Permeable Pavement Research Highlights

Performance and effectiveness of permeable pavement systems

Michael Borst

Edison Environmental Center
Edison, New Jersey

Story Ave.
Louisville, Kentucky

Sietz Elementary School
Fort Riley, KS

Office of Research and Development
National Risk Management Research Laboratory
Water Systems Division
Water Resources Recovery Branch

EPA designed and built a parking lot at the Edison Environmental Center.

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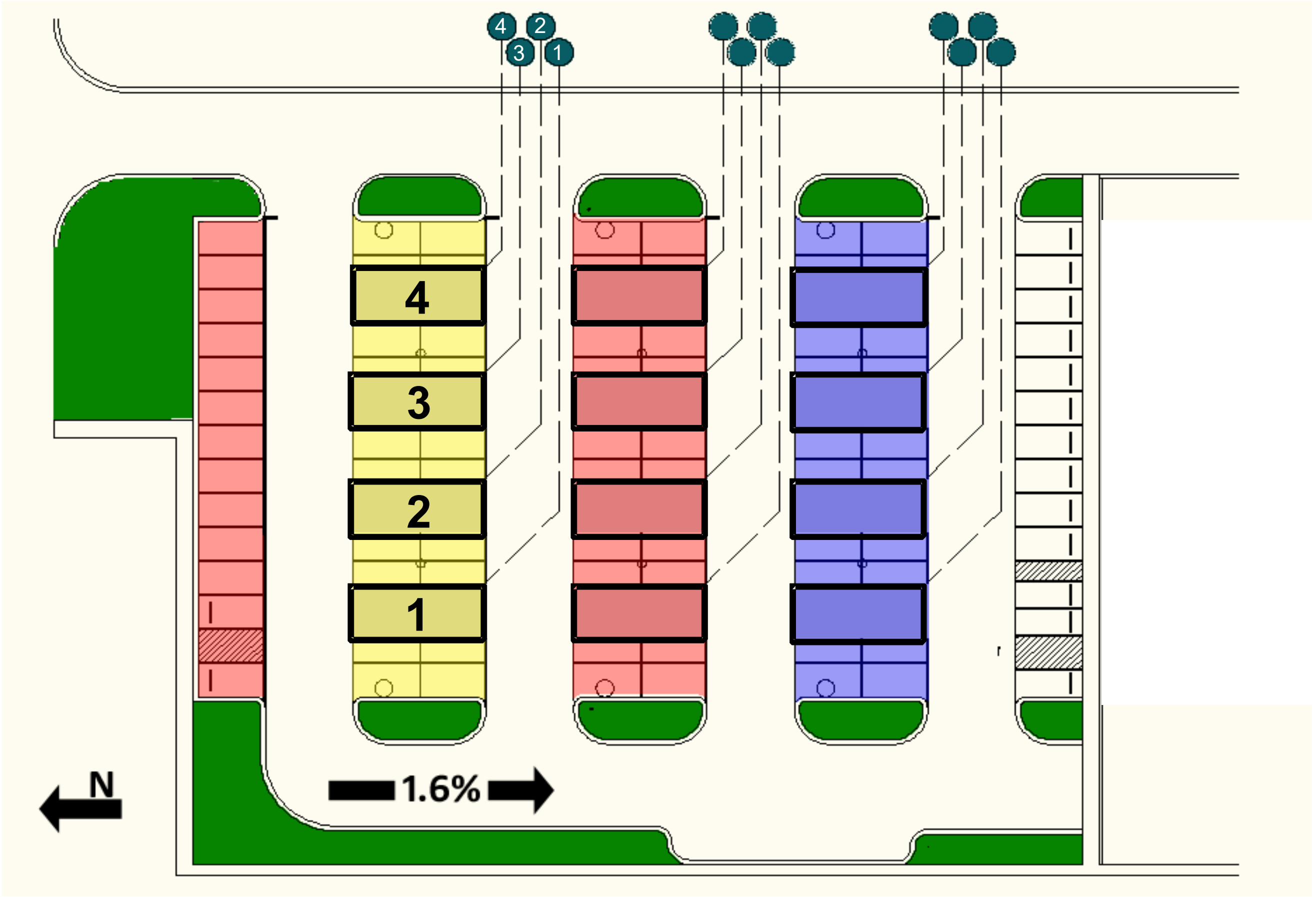
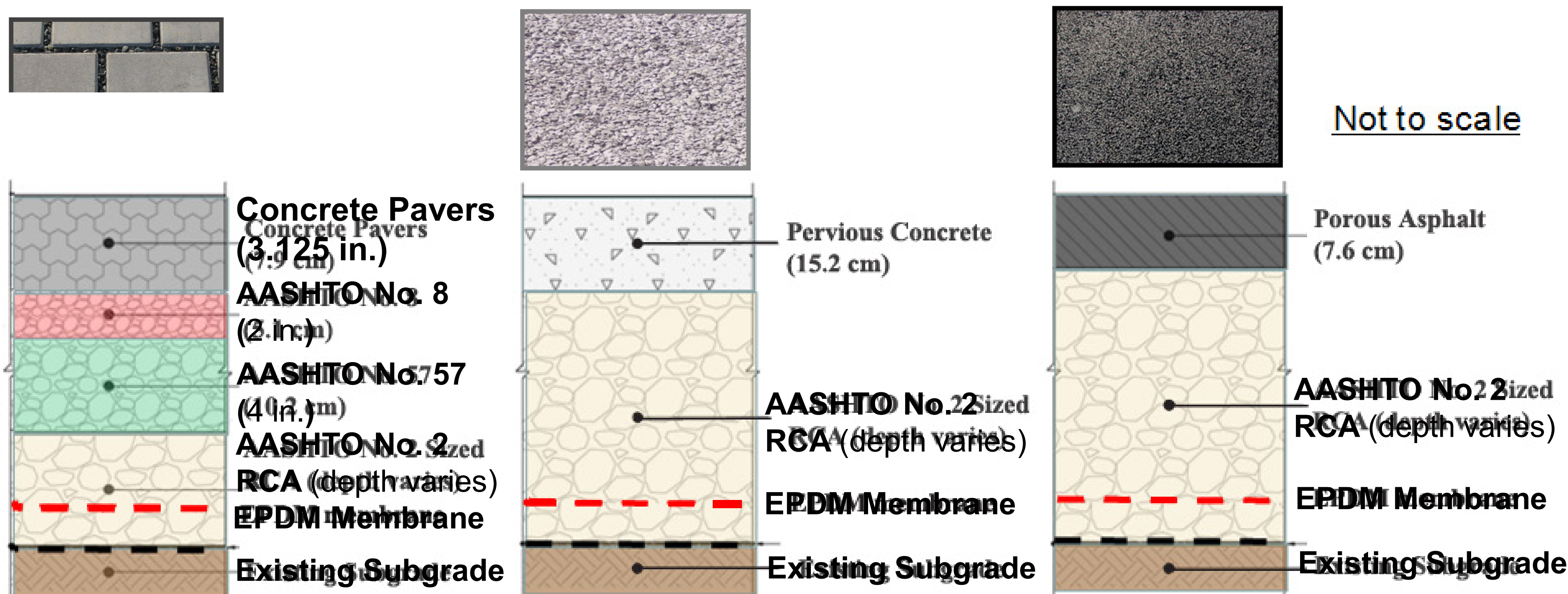
The design at the EEC incorporated water quality monitoring capabilities.



