United States Environmental Protection Agency

Permeable Pavement Research Highlights

Performance and effectiveness of permeable pavement systems

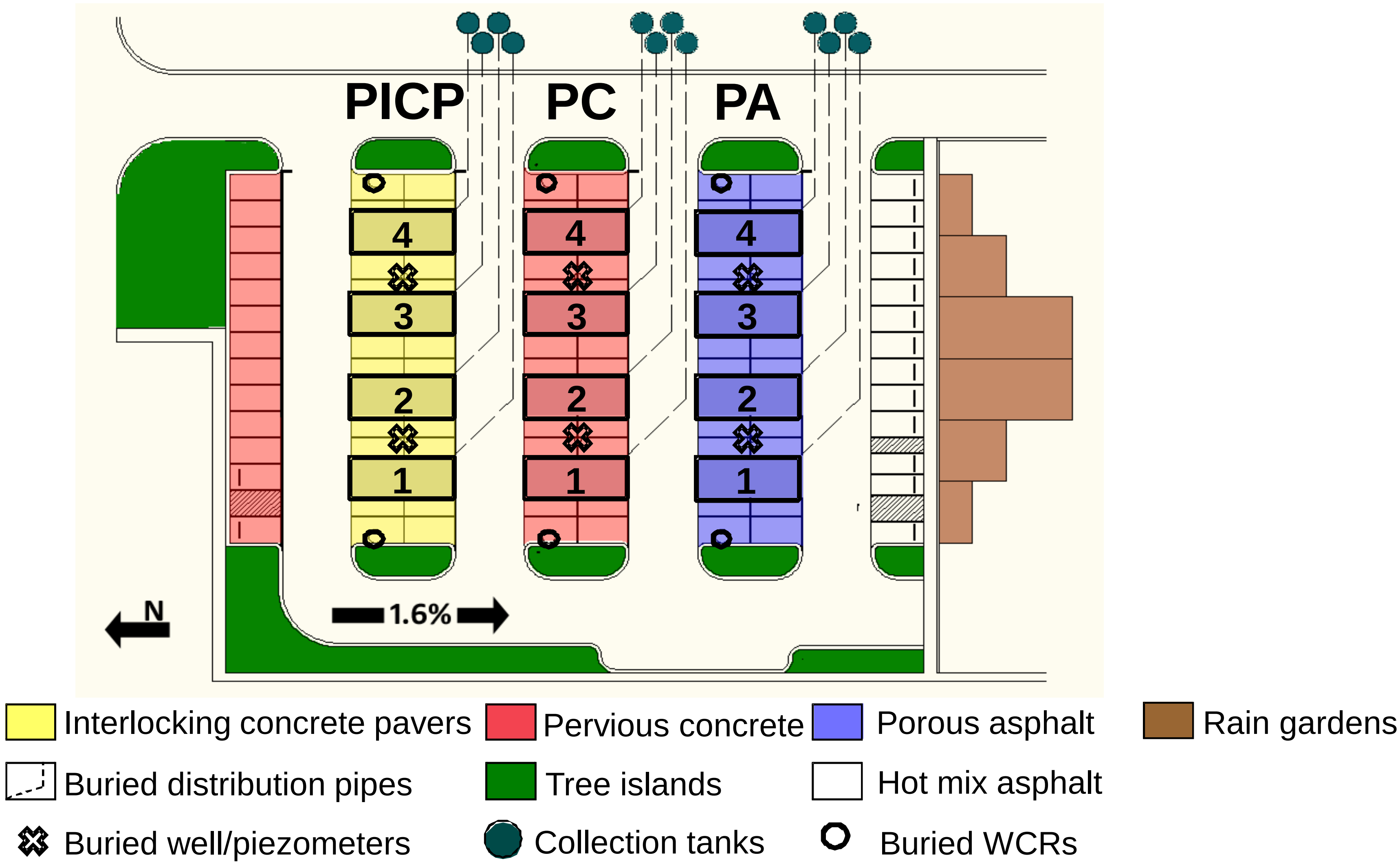
Michael Borst

Edison Environmental Center
Edison, New Jersey

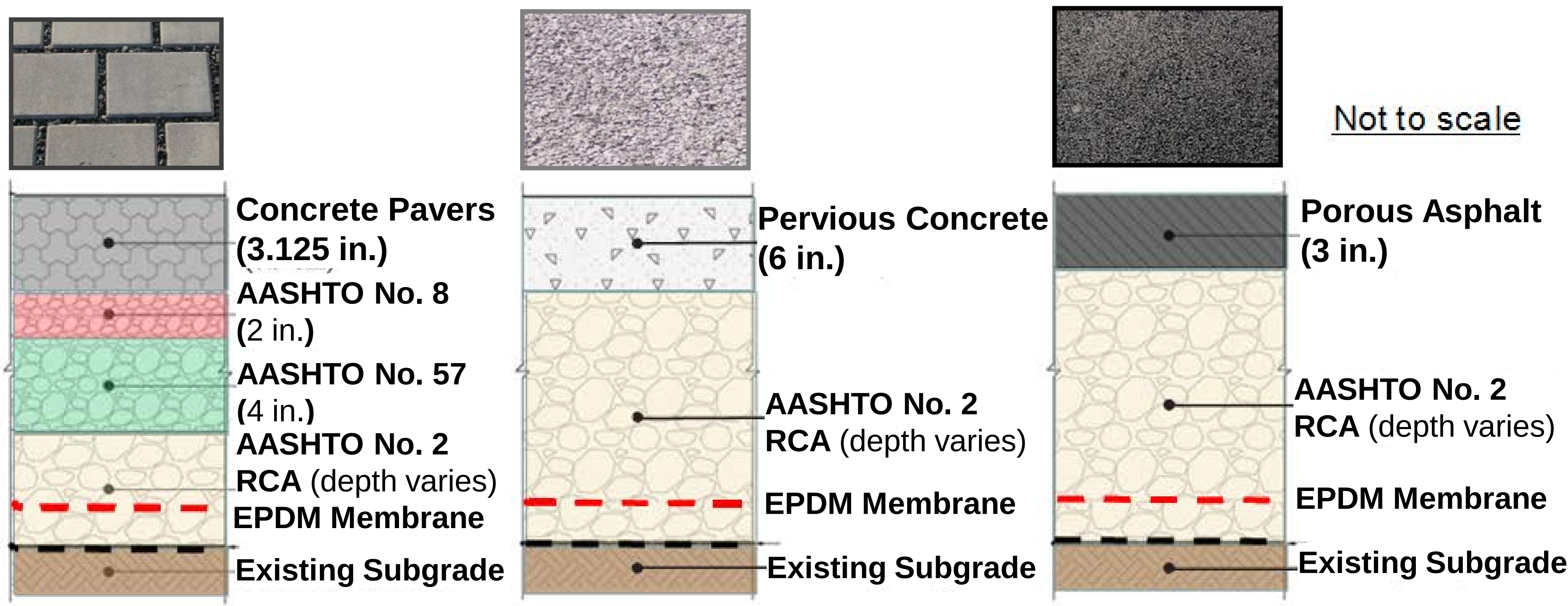
In-Street Application
Louisville, Kentucky

Office of Research and Development
National Risk Management Research Laboratory
Water Supply and Water Resource Division
Urban Watershed Management Branch

The design at the EEC incorporated water quality monitoring capabilities.



Vertical cross sections of permeable sections varied slightly from material to material.



Based on engineering drawings from Morris & Ritchie Associates, Inc. 2009

Four equally-sized and spaced lined sections collect infiltrating water from each monitored permeable surface with the balance infiltrating to the underlying soil.

Infiltrate drains from the lined sections to 1,500-gallon tanks on the east side of the parking lot where it can be sampled.

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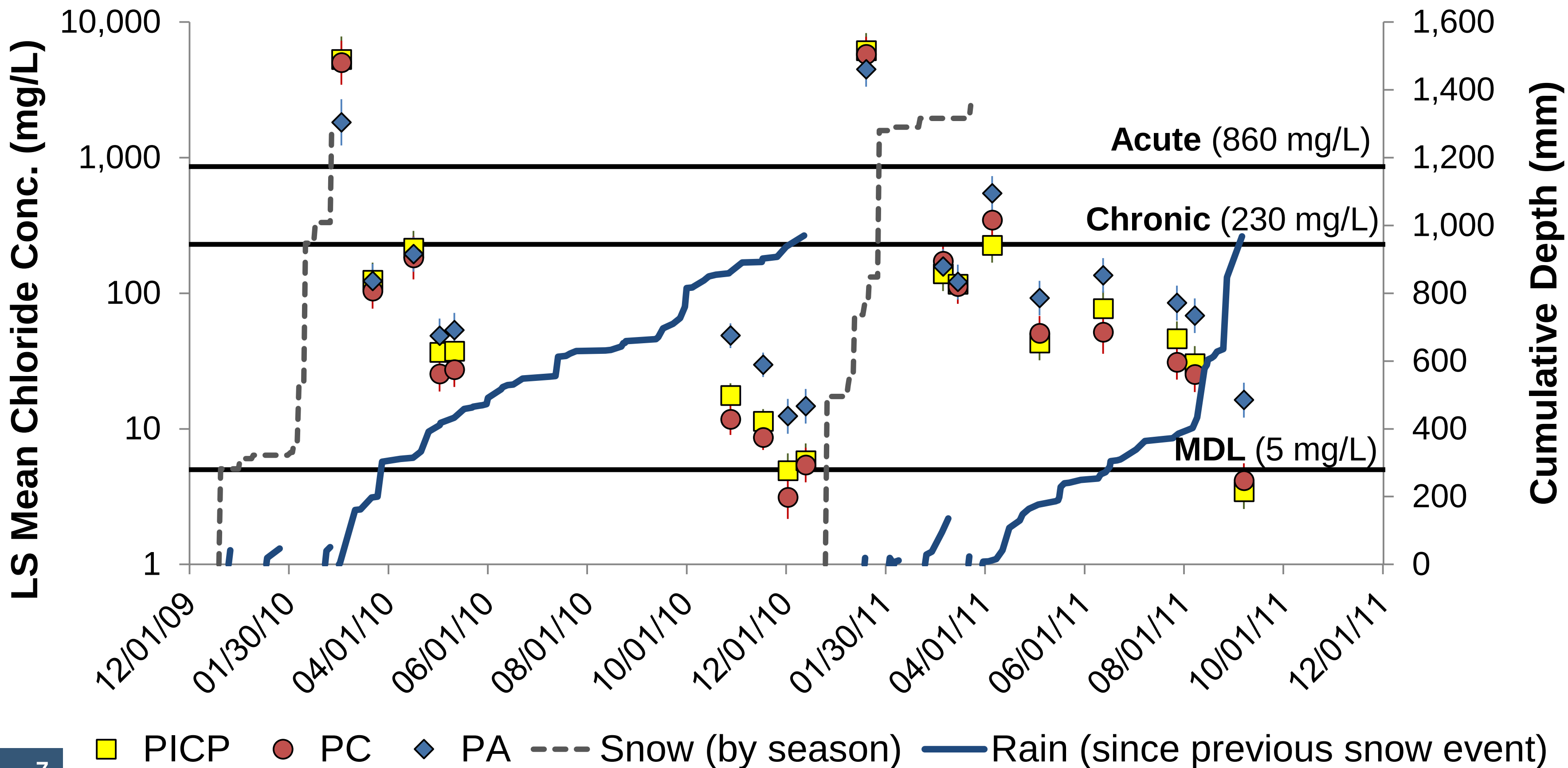
The permeable pavement parking lot at the Edison Environmental Center allows evaluation of water quality effects.

- Published or in review
  - Chloride
  - Speciated nitrogen
  - Organic carbon
  - Phosphate
  - pH
  - Eh
- In production
  - SVOCs
  - Metals
- Just starting
  - Microbial indicators

After winter salt application, chloride concentration decreases throughout the remainder of the year.



Bars represent 95% confidence intervals; snowfall data from NJ State Climatologist.
JAWRA 50(1) 29-41

Note: Preliminary Data

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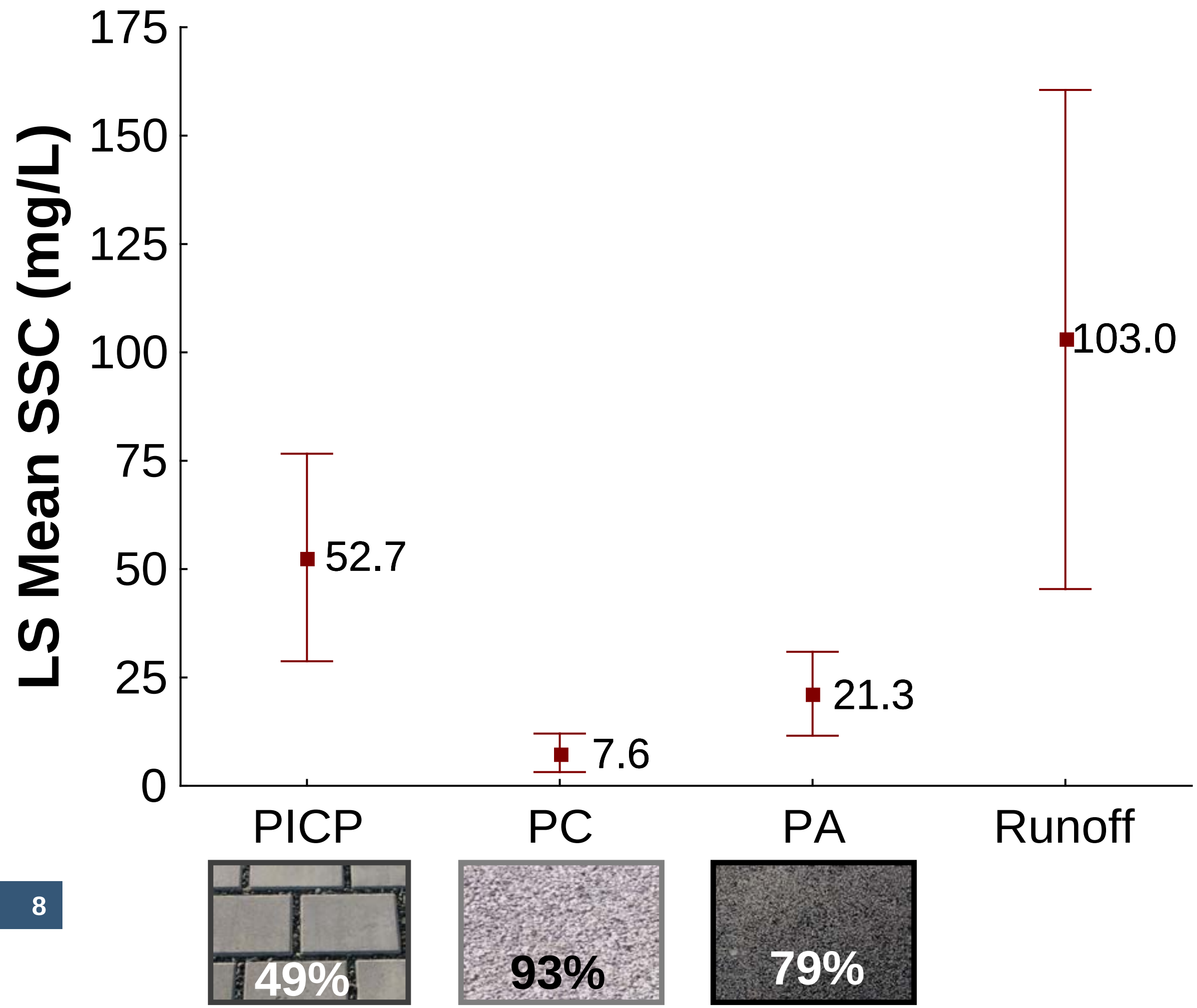
All permeable surfaces reduced Suspended Solids Concentration (SSC) to different degrees.



