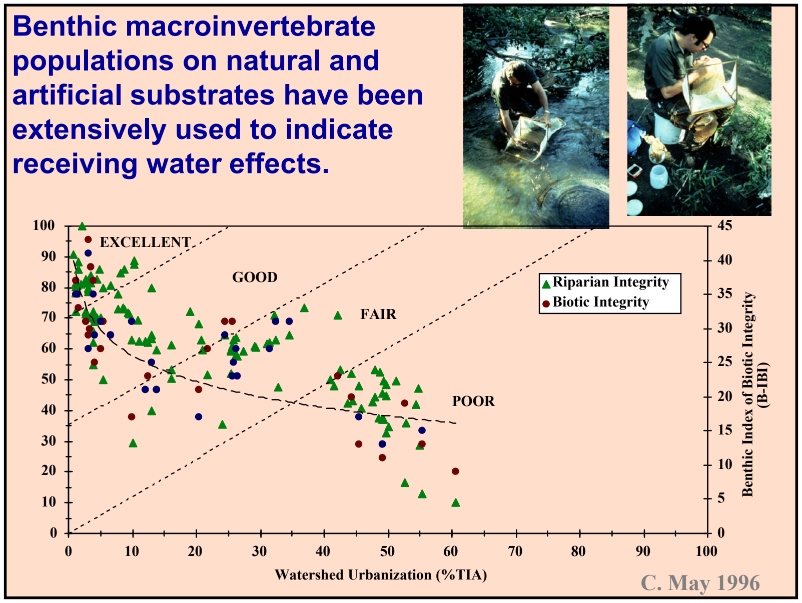

Stickleback
Sucker
Coho
Dace
Sculpin
Cutthroat
Coho
Cutthroat
Kelsey Creek
Bear Creek

74

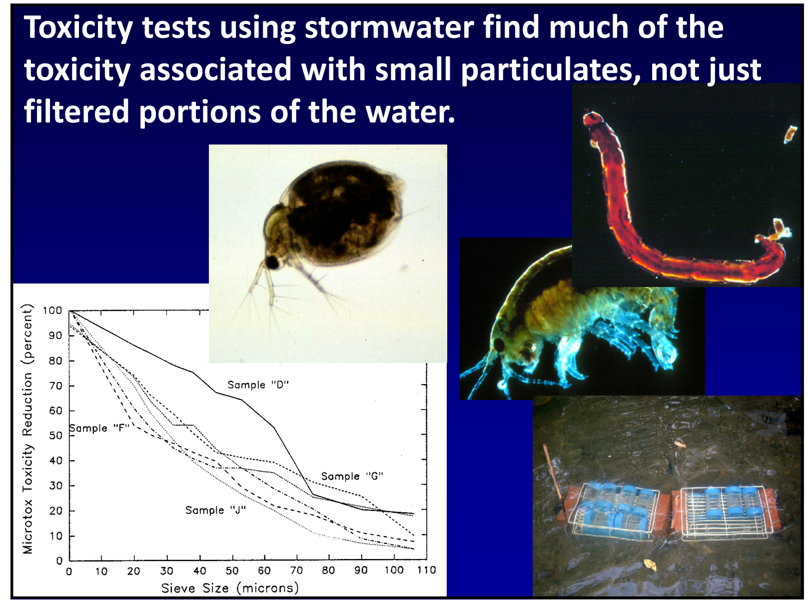
75


Microtox Toxicity Reduction (percent)
Others are Samples I and K
Sample "D"
Sample "F"
Sample "G"
Sample "J"
Sieve Size (microns)

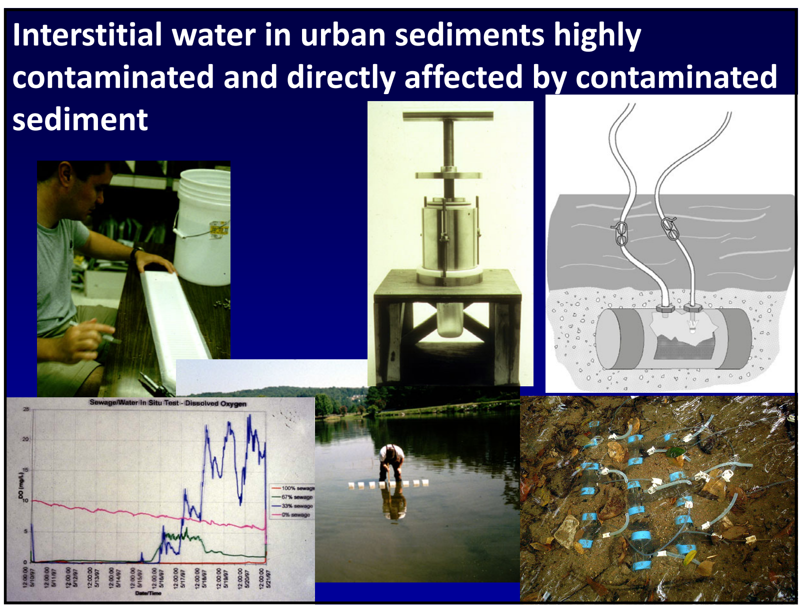
76


Benthic macroinvertebrate populations on natural and artificial substrates have been extensively used to indicate receiving water effects.
EXCELLENT
GOOD
FAIR
POOR
Riparian Integrity
Biotic Integrity
Watershed Urbanization (%TIA)
Benthic Index of Biotic Integrity (B-IBI)
C. May 1996