Interlocking concrete pavers
Pervious concrete
Porous asphalt
Buried distribution pipes
Tree islands
Hot mix asphalt
Buried well/piezometers
Collection tanks
Buried WCRs

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



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

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

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Infiltrate drains from the lined sections to 1,500-gallon tanks on the east side of the parking lot where we can collect samples.

The tanks allow us to collect the entire runoff for rain events through ~38 mm.

- Published or in review
  - Chloride
  - Speciated nitrogen
  - Organic carbon
  - Phosphate
  - pH
  - Eh
  - SVOCs
  - Metals
  - Microbials

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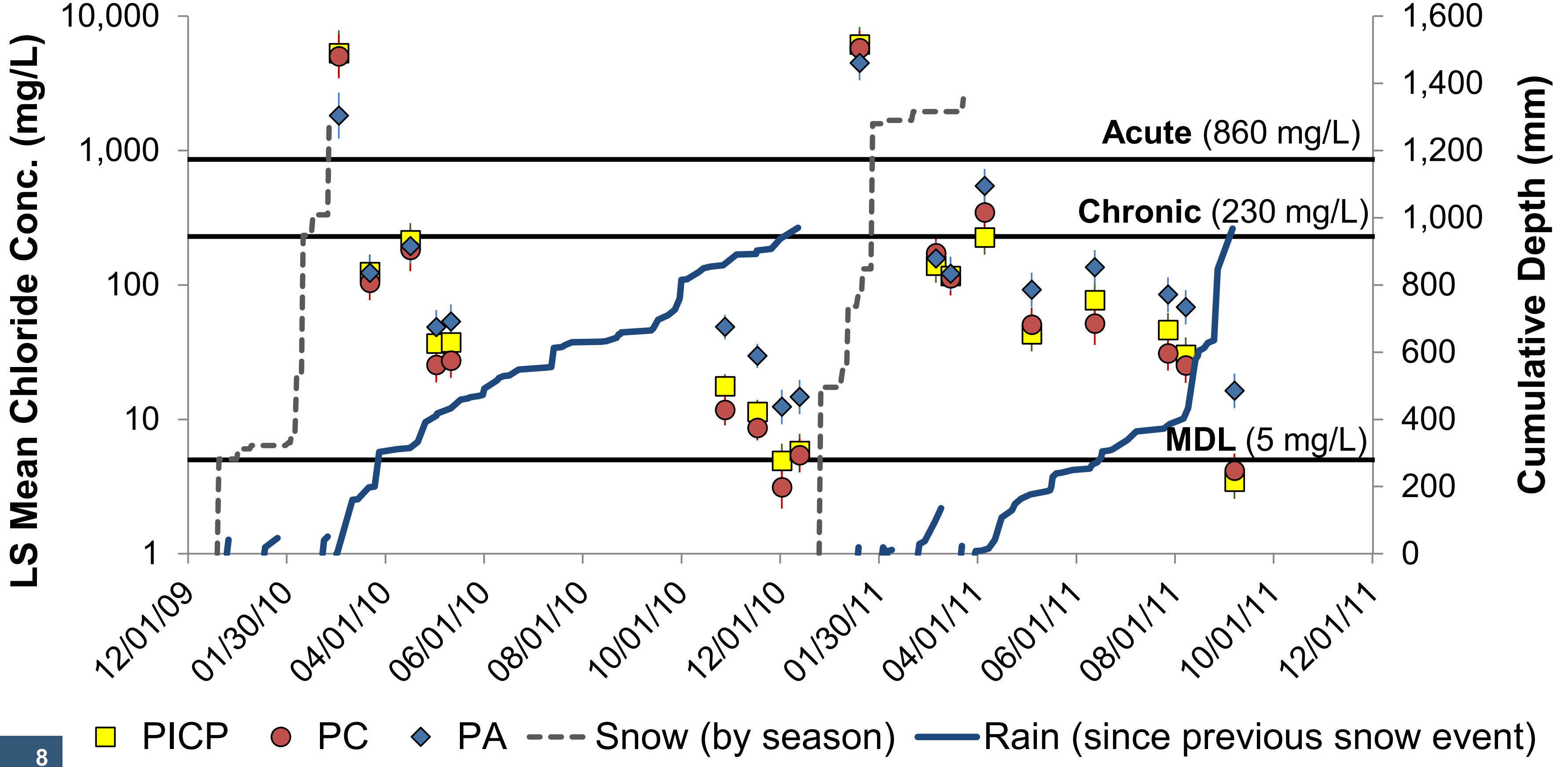
After winter salt application, chloride concentration decreases throughout the remainder of the year.