Date Range:
1/26/2010 – 6/4/2013

Events sampled:
42 (PICP, PC, and PA)
28 (Runoff)

Note: NSQD TSS commercial median 98 mg/L

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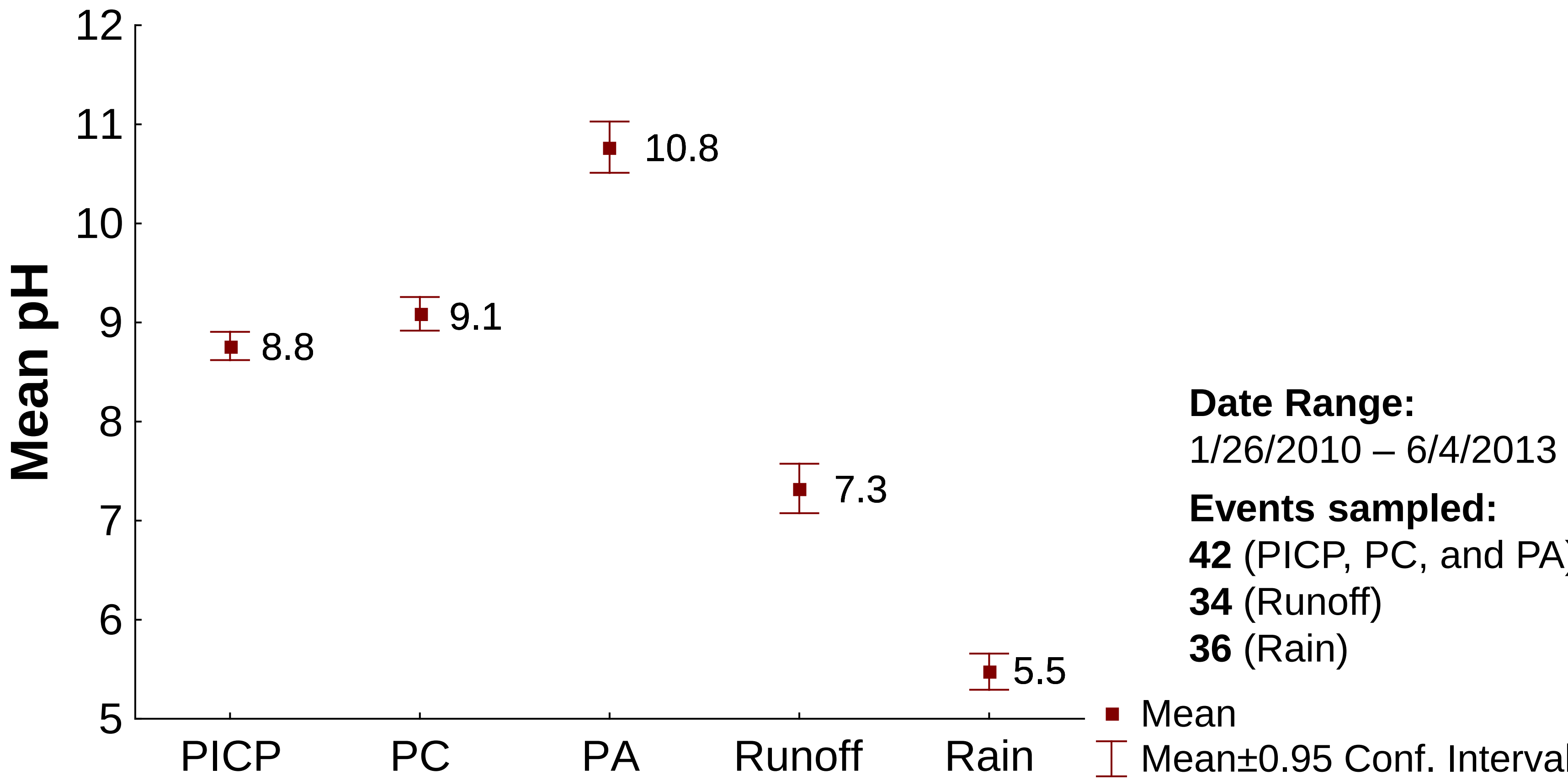
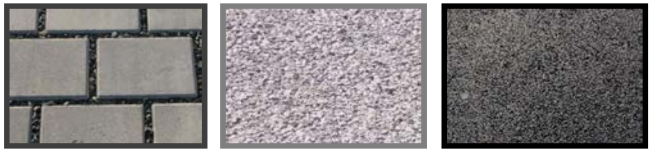
Acidic rainfall is buffered by all pavement surfaces, and PA exfiltrate is surprisingly basic.



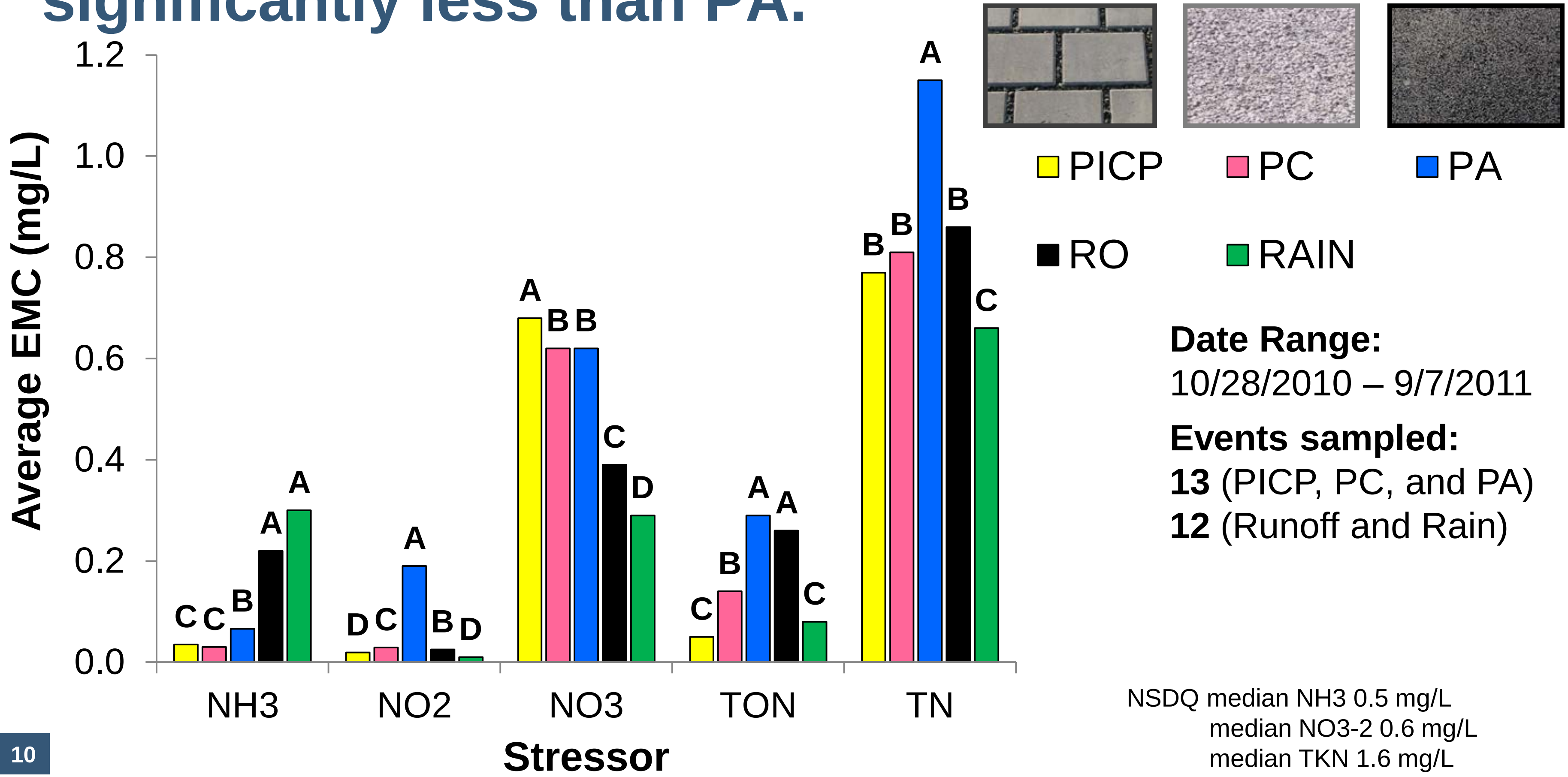


Date Range:
1/26/2010 – 6/4/2013

Events sampled:
42 (PICP, PC, and PA)
34 (Runoff)
36 (Rain)

NSQD median for commercial property 7.3

TN concentrations in PICP, PC, and runoff were not significantly different, but all three were significantly less than PA.



Date Range:
10/28/2010 – 9/7/2011

Events sampled:
13 (PICP, PC, and PA)
12 (Runoff and Rain)

NSDQ median NH3 0.5 mg/L
median NO3-2 0.6 mg/L
median TKN 1.6 mg/L

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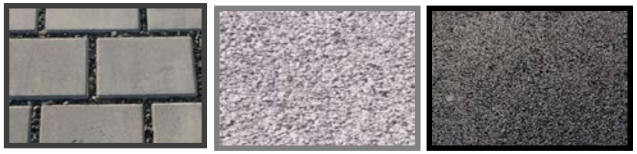
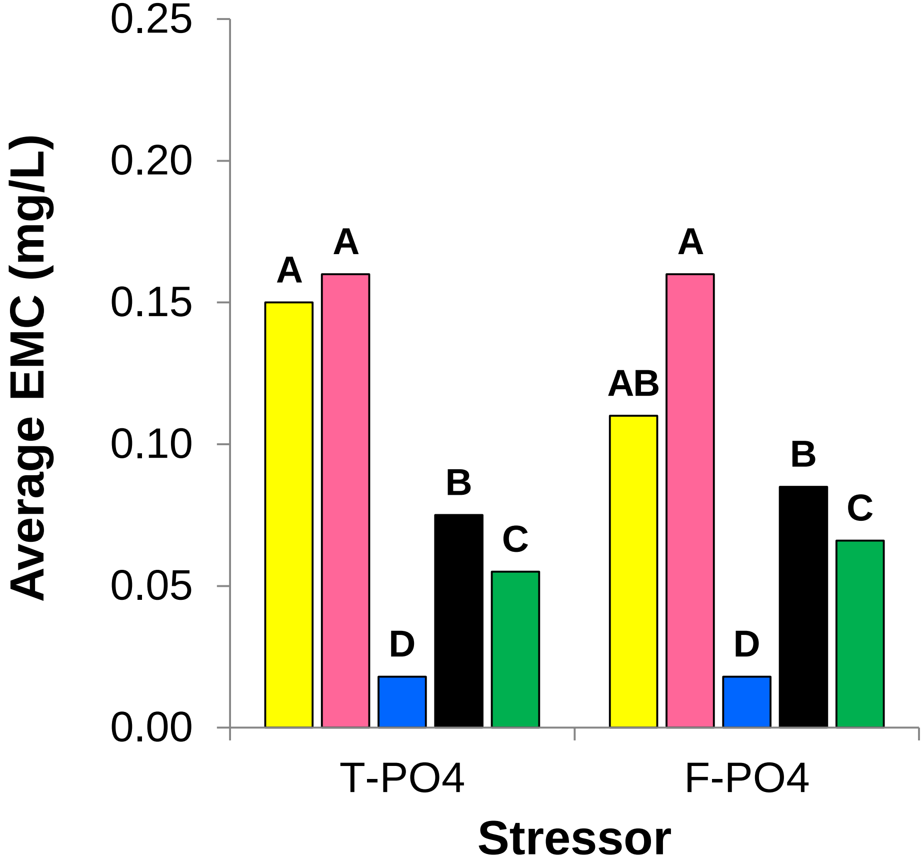
Total phosphate concentrations in PICP and PC were significantly larger than in the runoff, and all were significantly larger than PA.

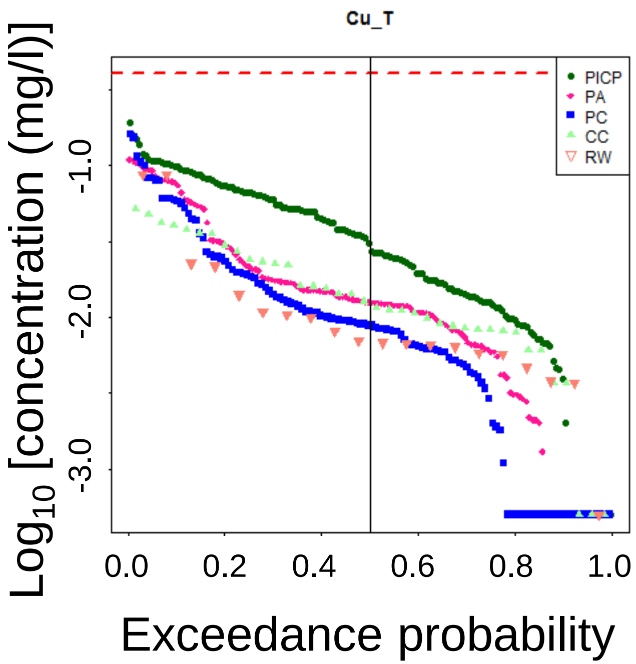


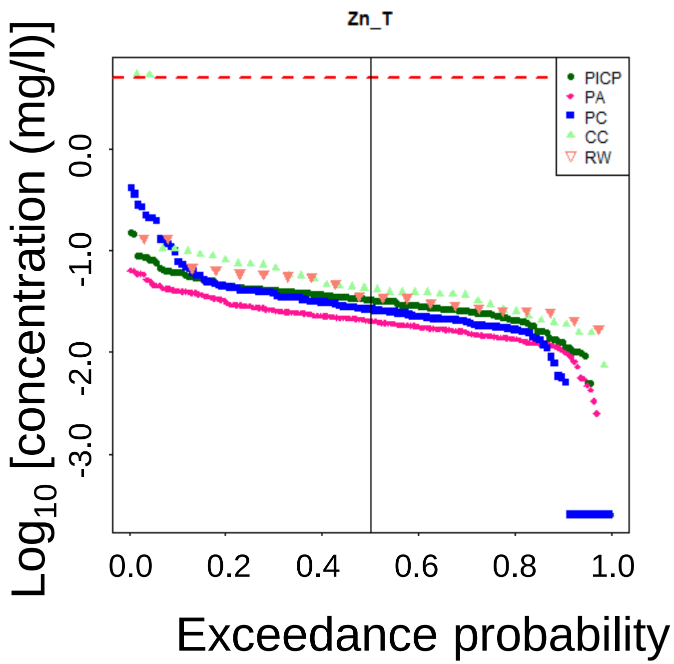


Date Range:
10/28/2010 – 9/7/2011

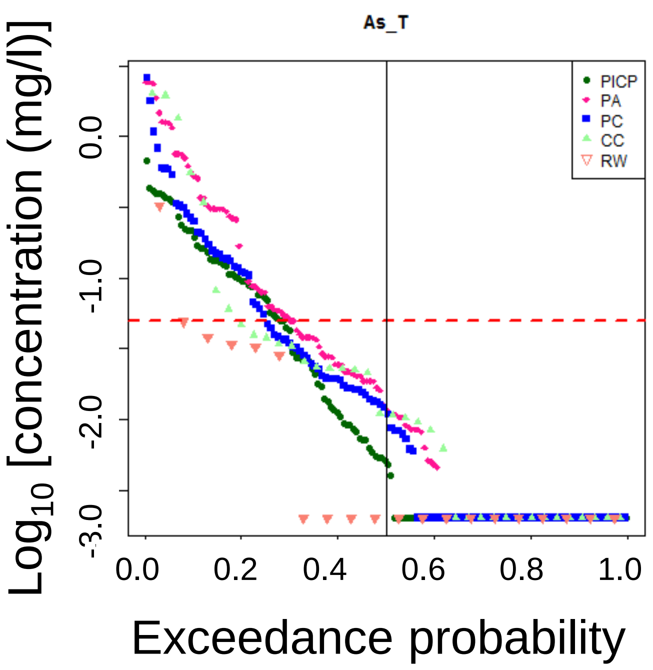
Events sampled:
13 (PICP, PC, and PA)
12 (Runoff and Rain)

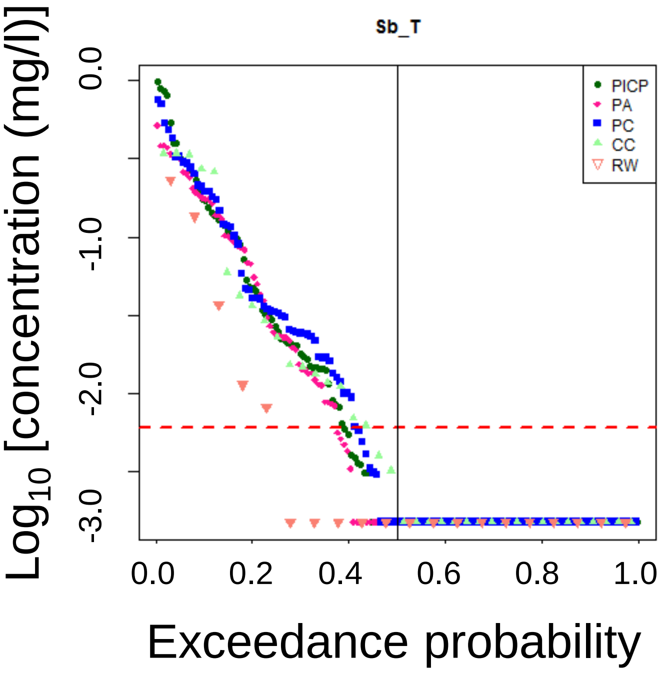
The concentration of priority-pollutant metals were generally less than the groundwater discharge limit.