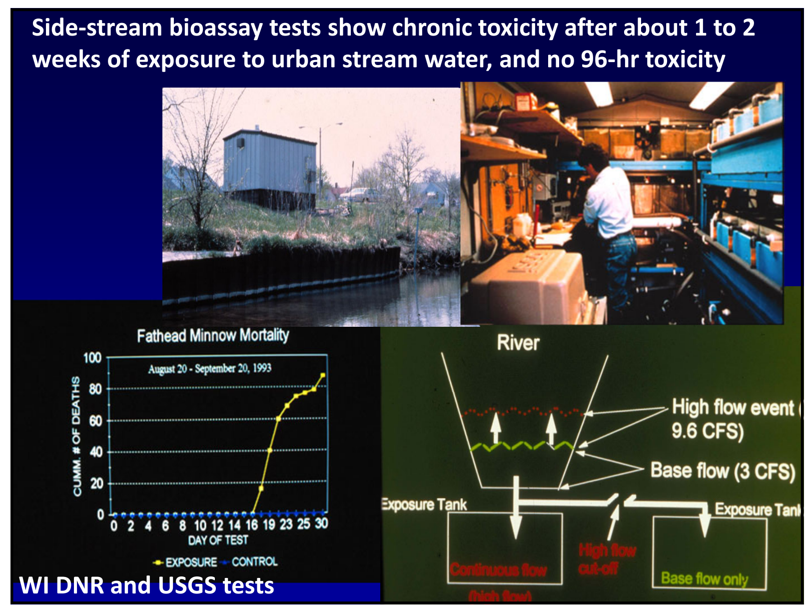
77


Toxicity tests using stormwater find much of the toxicity associated with small particulates, not just filtered portions of the water.
Microtox Toxicity Reduction (percent)
Sieve Size (microns)
Sample "D"
Sample "F"
Sample "G"
Sample "J"

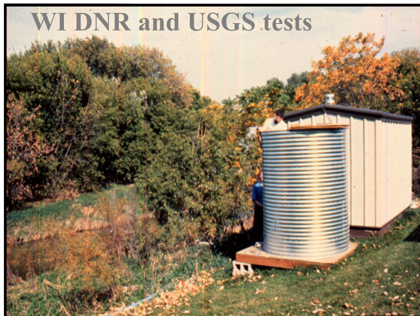
78

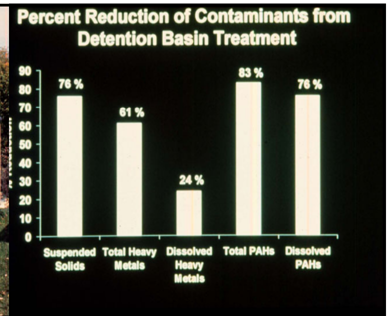

Interstitial water in urban sediments highly contaminated and directly affected by contaminated sediment
Sewage/Water In Situ Test - Dissolved Oxygen

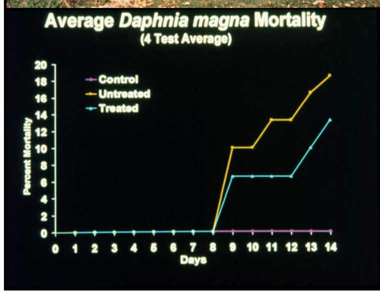
79


Side-stream bioassay tests show chronic toxicity after about 1 to 2 weeks of exposure to urban stream water, and no 96-hr toxicity
Fathead Minnow Mortality
August 20 - September 20, 1993
CUMM. # OF DEATHS
DAY OF TEST
EXPOSURE
CONTROL
River
High flow event (9.6 CFS)
Base flow (3 CFS)
Exposure Tank
Exposure Tank
Continuous flow
High flow cut-off
Base flow only
WI DNR and USGS tests

80







Side-stream bioassay tests demonstrated the benefits of stormwater controls for the removal of fine particulates. Residual toxicity remains, however.

81

Conclusions

- Understanding sediment sources and transport in urban areas requires many nested tests and experiments at different locations and scales, from source areas to receiving water sediments.
- Urban hydrology also requires a similar nested approach at different scales. Most traditional hydrology assumptions are poorly applicable to small and intermediate urban-area storms and associated problems.

82

82