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

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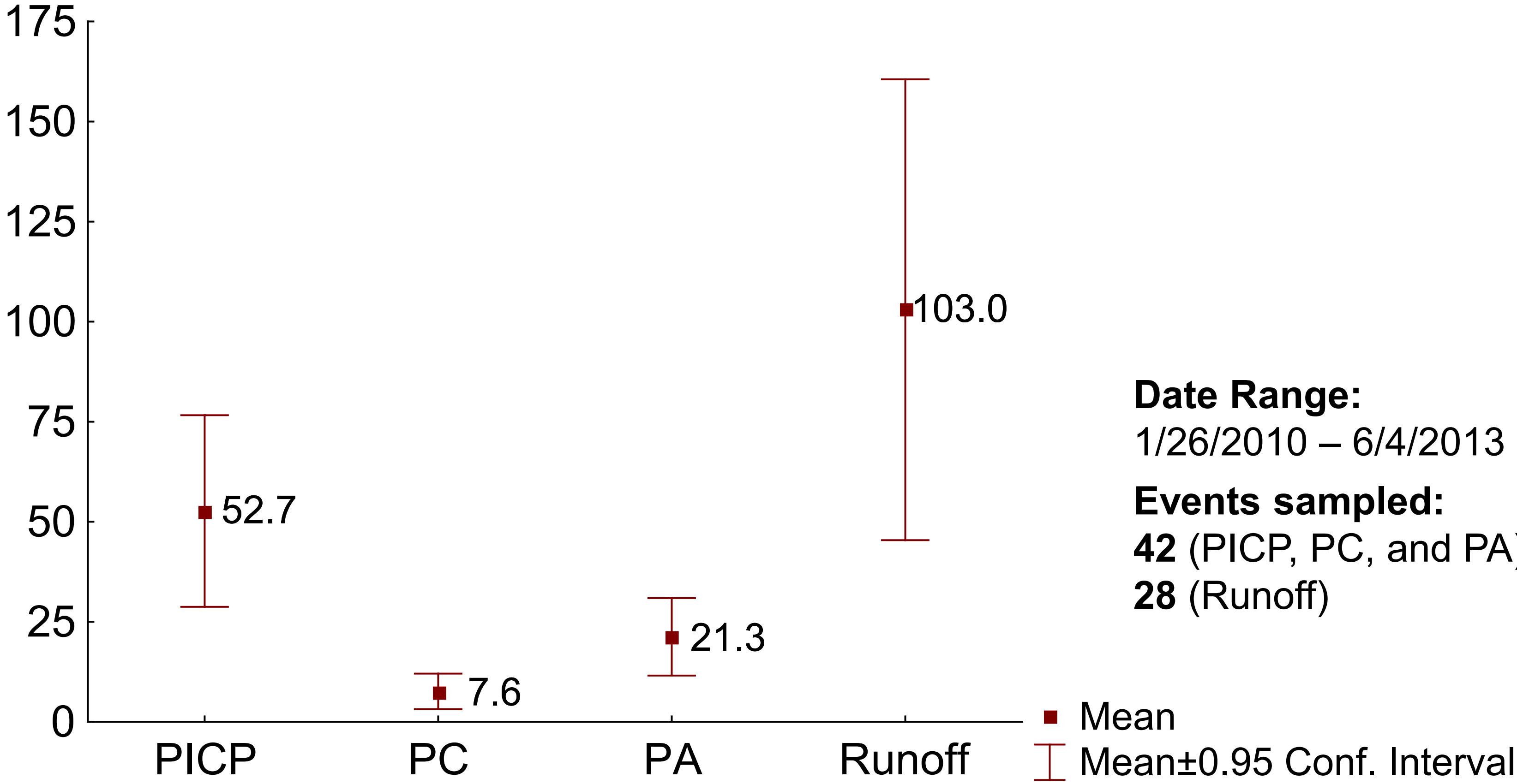
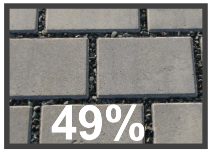
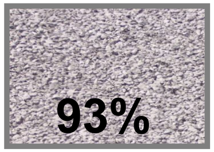
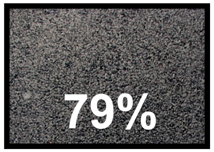
All permeable surfaces reduced Suspended Solids Concentration (SSC) to different degrees.









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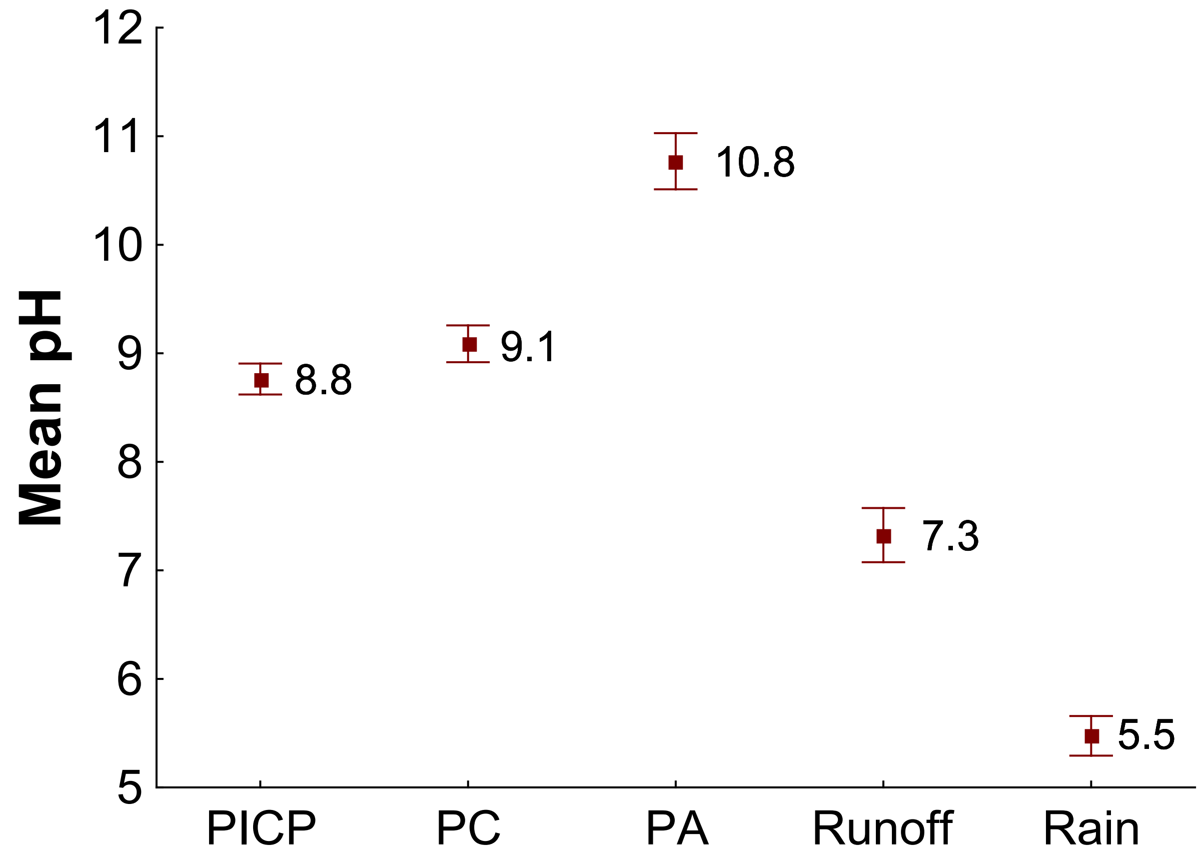
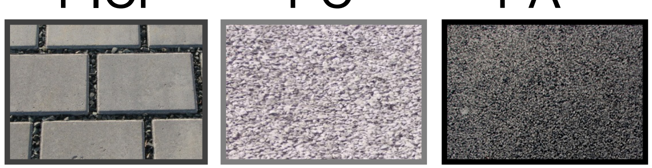
Acidic rainfall is buffered by all pavement surfaces, and PA exfiltrate is surprisingly basic.