Arsenic and antimony sometimes exceeded the groundwater limits





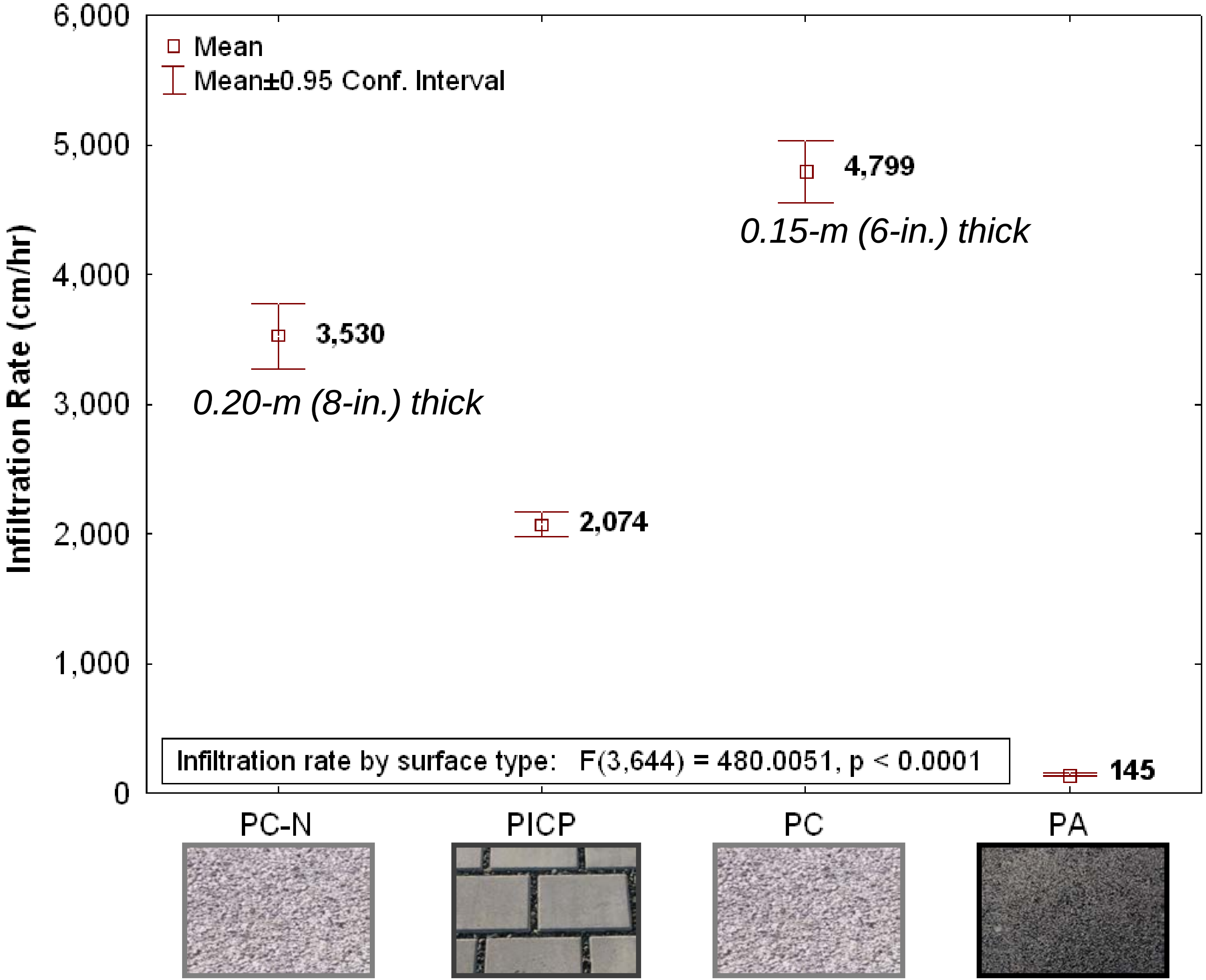
Surface results:

- The three surfaces have very large infiltration rates.
- Clogging progresses from upgradient to downgradient.
- Microtopography partly determines clogging pathway.
- 5 to 7% of the captured water evaporates through the surfaces.

The infiltration rate varies among the four tested surfaces, but all surfaces are sufficient to handle maximum expected direct rainfall rates.

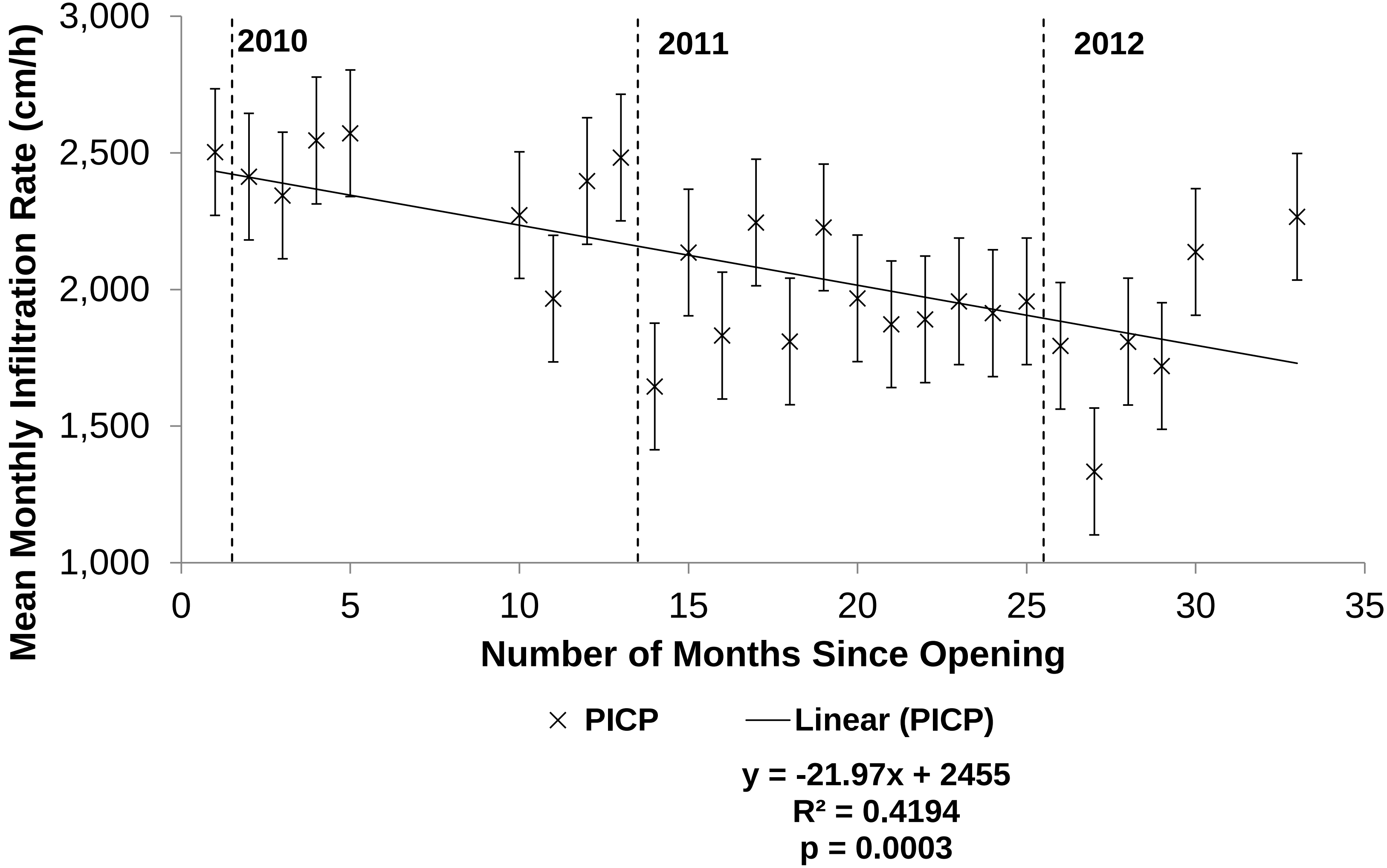
100-year, 5-minute rainfall intensity

• Edison, NJ
20.8 cm/hr (8.2 in/hr)



J. Hydrol. Eng. DOI: 10.1061

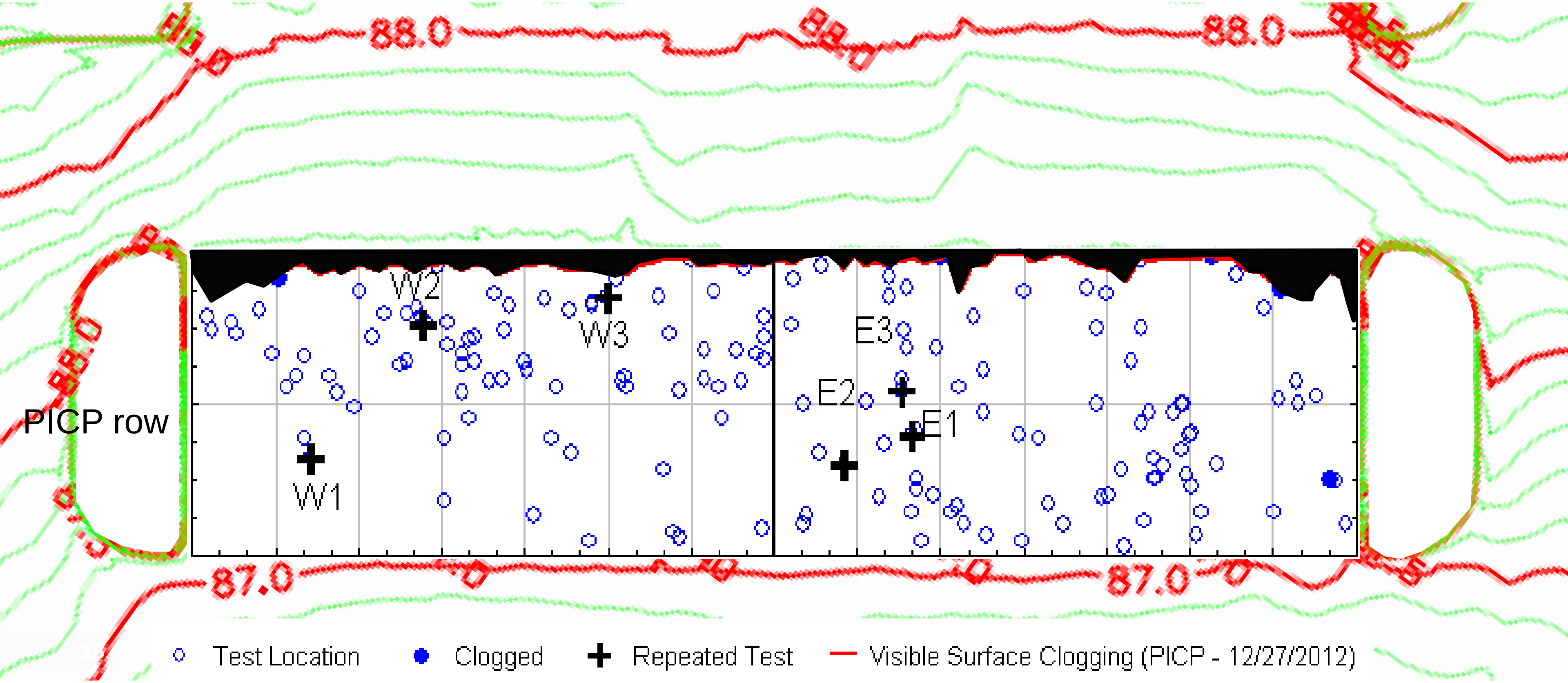
Infiltration decreased with age for the three surfaces that received run-on from driving lane.



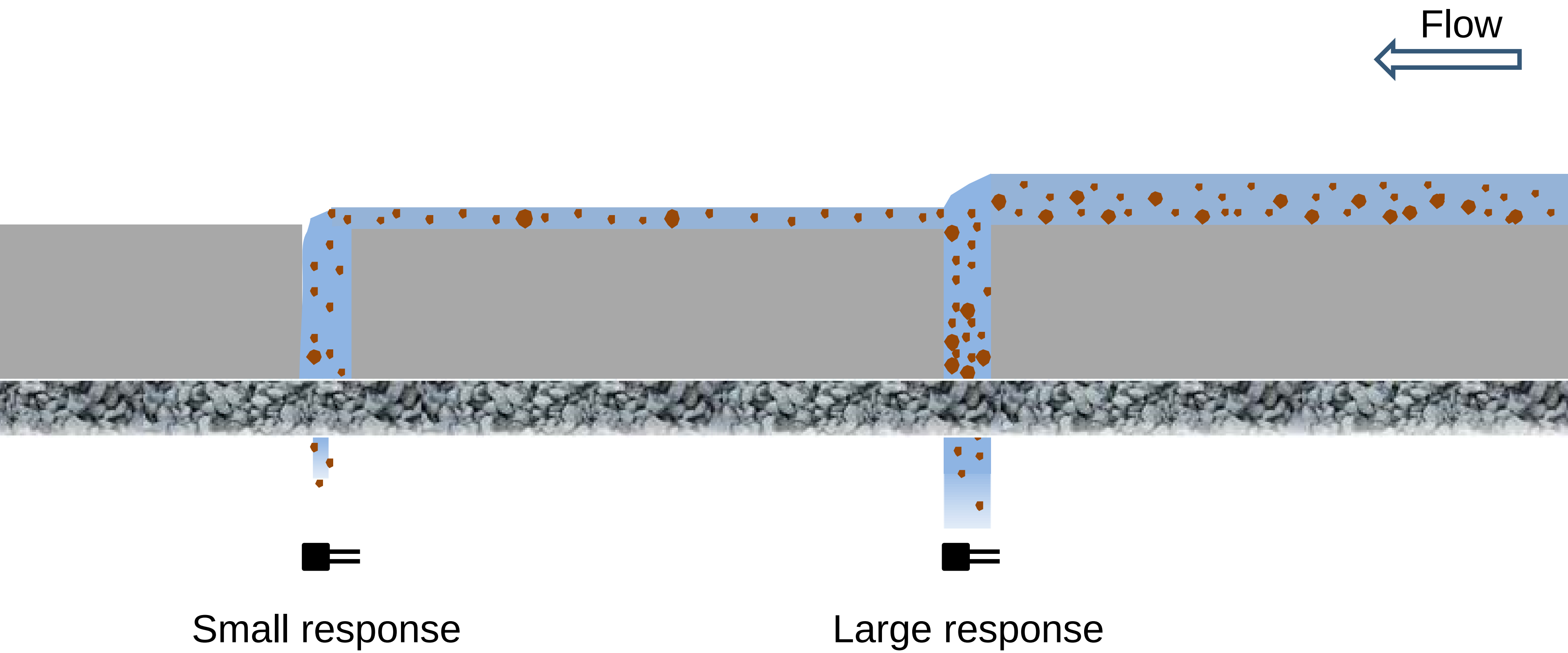
Bars represent standard error.

Sediment accumulates (*and clogging progresses*) from the upgradient edge.

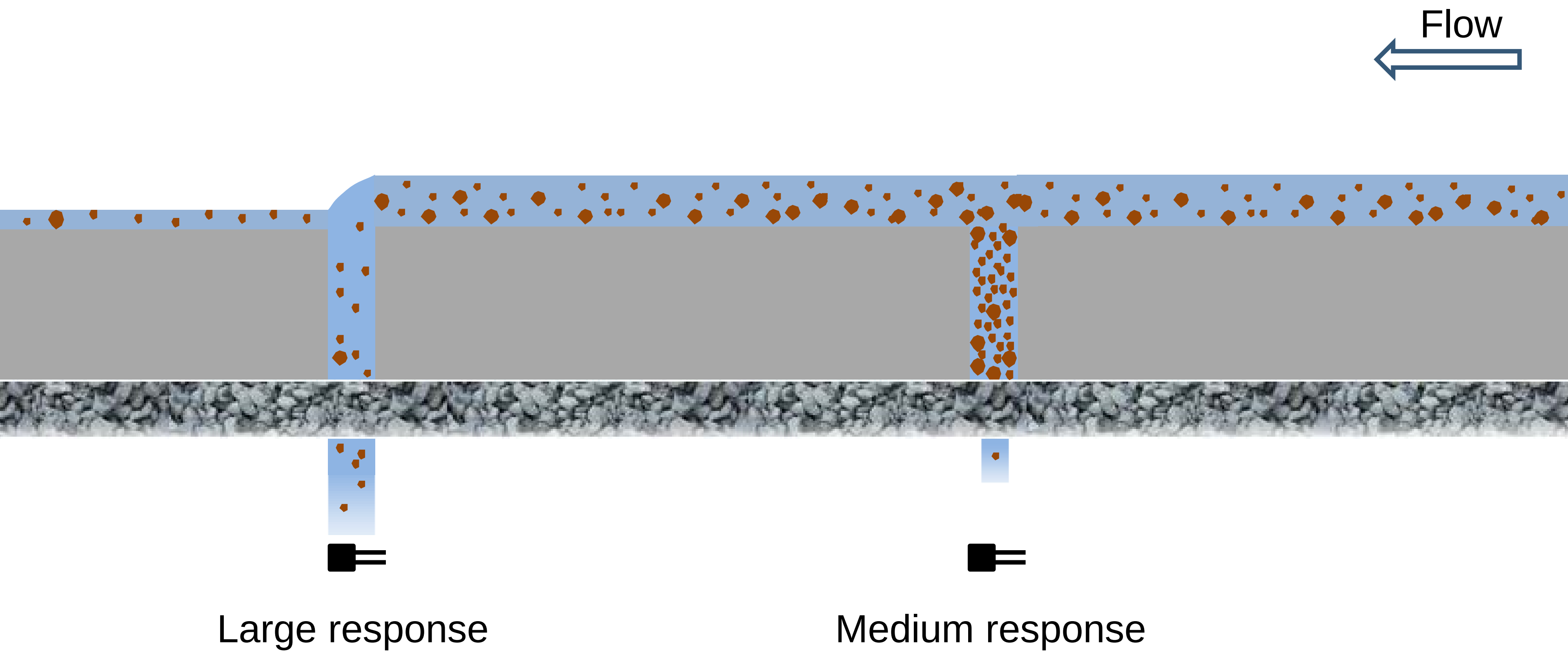
The surface clogging progression varied because of microtopography.



We developed a working hypothesis of the mechanics of the clogging processes.



As gaps fill with sediment, the location of the primary infiltration moves downgradient.



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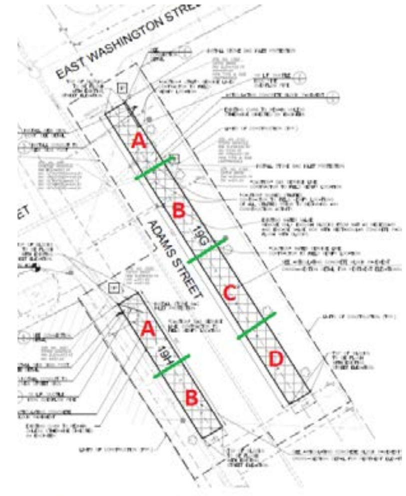
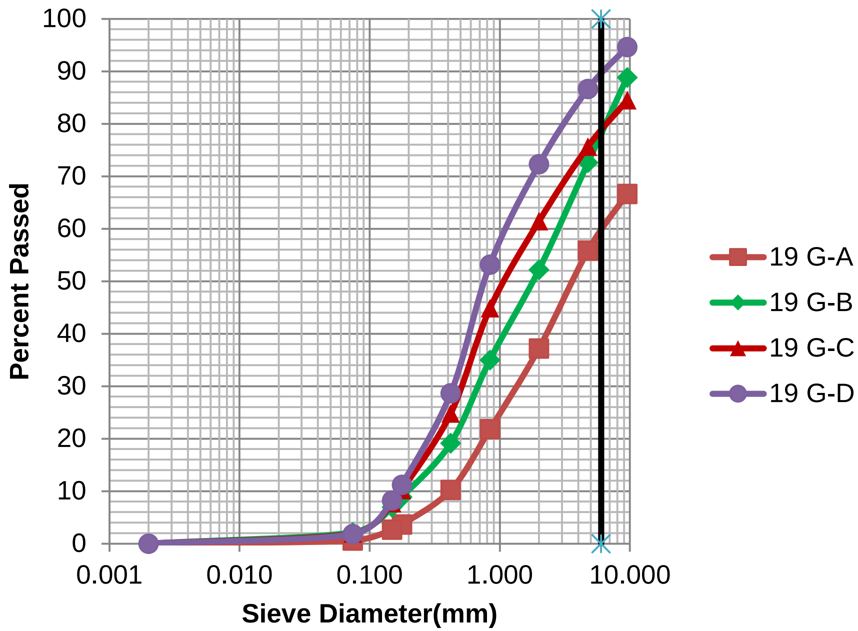
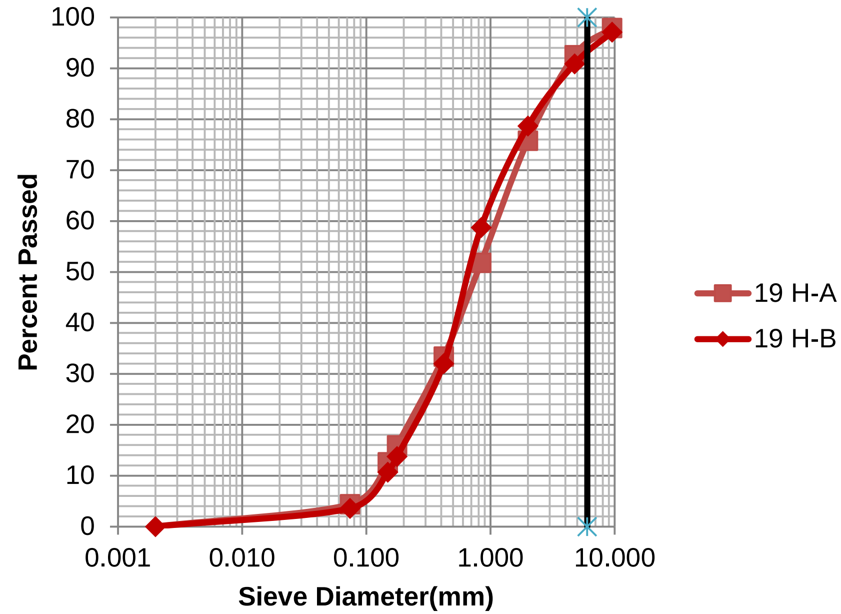
Recovered sediment particle size analysis shows initial accumulation of fines in the upgradient sections.





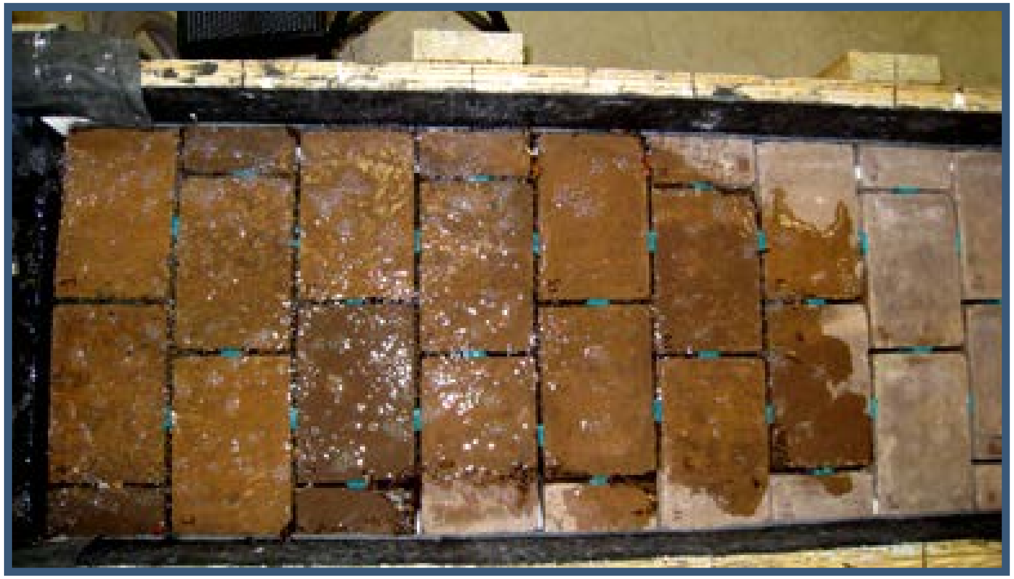
Mar. – May 2012
(9 in. rainfall)



Dec. 2011 – May 2012
(19 in. rainfall)

Data source:
Amirhossein Ehsaei – University of Louisville

Flume tests show the progressive infiltration of the runoff that leads to the clogging.



Photos: Amir Ehsaei
University of Louisville

The flume tests are showing the same general pattern of accumulated sediment as observed in the field.

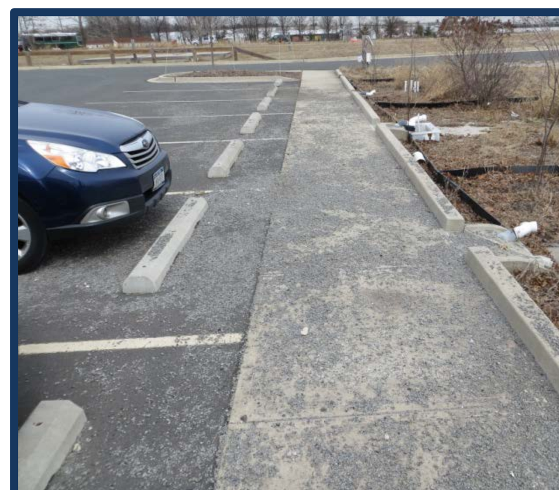
Inorganic material near up gradient edge

Organic material near down gradient edge

Photos: Amir Ehsaei
University of Louisville

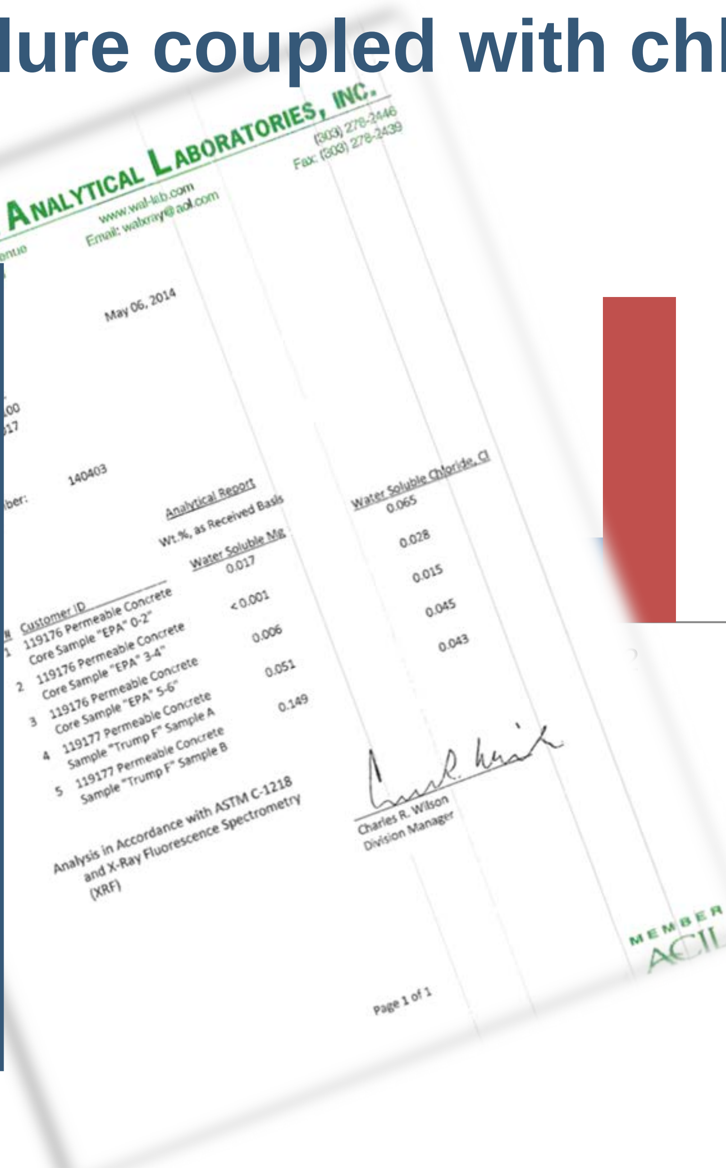
Large portions of the pervious concrete disaggregated.

The problem first became apparent about 18 months after pouring concrete. It was repaired by the contractor in May 2011, but has recurred.



Is structural failure coupled with chloride?

April 14, 2014



WYOMING ANALYTICAL LABORATORIES, INC.

www.wal-lab.com
Email: walxray@aol.com
(303) 278-2446
Fax: (303) 278-2439

May 06, 2014

140403

Analytical Report

Wt.%, as Received Basis

#	Customer ID	Water Soluble Mg	Water Soluble Chloride, Cl
1	119176 Permeable Concrete Core Sample "EPA" 0-2"	0.017	0.065
2	119176 Permeable Concrete Core Sample "EPA" 3-4"	< 0.001	0.028
3	119176 Permeable Concrete Core Sample "EPA" 5-6"	0.006	0.015
4	119177 Permeable Concrete Sample "Trump F" Sample A	0.051	0.045
5	119177 Permeable Concrete Sample "Trump F" Sample B	0.149	0.043

Analysis in Accordance with ASTM C-1218 and X-Ray Fluorescence Spectrometry (XRF)

Charles R. Wilson
Division Manager

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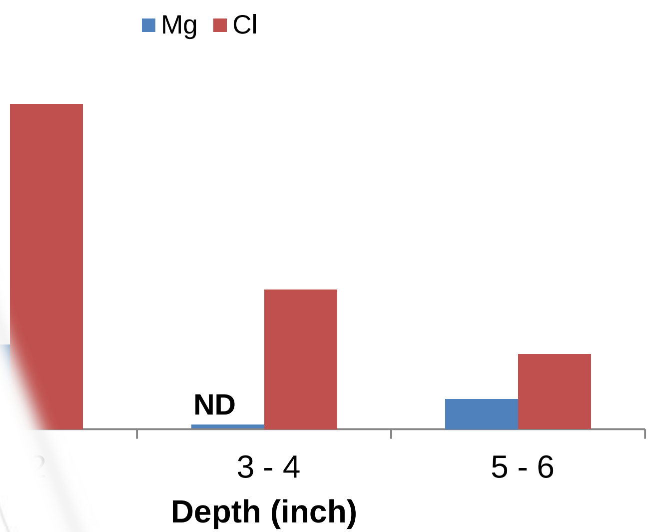

NRMCA revised O&M guidance (2015)

"Deicing chemicals should not be used on any type of concrete in the first year."