Mean
Mean±0.95 Conf. Interval

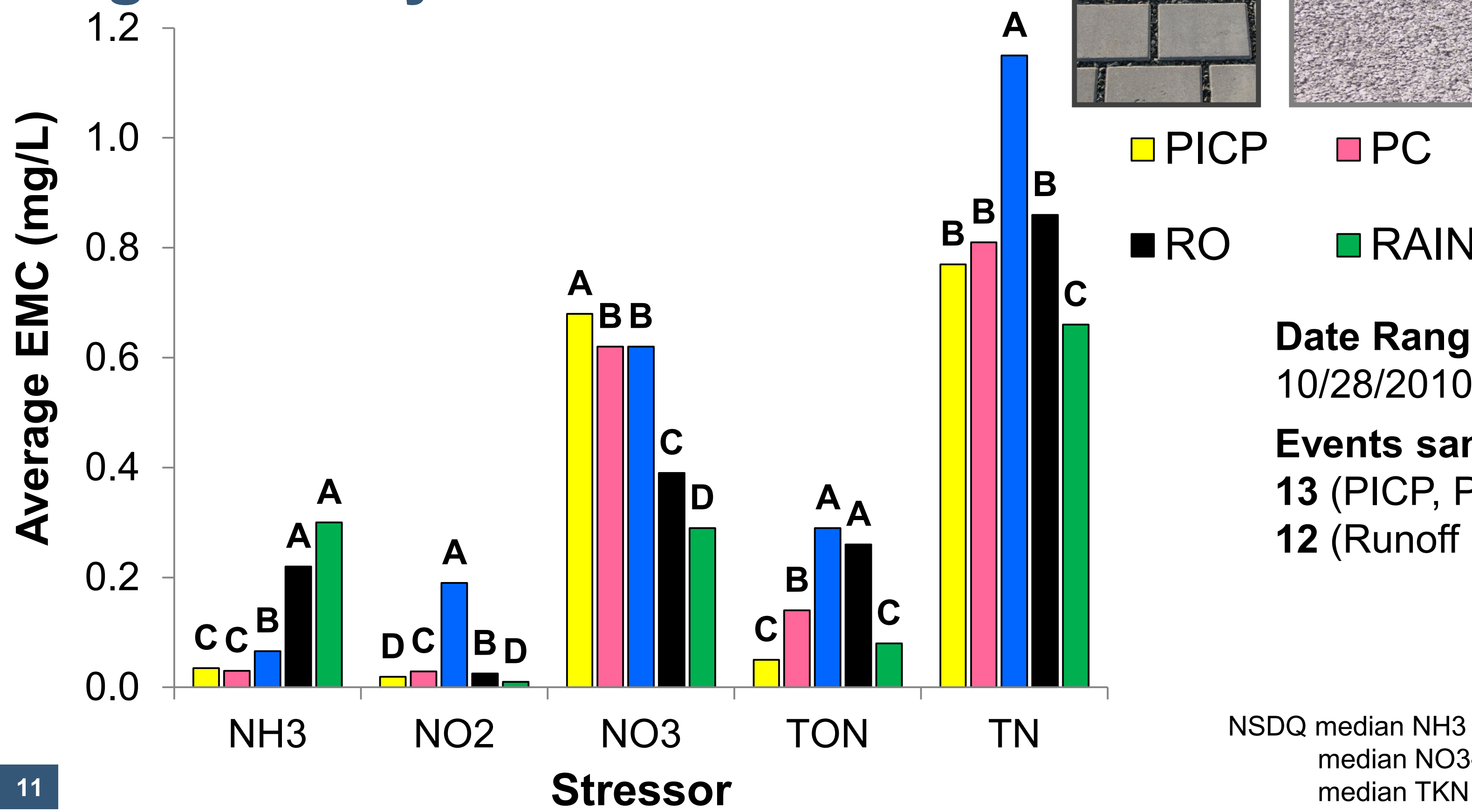
Date Range:
1/26/2010 – 6/4/2013

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 NH_3 0.5 mg/L
median NO3-2 0.6 mg/L
median TKN 1.6 mg/L

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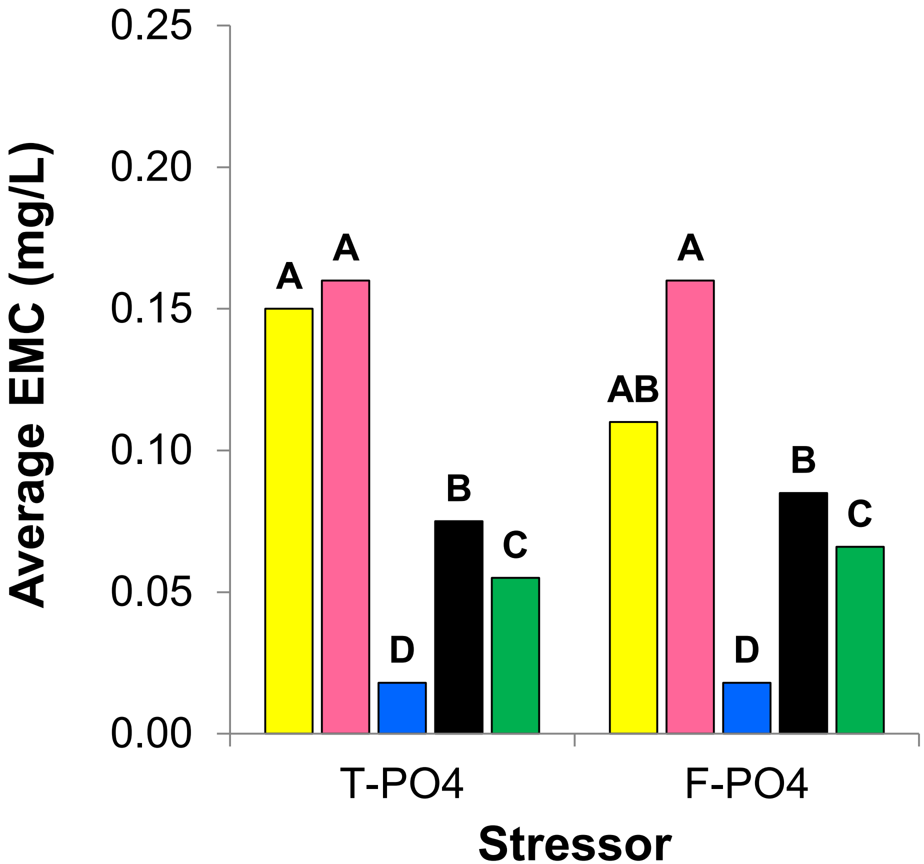
Total phosphate concentrations in PICP and PC were significantly larger than in the runoff, and all were significantly larger than PA.