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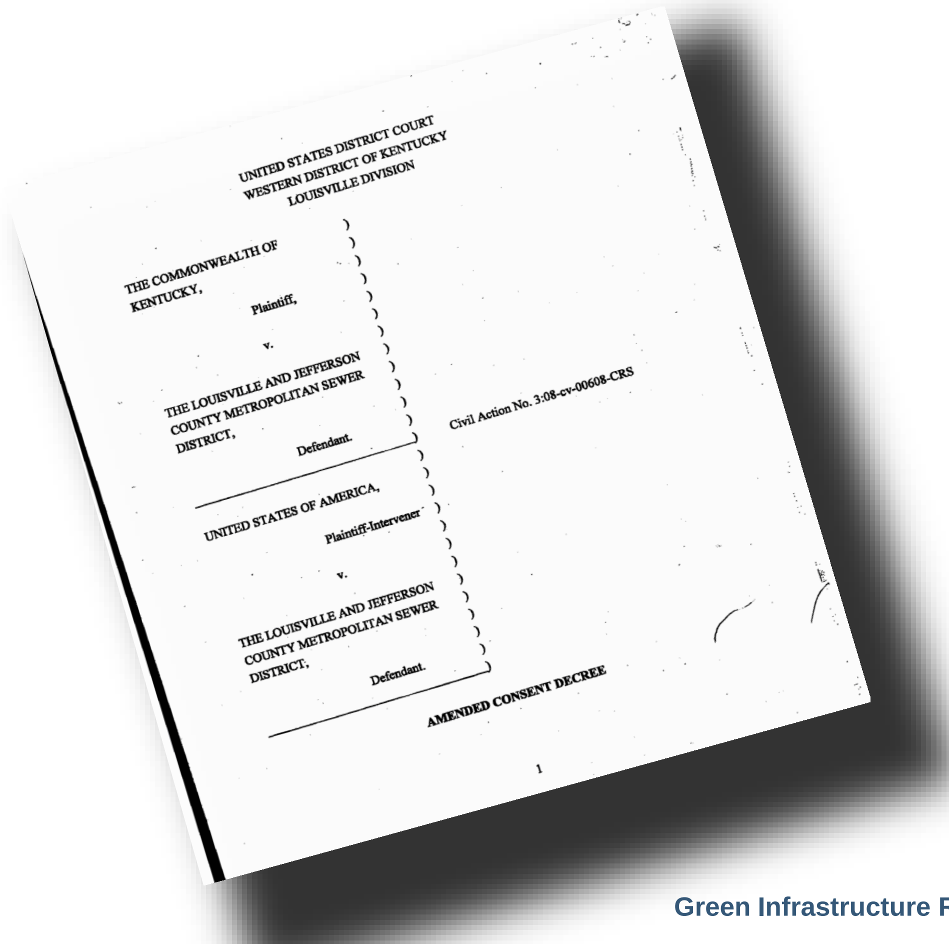
In 2011, Louisville MSD installed permeable pavement strips in parking lanes near the catch basins in the Butchertown section of Louisville.

In-Street Application
Louisville, Kentucky



UNITED STATES DISTRICT COURT
WESTERN DISTRICT OF KENTUCKY
LOUISVILLE DIVISION

THE COMMONWEALTH OF KENTUCKY,
Plaintiff,

v.

THE LOUISVILLE AND JEFFERSON COUNTY METROPOLITAN SEWER DISTRICT,
Defendant.

Civil Action No. 3:08-cv-00608-CRS

UNITED STATES OF AMERICA,
Plaintiff-Intervener

v.

THE LOUISVILLE AND JEFFERSON COUNTY METROPOLITAN SEWER DISTRICT,
Defendant.

AMENDED CONSENT DECREE

1

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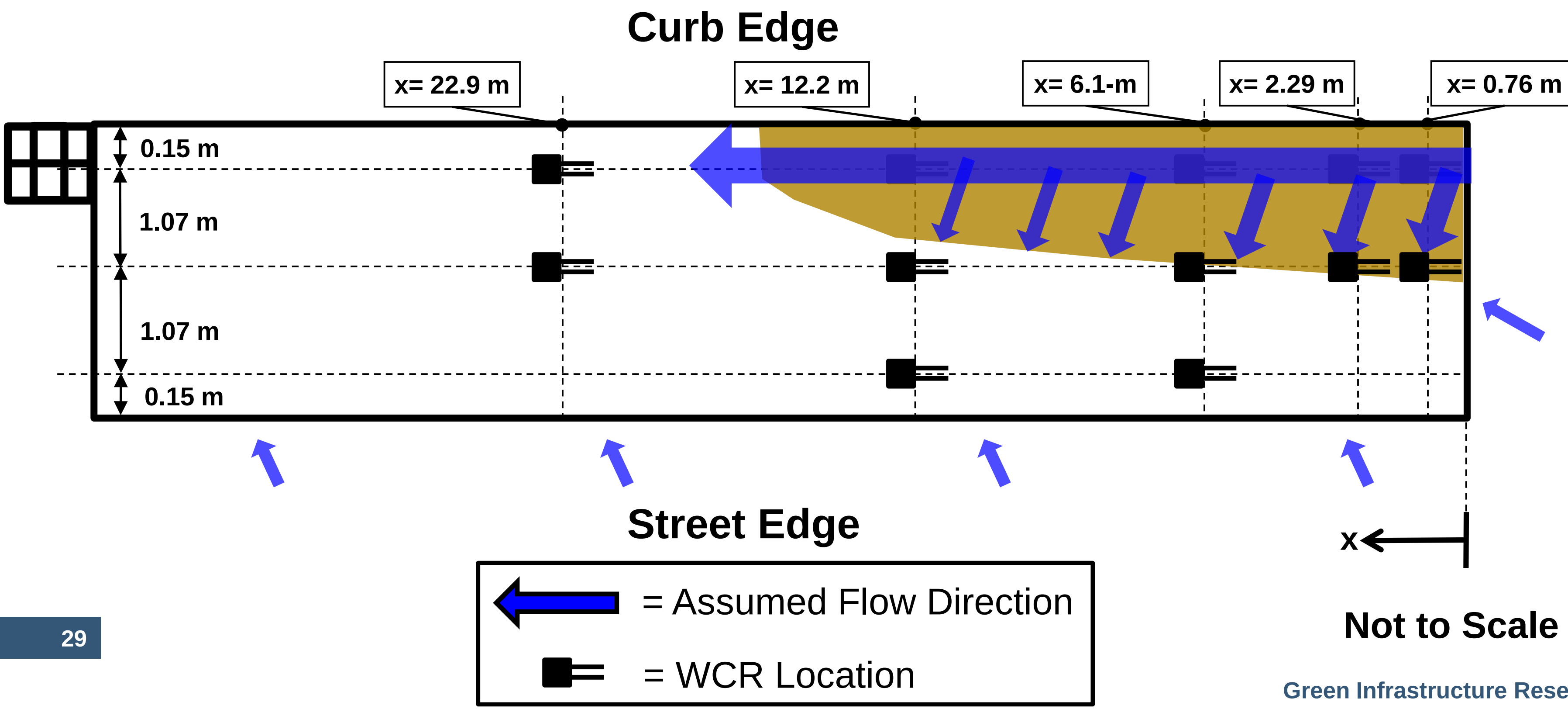
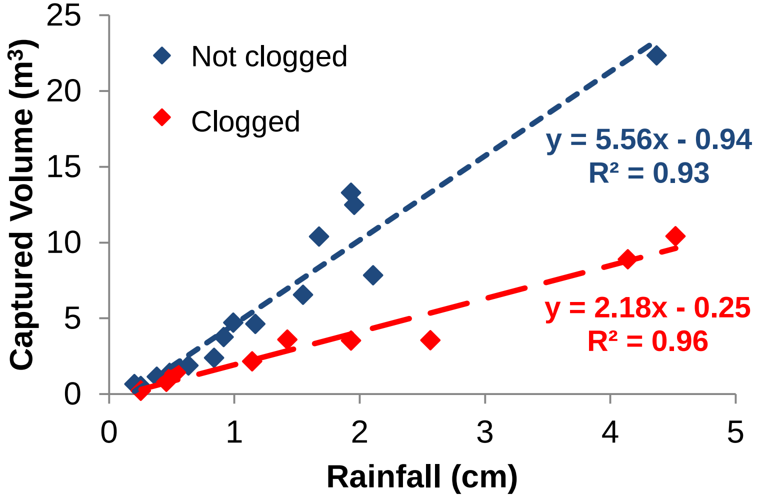
There are large variation in infiltration rates at small geographic scales.

Measurement location	Expected rate from “nearby” geotechnical survey 4.3 cm/hr			
	Control 19G		Control 19H	
	Infiltration rate (cm/hr)	USDA soil texture classification (% sand/silt/clay)	Infiltration rate (cm/hr)	USDA soil texture classification (% sand/silt/clay)
Upgradient	0.114	Sandy Loam (58/34/8)	0.258	Sandy Loam (55/36/9)
Middle	0.108	Loam (50/33/17)	0.780	Silt Loam (35/50/15)
Downgradient	0.012	Silty Clay Loam (18/52/30)	0.096	Sandy Loam (62/25/13)
Average	0.078		0.378	

In this curb and gutter system, we expected concentrated flow along the curb to transport and deposit sediment from the drainage area.



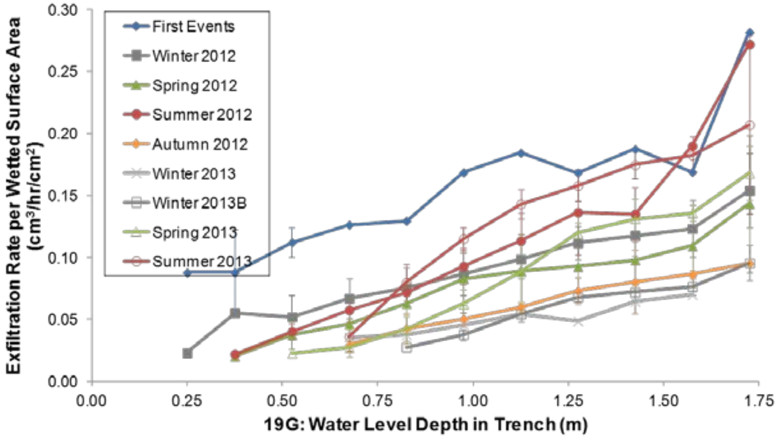


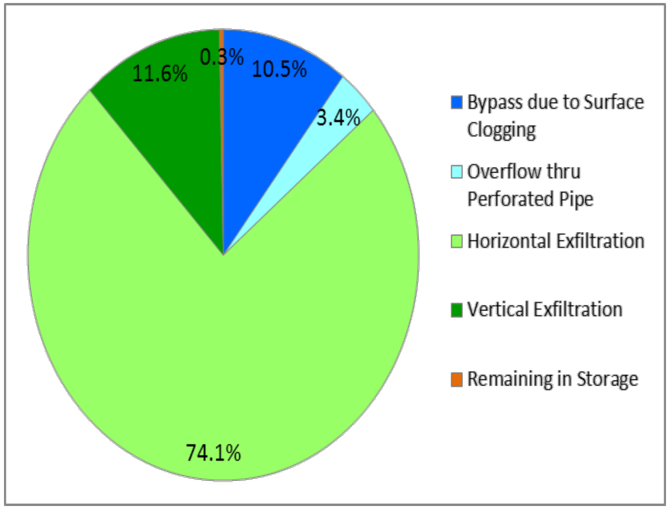
Findings:

- There are very large variations in soil hydraulic conductivity at small spatial scales.
- Clogged does not mean sealed.
- Embedded instruments can be used monitor the clogging progression.
- Clogging distance is proportional to rainfall depth and not time.
- Static volumetric design may cause oversized stormwater controls.

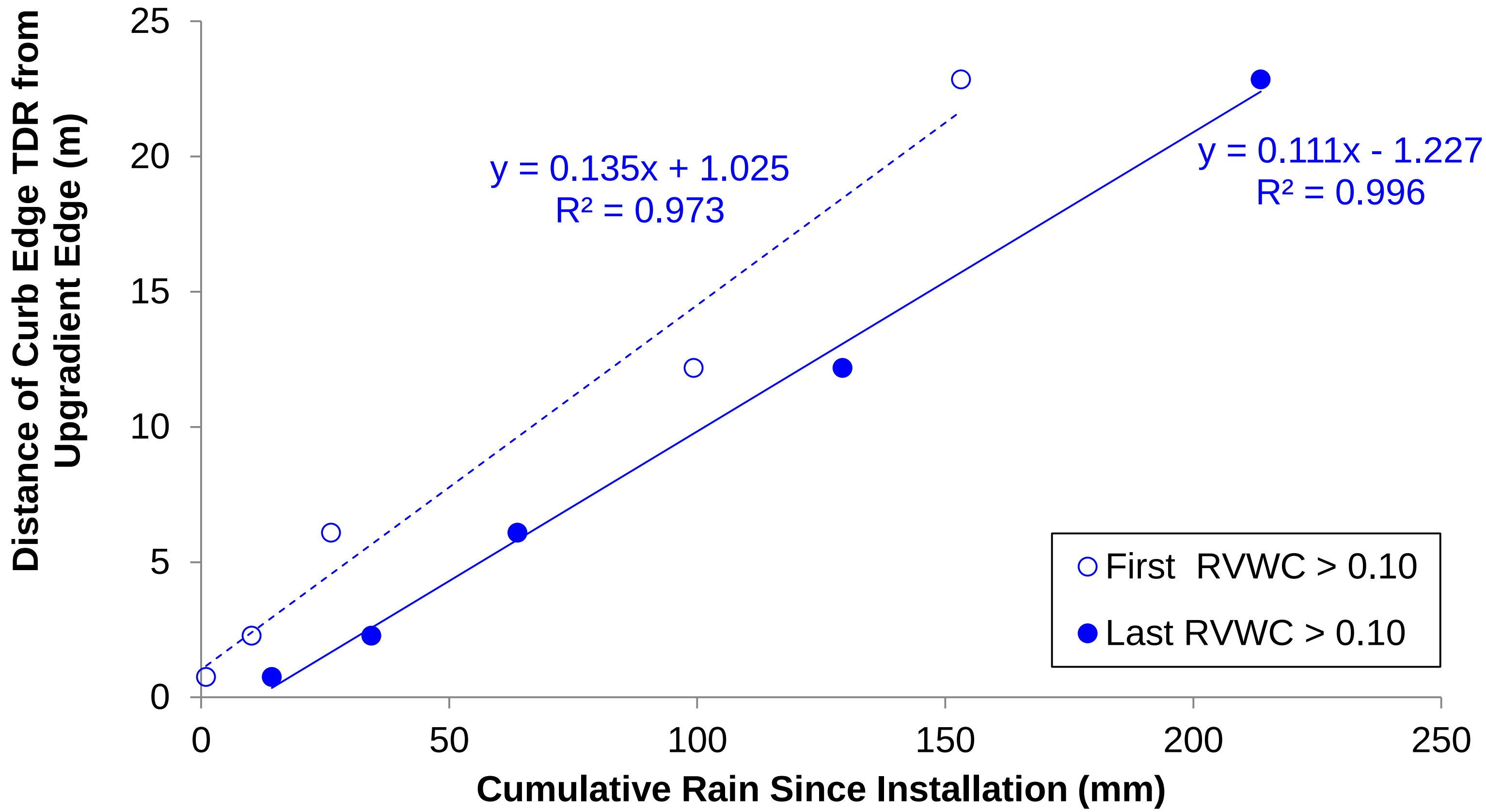
Findings:

- Exfiltration rates vary with age.
- Exfiltration rates vary with water depth and constant hydraulic flux is not representative of exfiltration processes.
- Much of the exfiltration occurs through the sides.
- SCM geometry is important.