Date Range:
10/28/2010 – 9/7/2011

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

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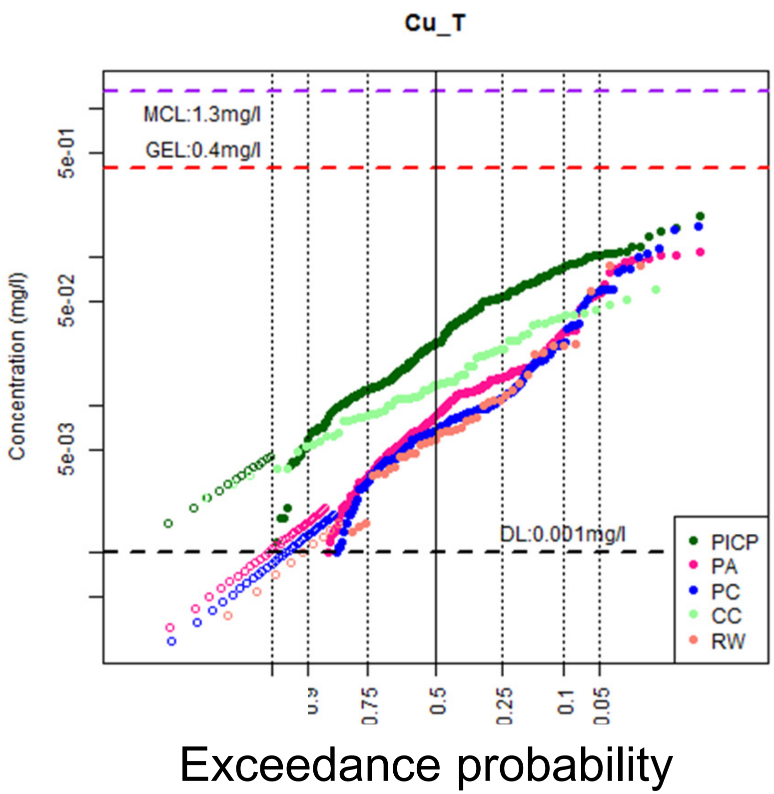
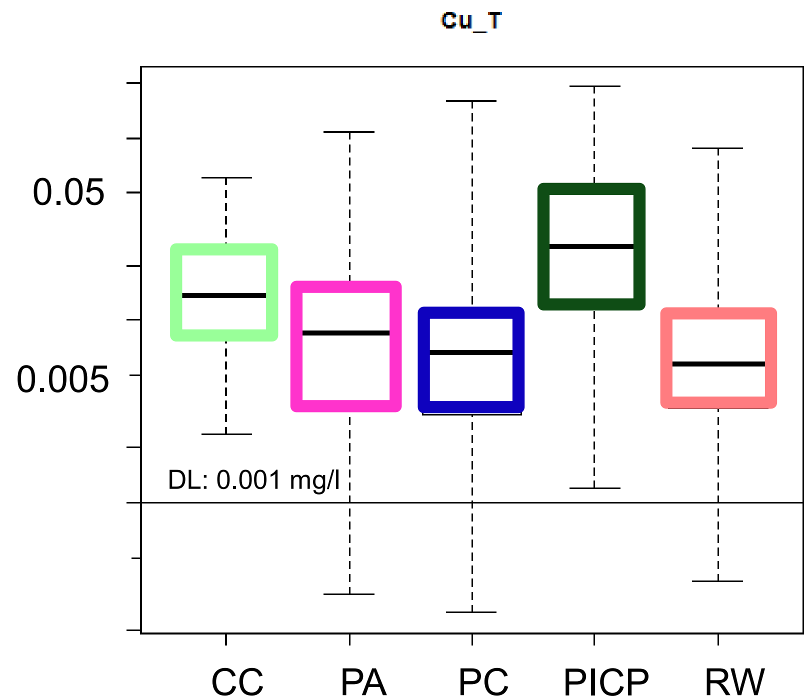
The concentration of priority-pollutant metals were generally less than the groundwater discharge limit.





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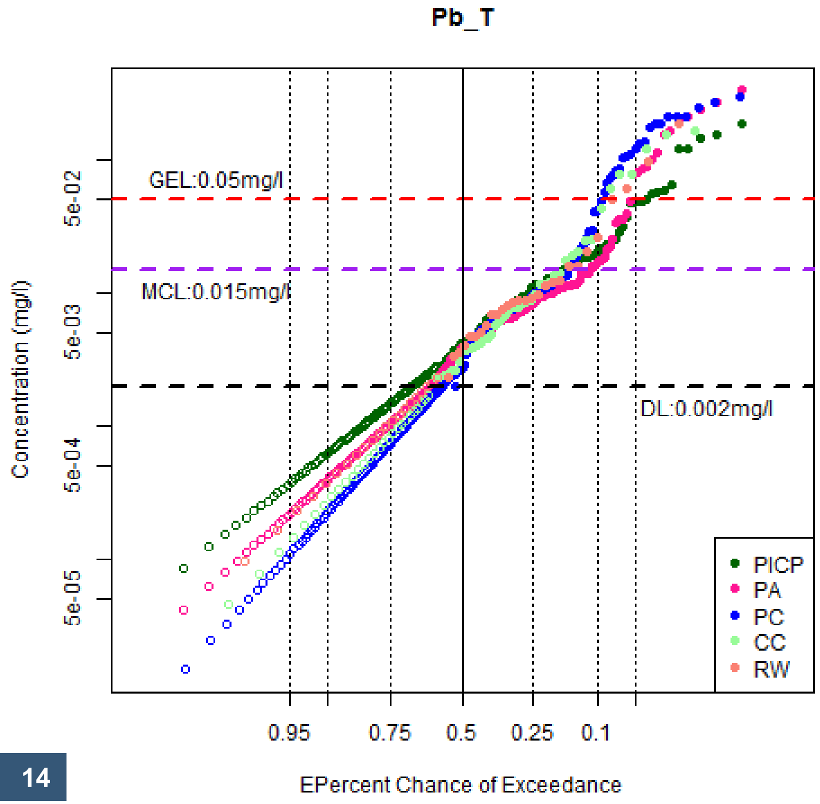
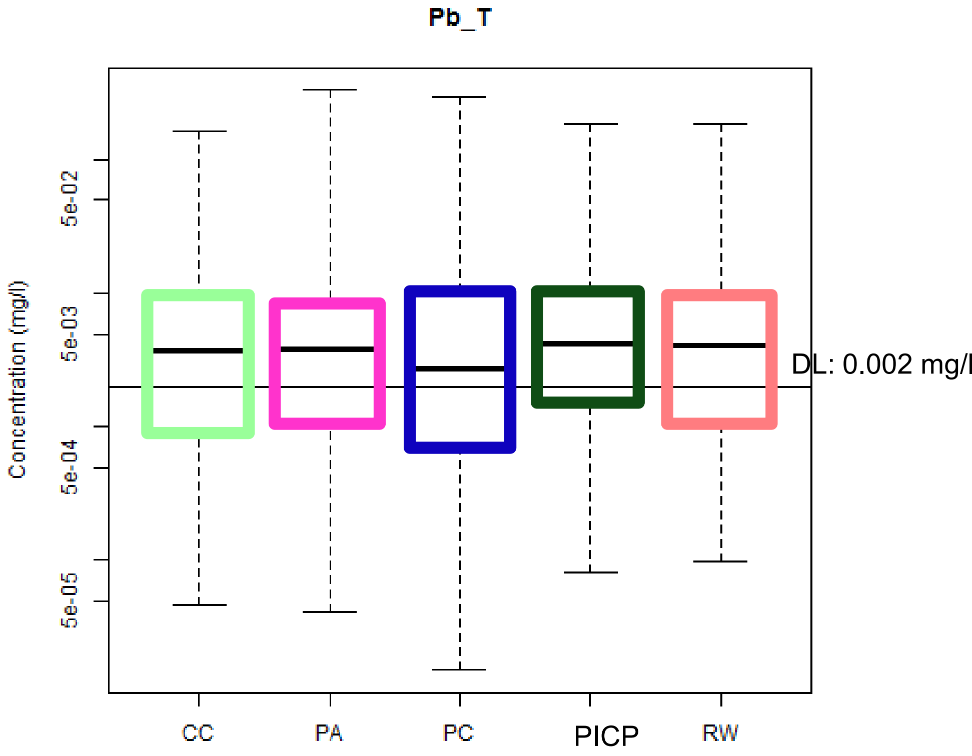
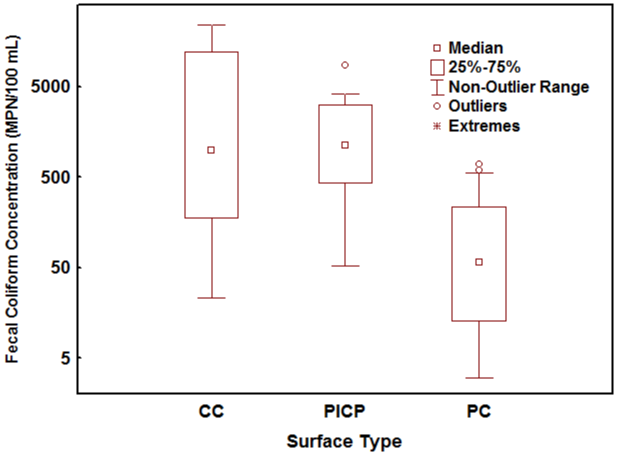
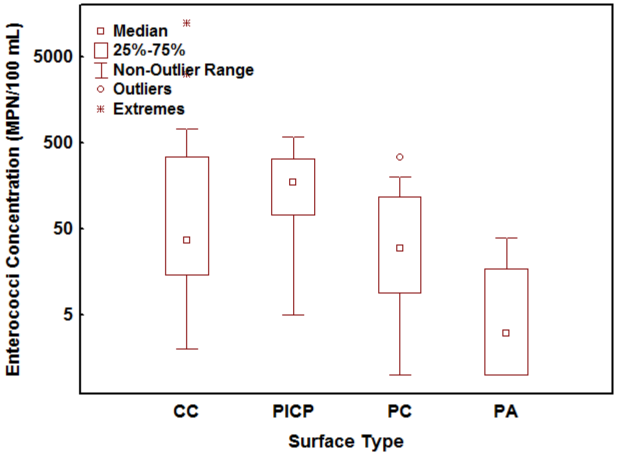
Total lead concentration does not differ across sources and sometimes exceeds regulatory limits.