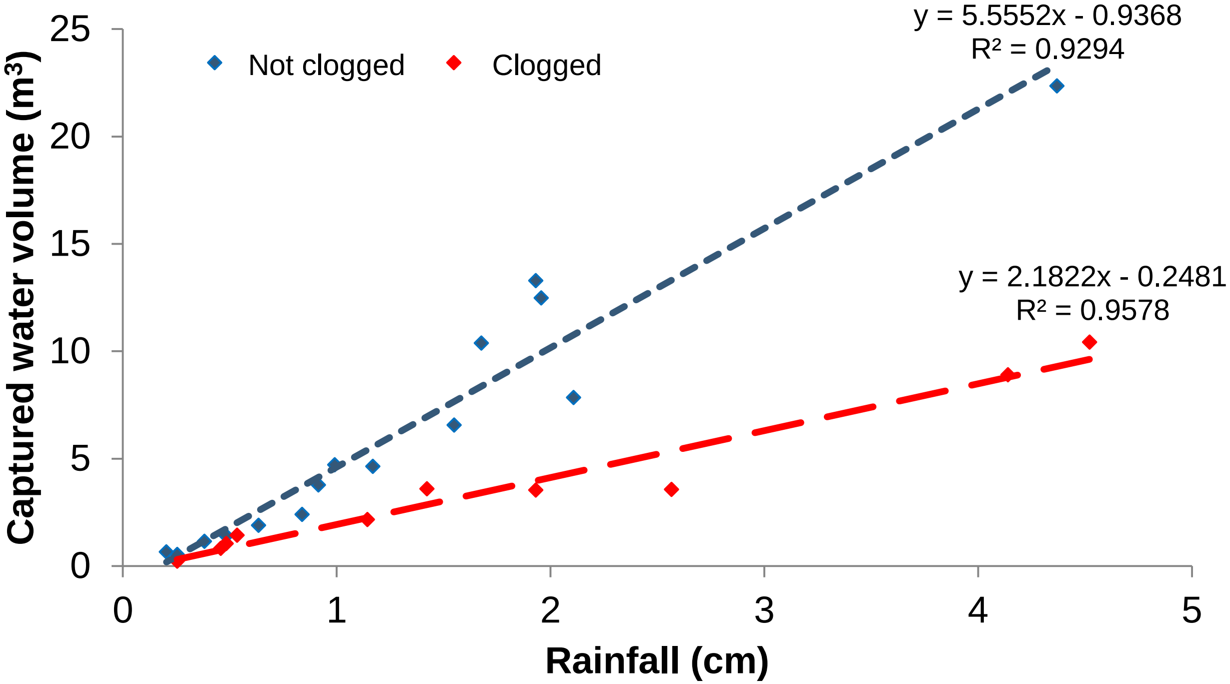


Installed instruments can be used to determine the control's longitudinal clogging rate.



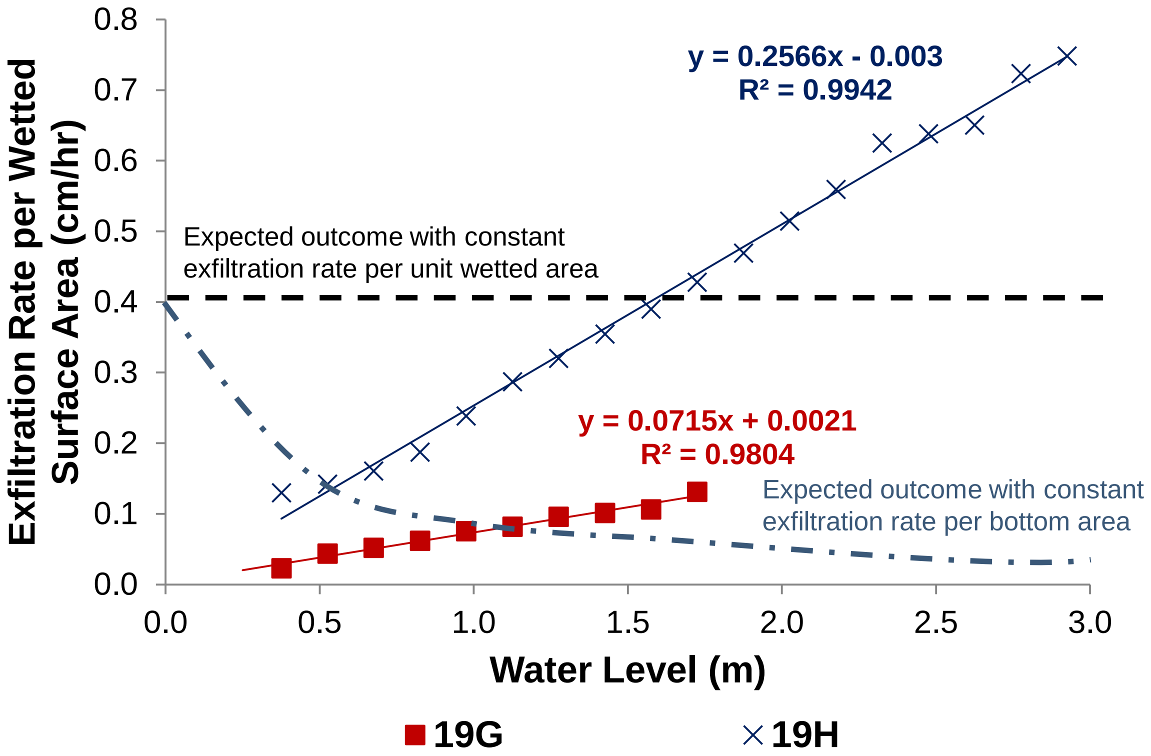
Control Louisville 19G
Response threshold 0.10 RVWC
The initial clogging rate was about 0.123 m per mm (10 ft per inch) of rain.

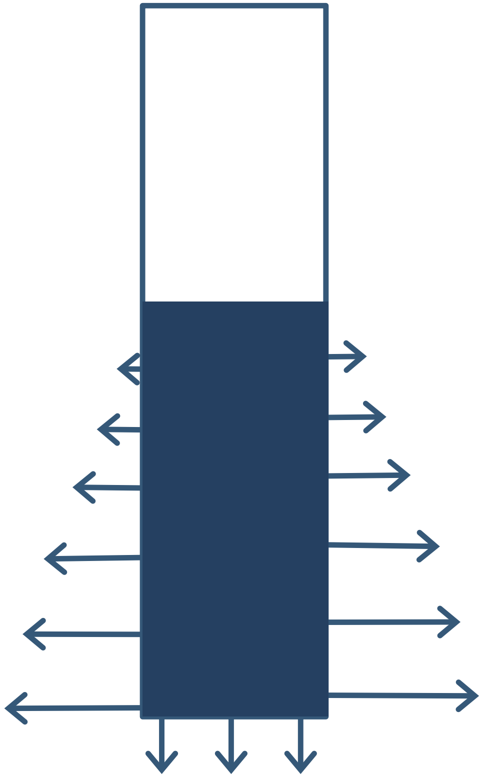
Even when clogged, the surface is not sealed.



Louisville control 19H
Level data at 1-minute intervals
Rainfall data at 5-minute intervals MSD gauge TR05

Constant exfiltration across wetted perimeter or base is not supported by the measurements.

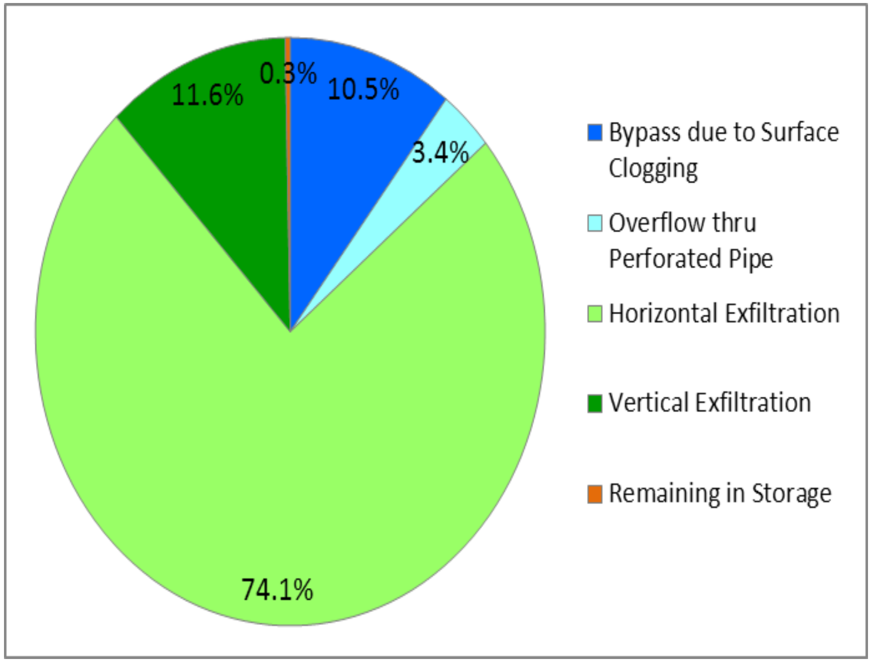




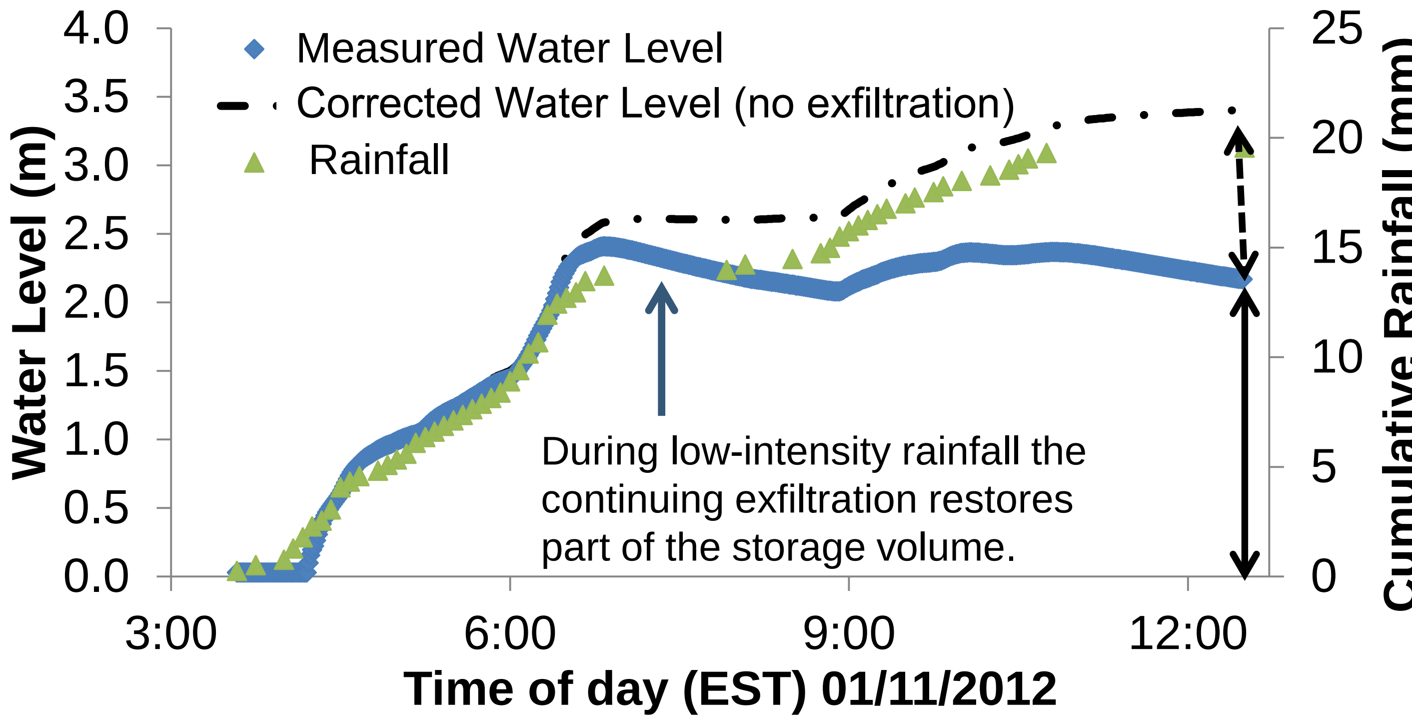
Modeling the fate of runoff showed that most of the captured water exfiltrated laterally through the side walls.

Subsurface flow patterns and interactions with groundwater will be the emphasis of near-term studies in KY and KS.

Flow patterns will also be investigated in Philadelphia under the NCER cooperative agreements.



Intra-event exfiltration can be significant



Static sizing criterion may significantly oversize the SCM.

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Maintenance:

- Multiple techniques were implemented.
- Each technique increased surface infiltration capacity, but did not always restore baseline conditions.
- Longevity of the restored infiltration capacity varied.
- Results are probably product specific.

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We have costs for maintenance activities undertaken to date but have concerns about scaling.

Cost of initial maintenance techniques			
Method	Cost ($)	Area maintained (ft^2)	Unit cost ($/ ft^2)
Sweeping	370	960	0.385
Air jetting & brush	921	1,400	0.658

Note: We expect some economy of scale to produce lower unit costs when additional controls are built.

Sweeping was only done to control 19G. Fixed mobilization / demobilization costs may skew unit cost estimate

Data source: URS

Construction costs have been essentially proportional to volume.

Item	Quantity	Unit Cost ($)	Extended Cost ($)	Fraction (%)
No. 57 Aggregate	52 CY	0.61	3,172	6.6
Geogrid	1,400 SF	4.00	5,600	11.6
Pavers	1,400 SF	14.00	19,600	40.6
Earthwork	235 CY	35.00	8,225	17.1
No. 3 Aggregate	181 CY	40.00	7,240	15.0
Asphalt removal	1,400 SF	0.75	1,050	2.2
Overflow pipe	LS		1,200	2.5
Traffic control	LS		600	1.2
Survey & stake	LS		200	0.4
Erosion / sediment control	LS		200	0.4
Bonding	LS		650	1.3
Mobilization / Demobilization	LS		500	1.0
Total			$48,237	100.0

$126/sq yd

Semi-fixed costs 4.5% of total

$310/sq yd

Costs: November 2011 Louisville, KY Two paver strips. Excludes monitoring costs and change orders

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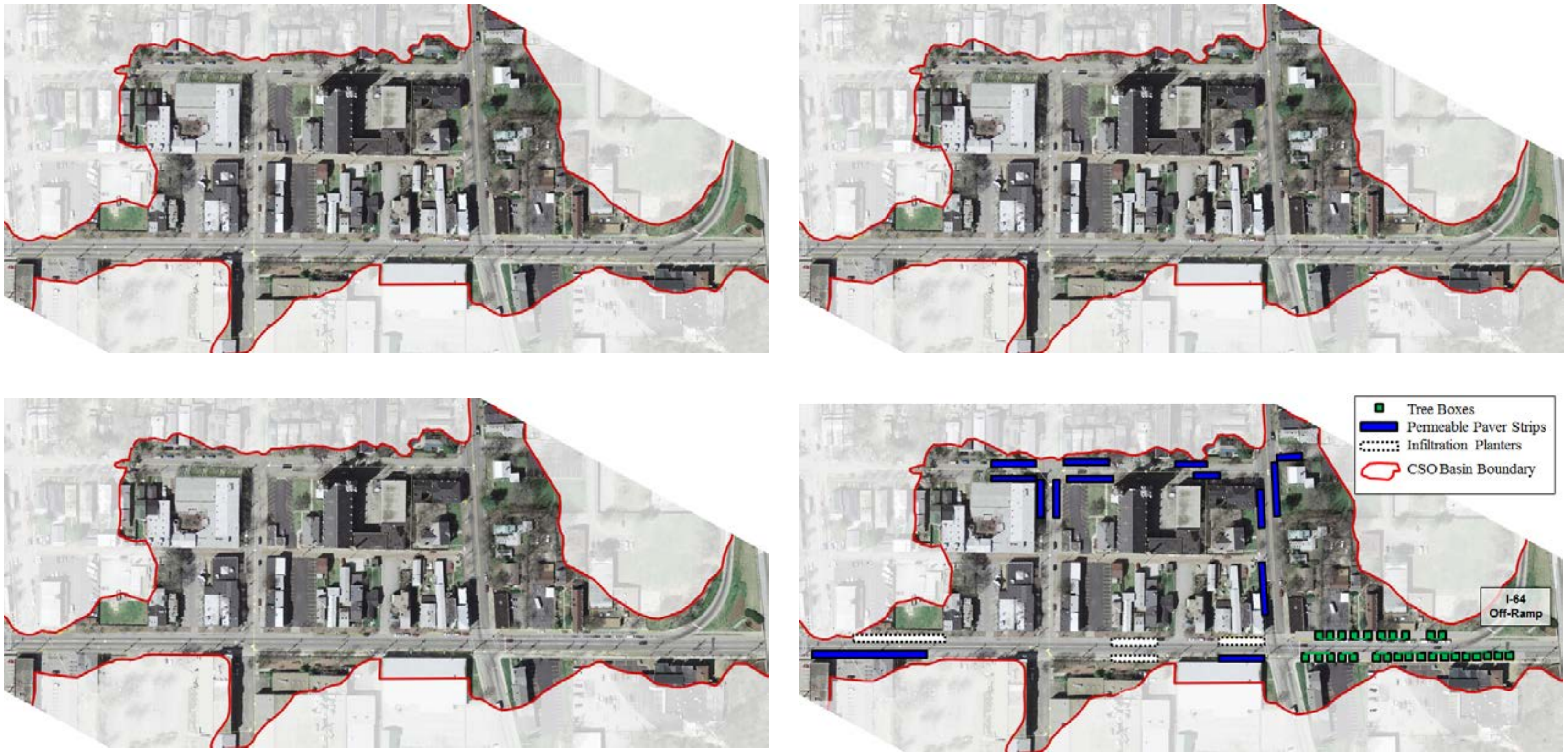
EFFECTIVENESS

Ideally, we wanted a Before-After Control-Impact (BACI) Study.