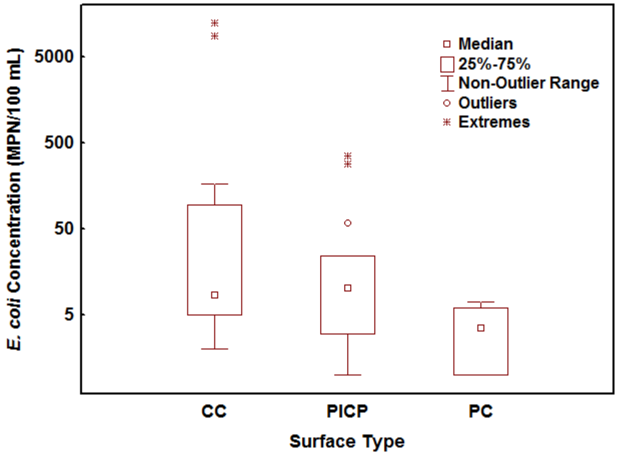




PA infiltrate consistently showed the smallest concentration of microbial indicators







Fecal coliform and *E. Coli* not detected in PA infiltrate.

From Selvakumar and O'Connor, 2017 Water Environment Research (90)1

The most popular question is about infiltration rates.

We measured infiltration rate at three randomly selected locations on each half of each surface monthly.

Modified ASTM C1701 apparatus

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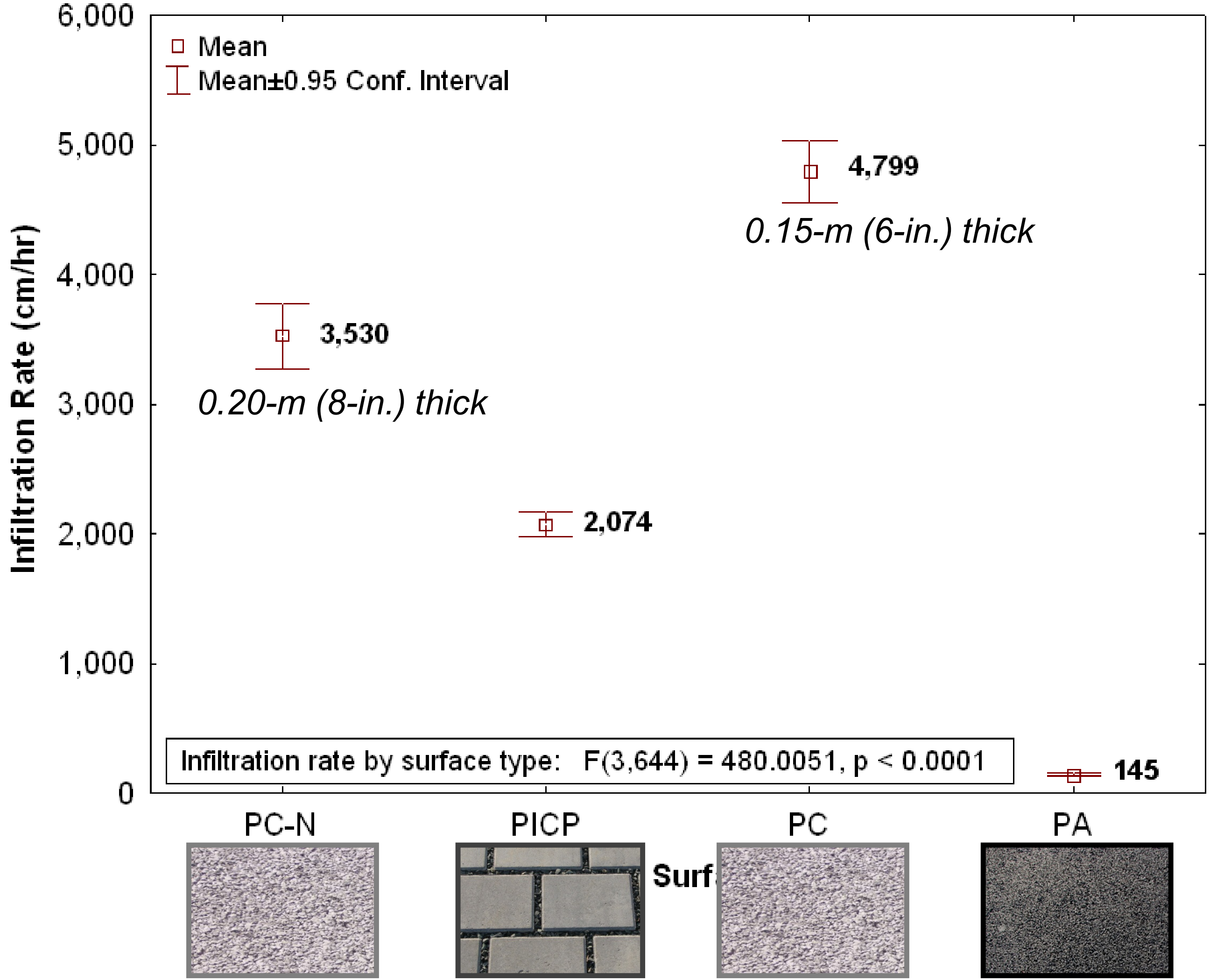
The infiltration rate varies among the four tested surfaces, but all surfaces are sufficient to handle maximum expected direct rainfall rates.