Control | Impact

Before | After



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Plan “B” created a virtual sewershed for comparison.

Modeled (InfoWorks) | **Measured**

Before

After

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The statistics allow determination of whether the "impact" had a measurable effect after adjusting for all other factors.

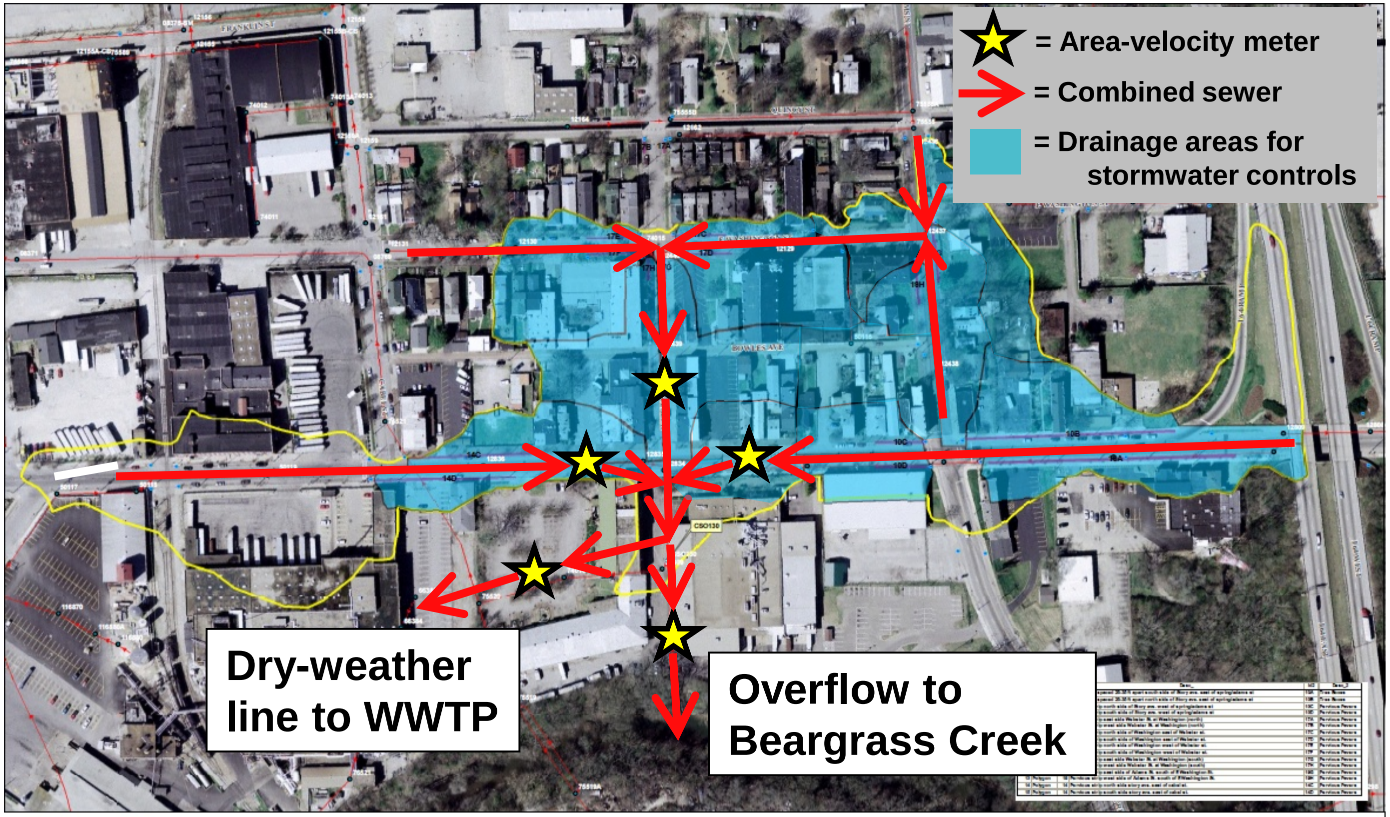
	Control	Impact
Before	• $X_{1,1}, X_{1,2}, X_{1,3}$ . . .	• $X_{2,1}, X_{2,2}, X_{2,3}$ …
After	• $X_{3,1}, X_{3,2}, X_{3,3}$ . . .	• $X_{4,1}, X_{4,2}, X_{4,3}$ . . .

In-sewer flows were measured at 5 locations for at least 1 year before construction to develop the preconstruction condition model using InfoWorks (Innovyze).

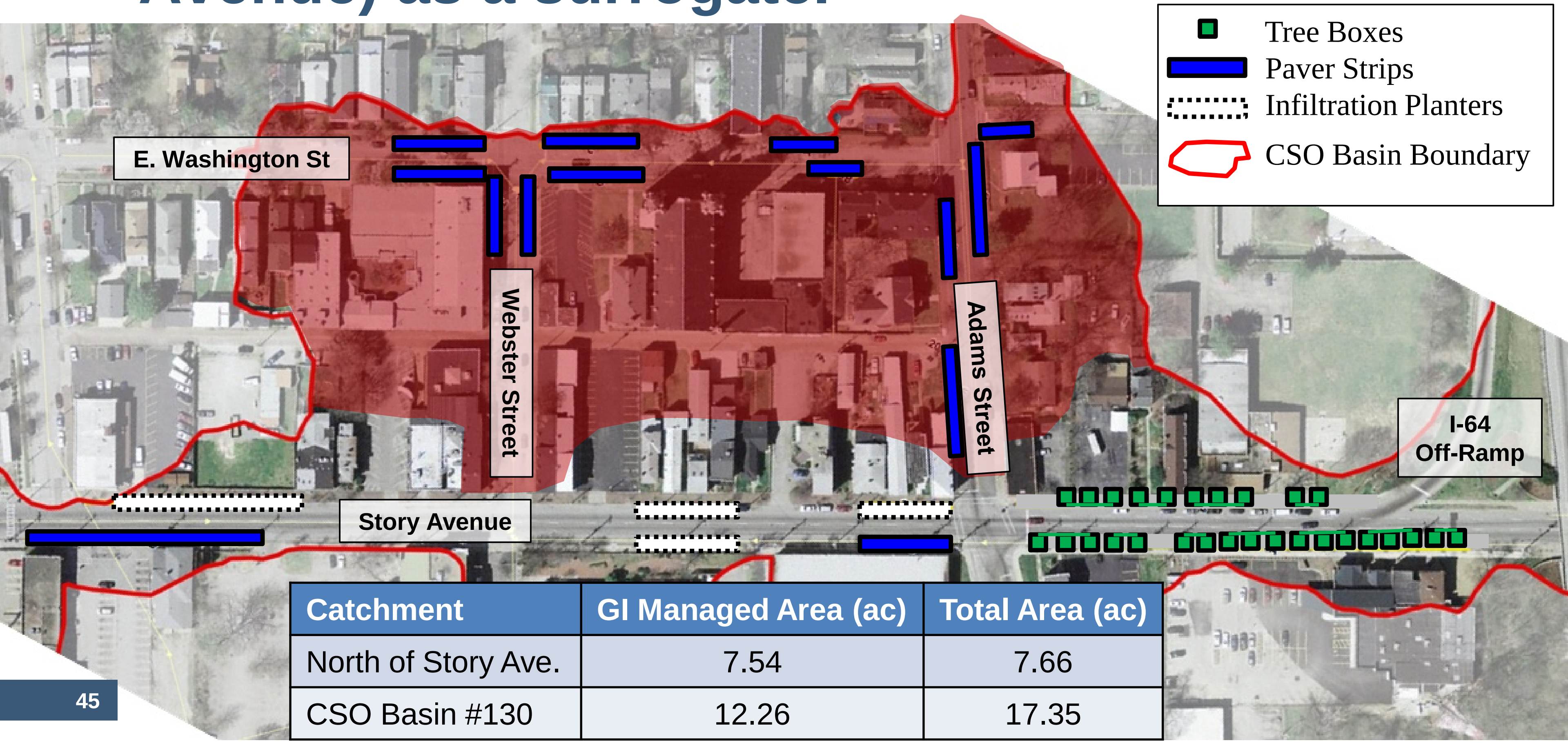
Sigma 920 area-velocity flow meters (later FloWav) were installed and managed by LJCMSD.

The flow meters separated the basin into 4 catchments, and catch basins were used to define 29 subcatchments.

Drainage areas were defined using 6-inch LIDAR data and refined with on-site observations.

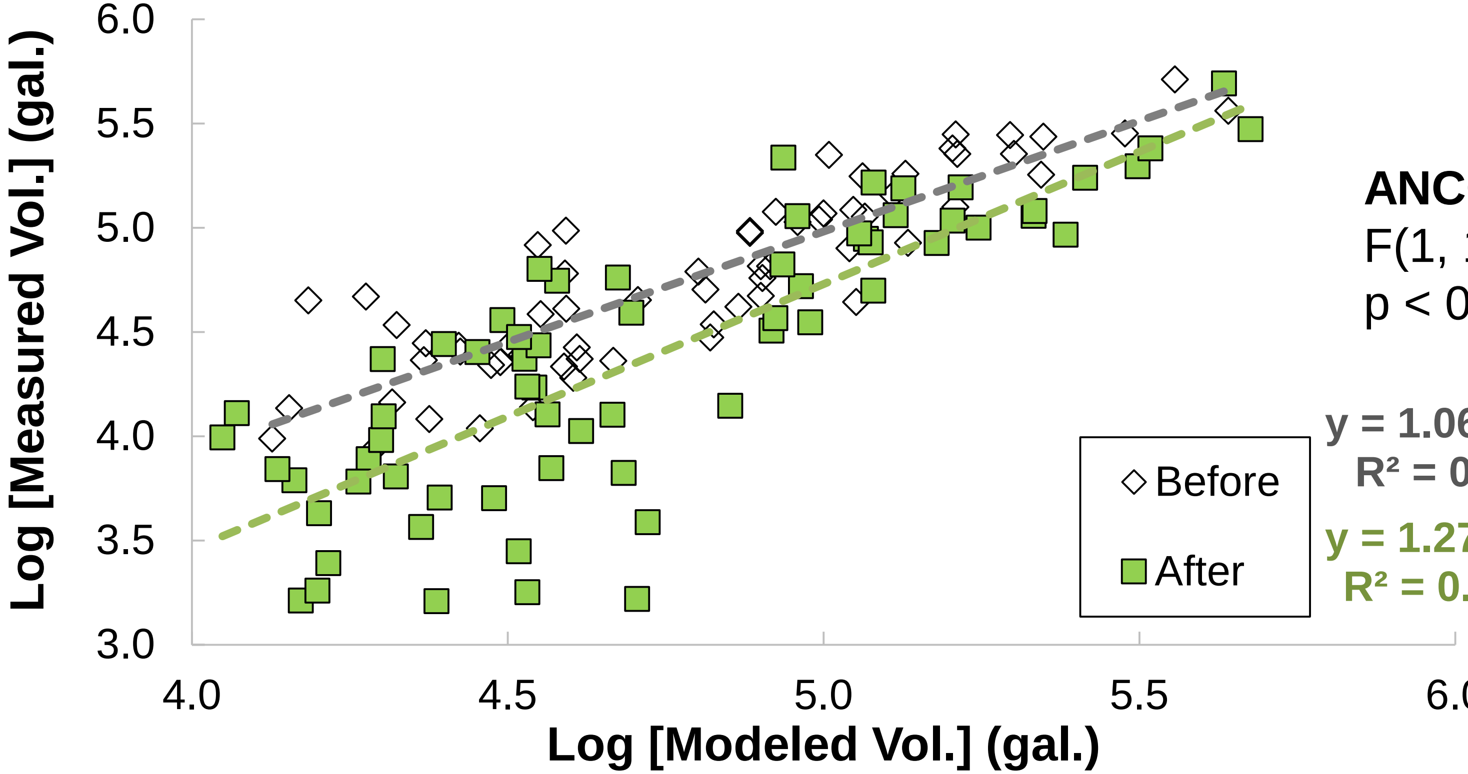


We selected the largest subsewershed area to evaluate the effectiveness (north of Story Avenue) as a surrogate.



Catchment	GI Managed Area (ac)	Total Area (ac)
North of Story Ave.	7.54	7.66
CSO Basin #130	12.26	17.35

Using the BACI approach, GI significantly reduced in-sewer flow volume per event.



ANCOVA Result:
F(1, 128) = 30.84
p < 0.0001

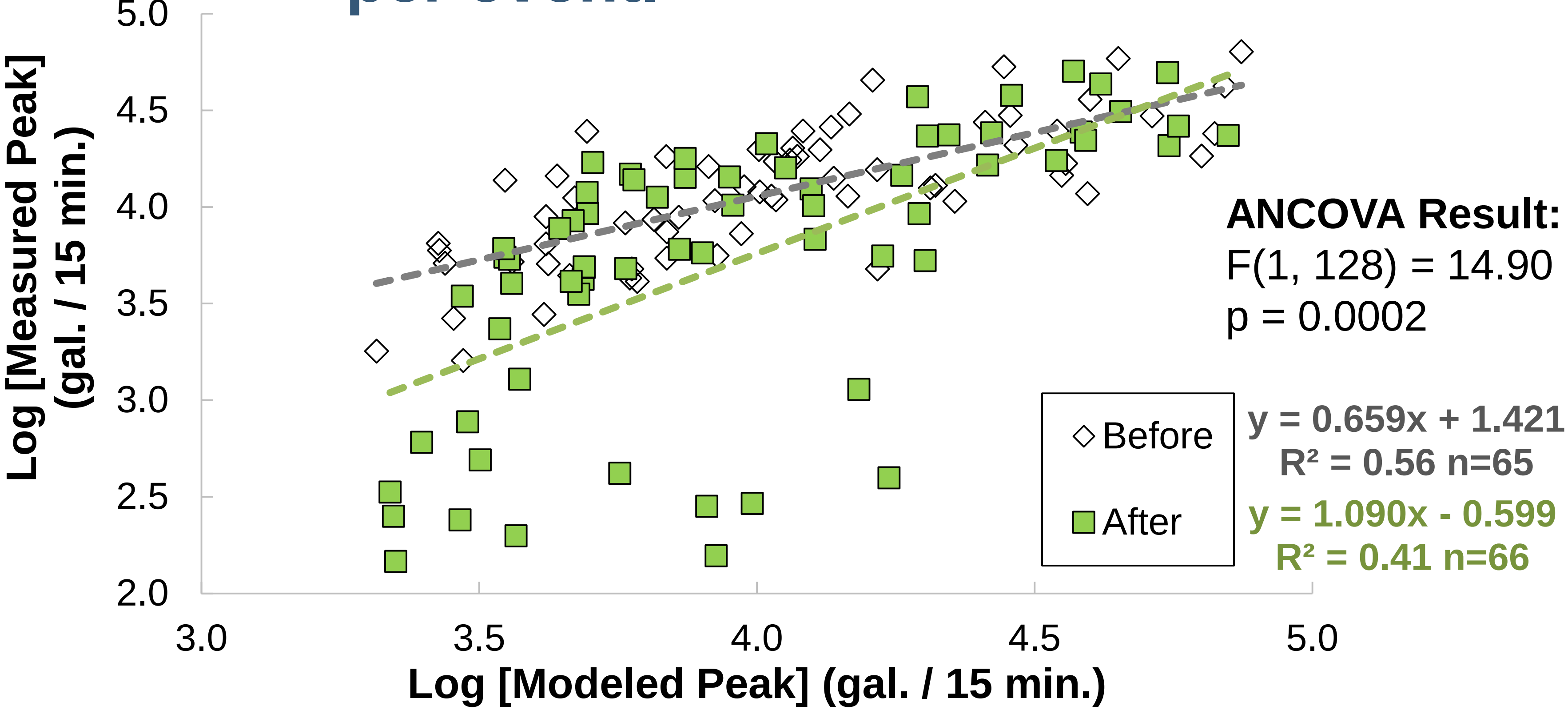
y = 1.061x - 0.320
R^2 = 0.78 n=65

y = 1.271x - 1.624
R^2 = 0.67 n = 66

Period	**Control** Mean (gal)	**Impact [GI]** Mean (gal)	**Predicted [GI]** (gal)	**% Change**
Before	63,509	59,319		
After	54,108	**24,623**	**50,053**	**– 51%**