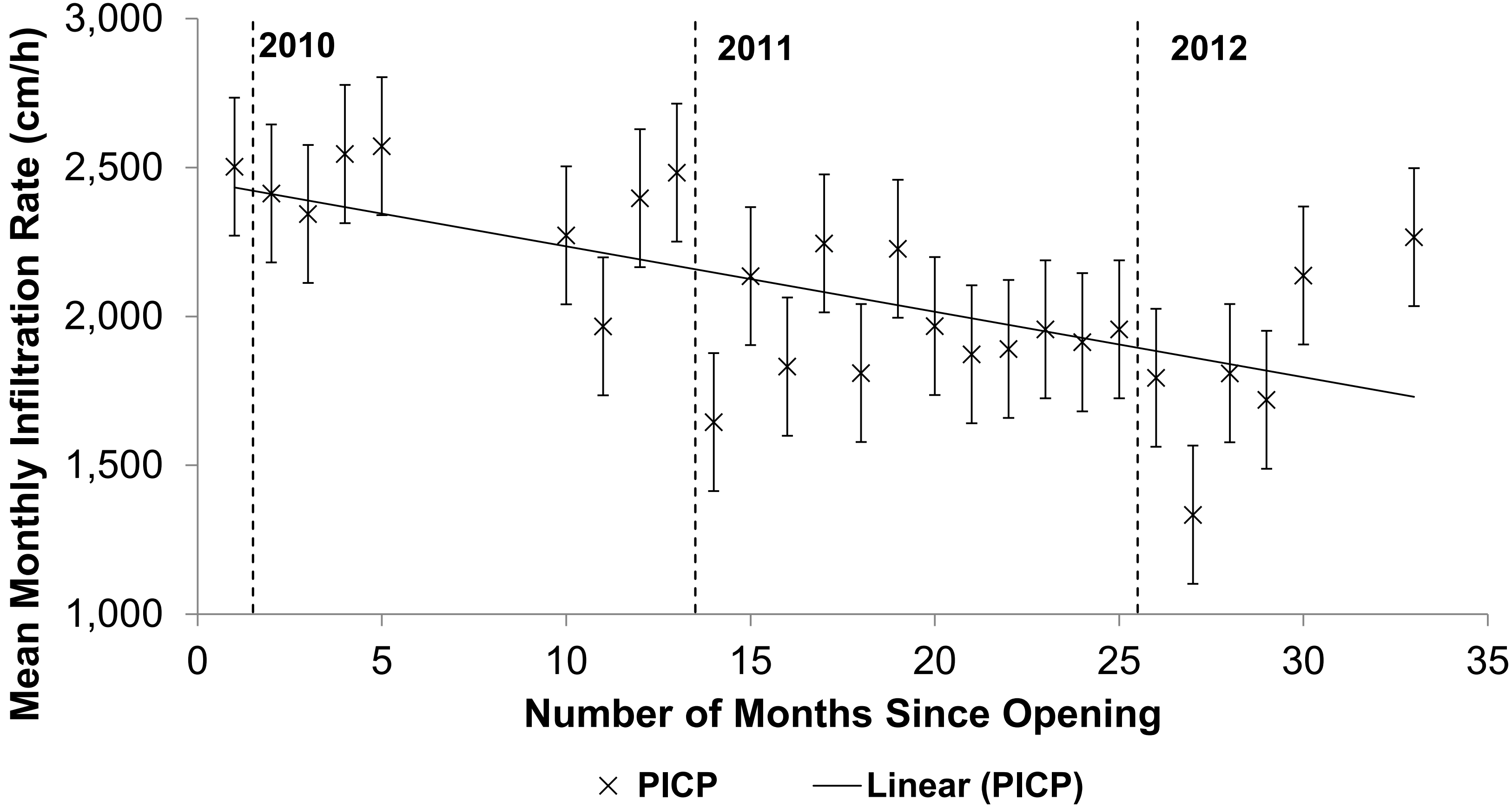
100-year, 5-minute rainfall intensity

- 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.



y = -21.97x + 2455
$R^2 = 0.4194$
p = 0.0003

Bars represent standard error.

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.

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

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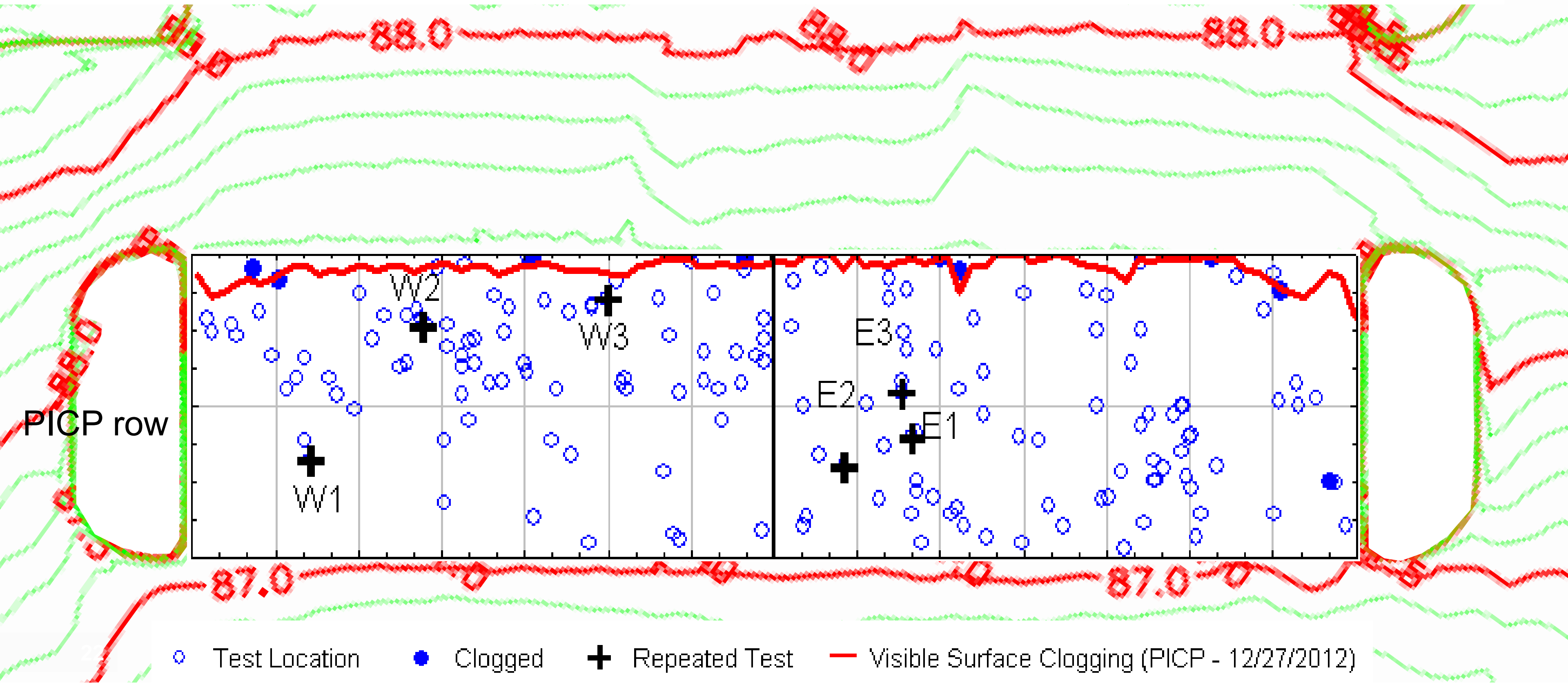
The surface clogging progression varied because of microtopography.