North of Story Avenue Catchment

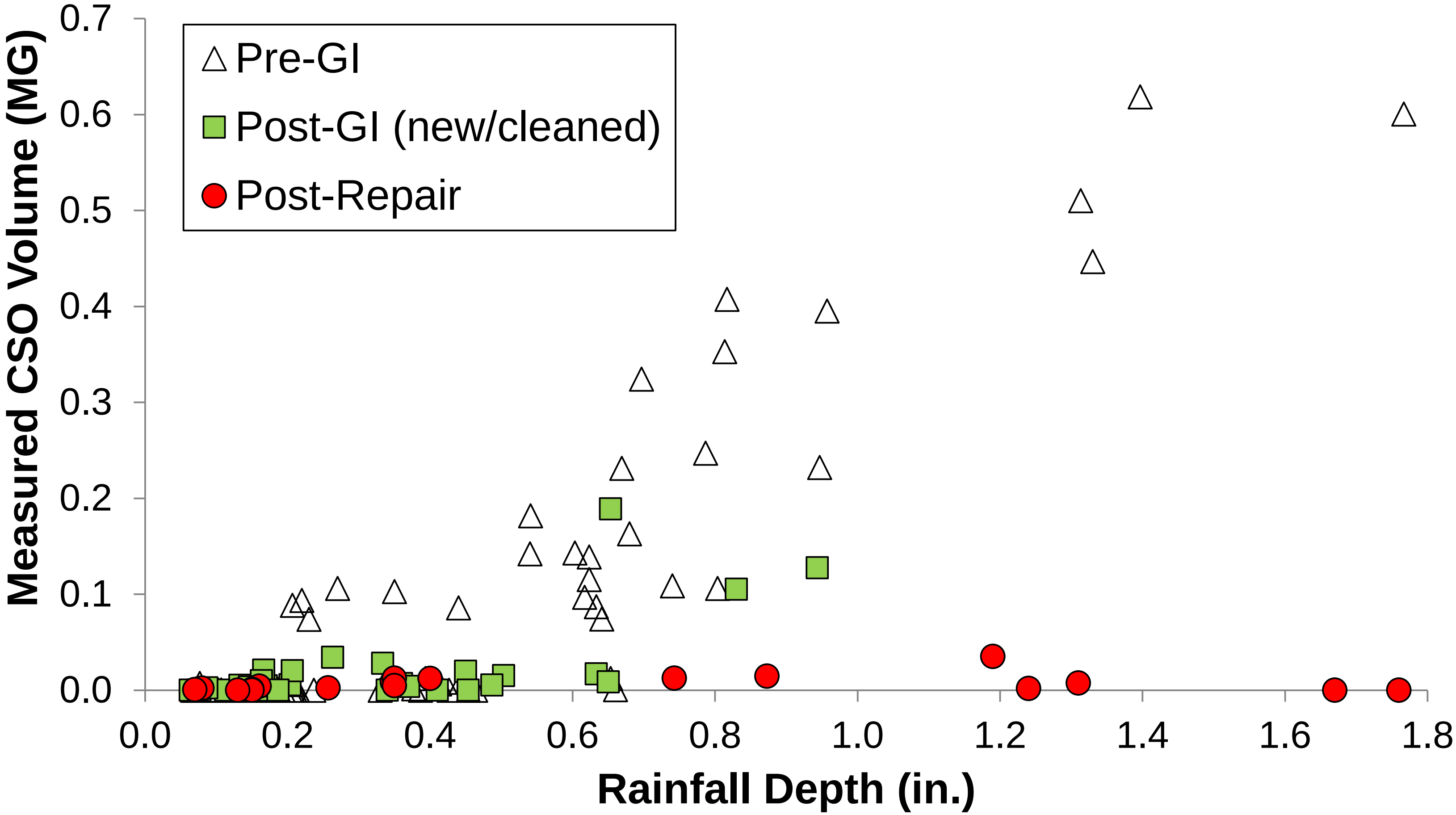
Using the BACI approach, GI also significantly reduced peak flow rates per event.



Period	Control (gal. / 15 min.)	Impact [GI] (gal. / 15 min.)	Predicted [GI] (gal. / 15 min.)	% Change
Before	11,051	12,122		
After	9,308	**5,313**	**10,826**	**– 51%**

North of Story Avenue Catchment

Results after replacing the dry-weather line are promising for meeting basin AAOV targets.



Repairs completed 11/06/2014)

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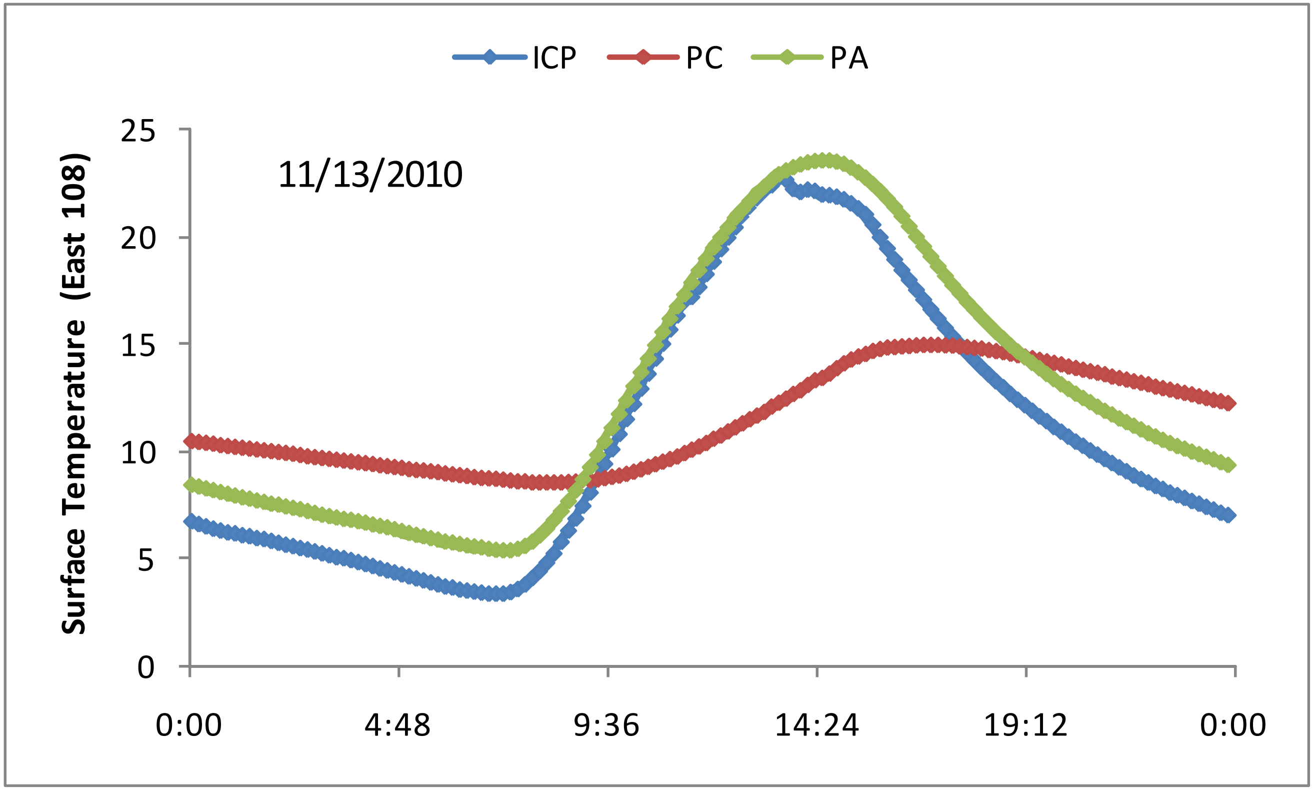
OTHER STUFF

The typical diurnal surface temperature pattern shows …..



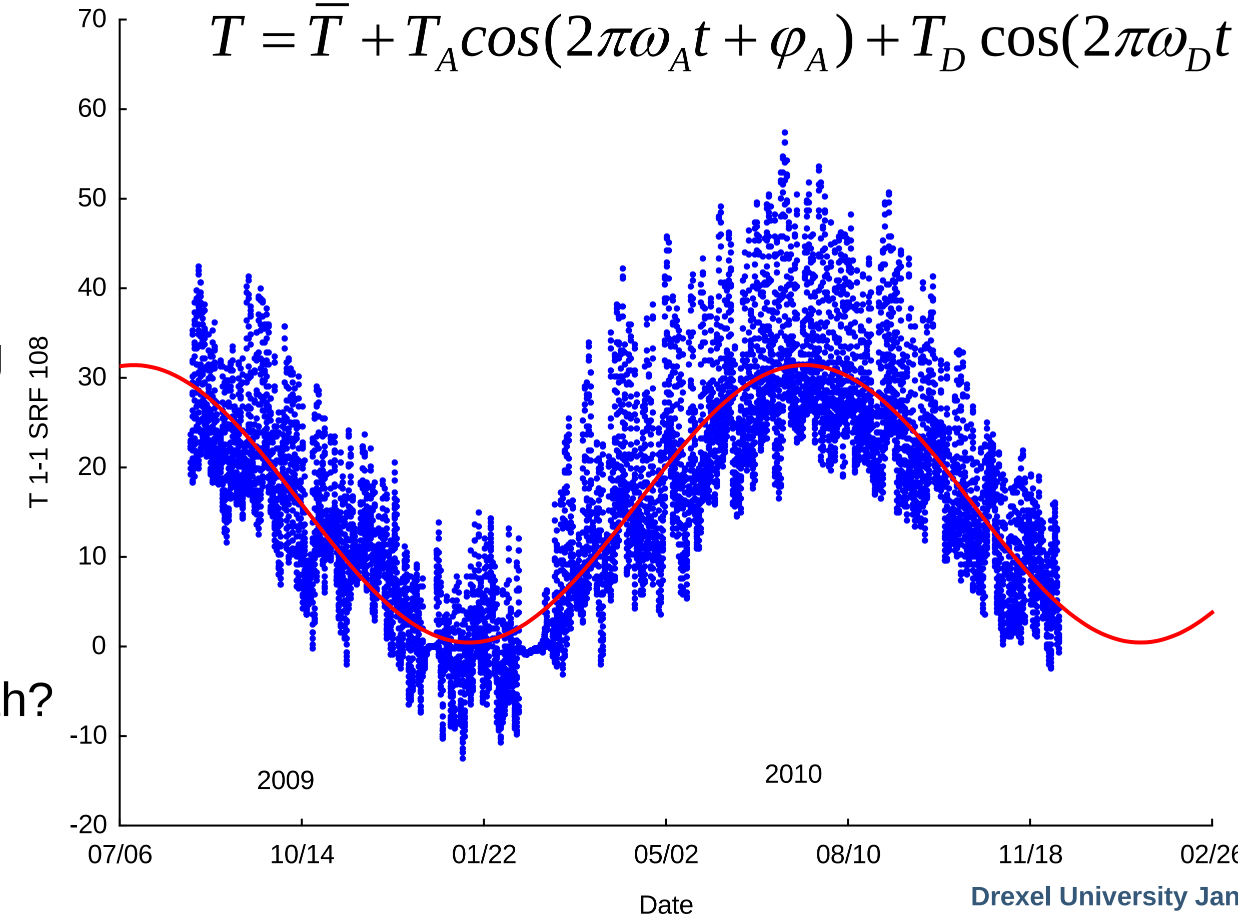
In the process of going from data to information.

$$T = \bar{T} + T_A cos(2\pi\omega_A t + \varphi_A) + T_D \cos(2\pi\omega_D t + \varphi_D)$$

Average and annual amplitude look reasonable. Daily varies during Year (monthly?).

Annual and daily phase shift?

Variation with depth?

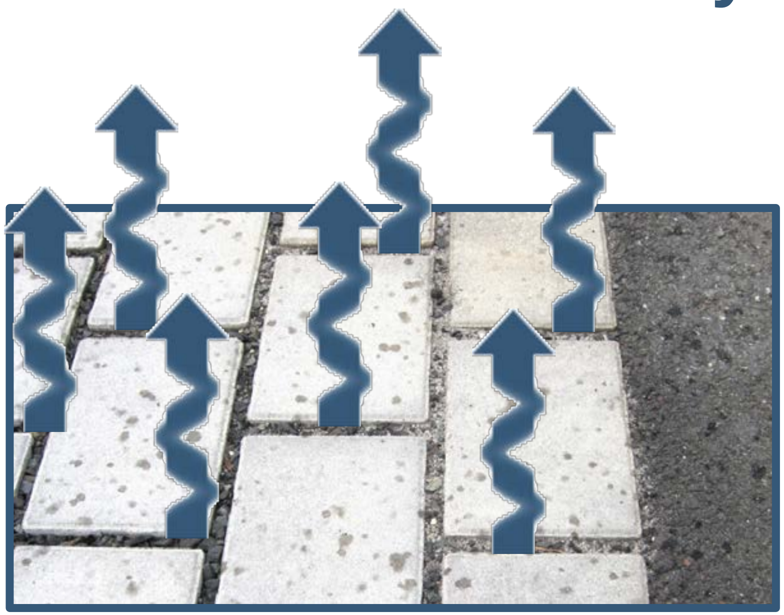


How do these surfaces affect the urban heat island?

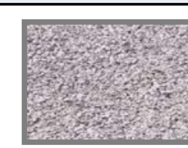
How do short and long wave radiation patterns differ among the surfaces?

United States Environmental Protection Agency

Annually, evaporation from the storage gallery accounted for a measureable part of the rainfall volume for this system.



	Percentage of rainfall volume on design drainage area that evaporated		
Surface	**PICP**	**PC**	**PA**
Section 1	5.8%	N/A (leaked)	3.9%
Section 2	4.4%	7.0%	5.6%
Section 3	3.9%	7.6%	2.4%
Section 4	5.8%	6.5%	4.2%
Average	**5.0%**	**7.0%**	**4.0%**


Design to help mitigate UHI?
Strategic select for arid v. humid areas?

Journal of Hydrological Processes 2014 DOI: 10.1002/hyp.10359

United States
Environmental Protection
Agency

Office of Research and Development
National Risk Management Research Laboratory
Water Supply and Water Resource Division
Urban Watershed Management Branch

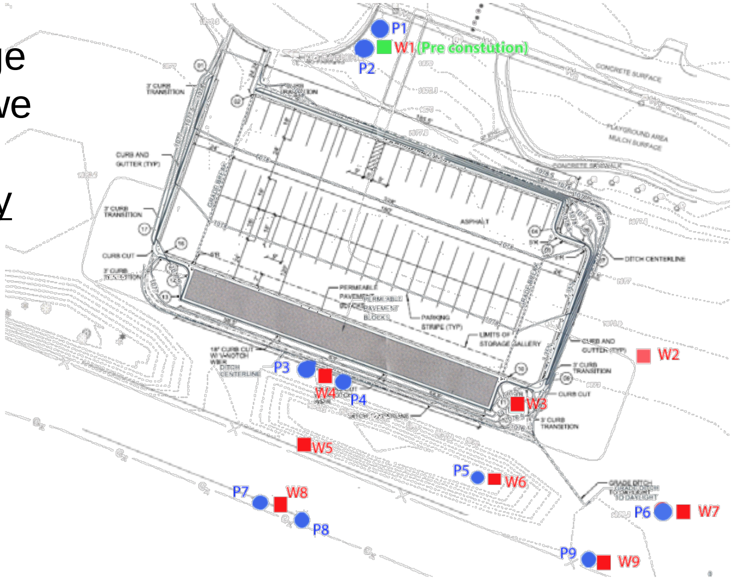
Green Infrastructure Research

Sneak preview of upcoming research

- How do SCMs interact with groundwater?
  - Hydrology
  - Chemistry
- What are the mechanics of SCMs?

Near-field monitoring of groundwater using wells and piezometers

In addition to monitoring the storage gallery infiltration and exfiltration, we are installing a collection of wells, piezometers, and tensiomters to try to monitor the subsurface processes.



We are starting a similar project in an urban setting in Louisville.

Google earth