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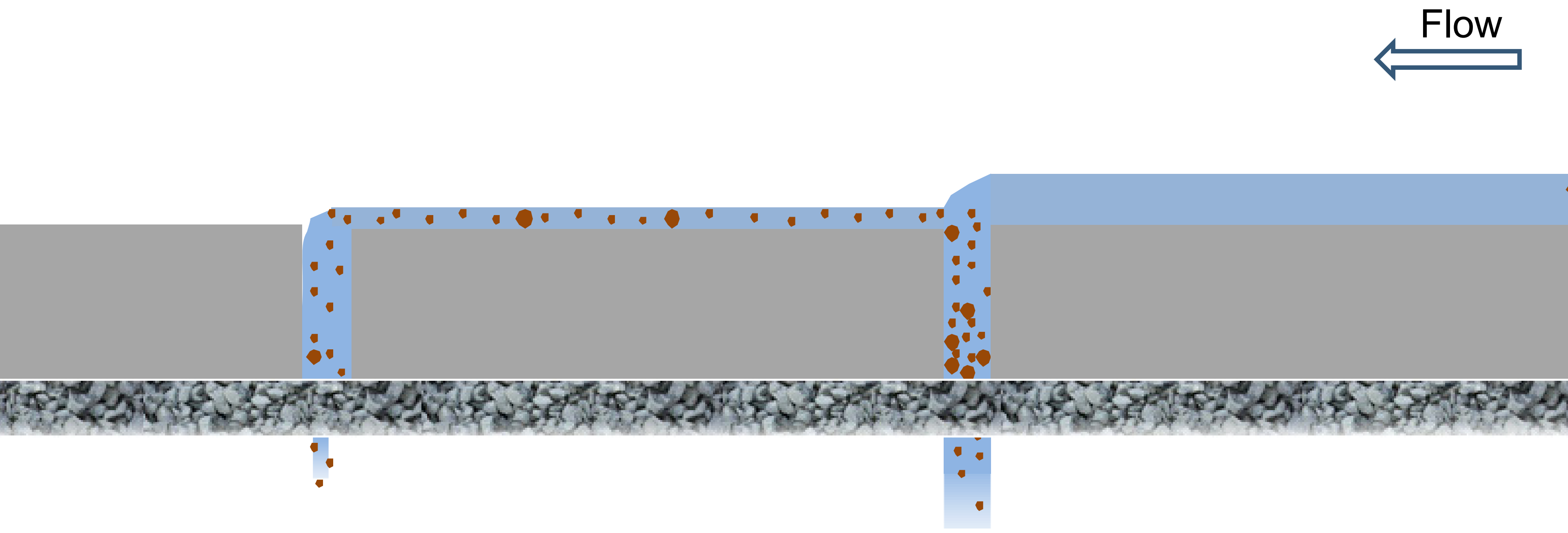
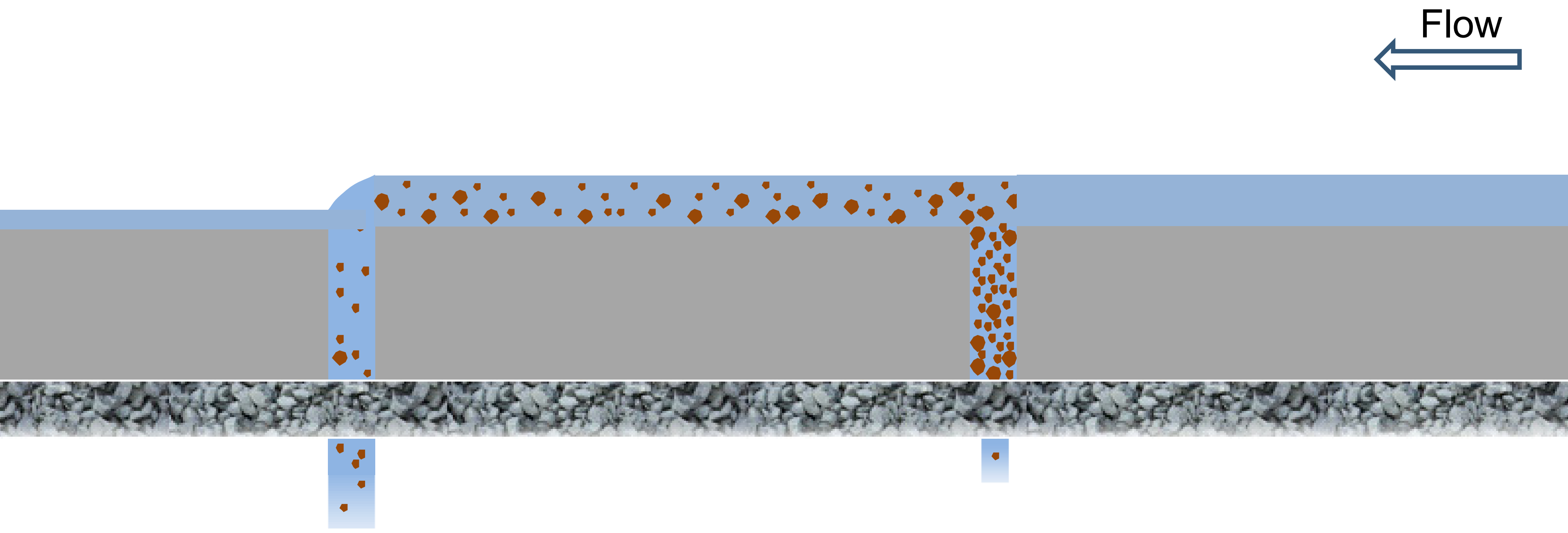
We developed a working hypothesis of the mechanics of the clogging processes.



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



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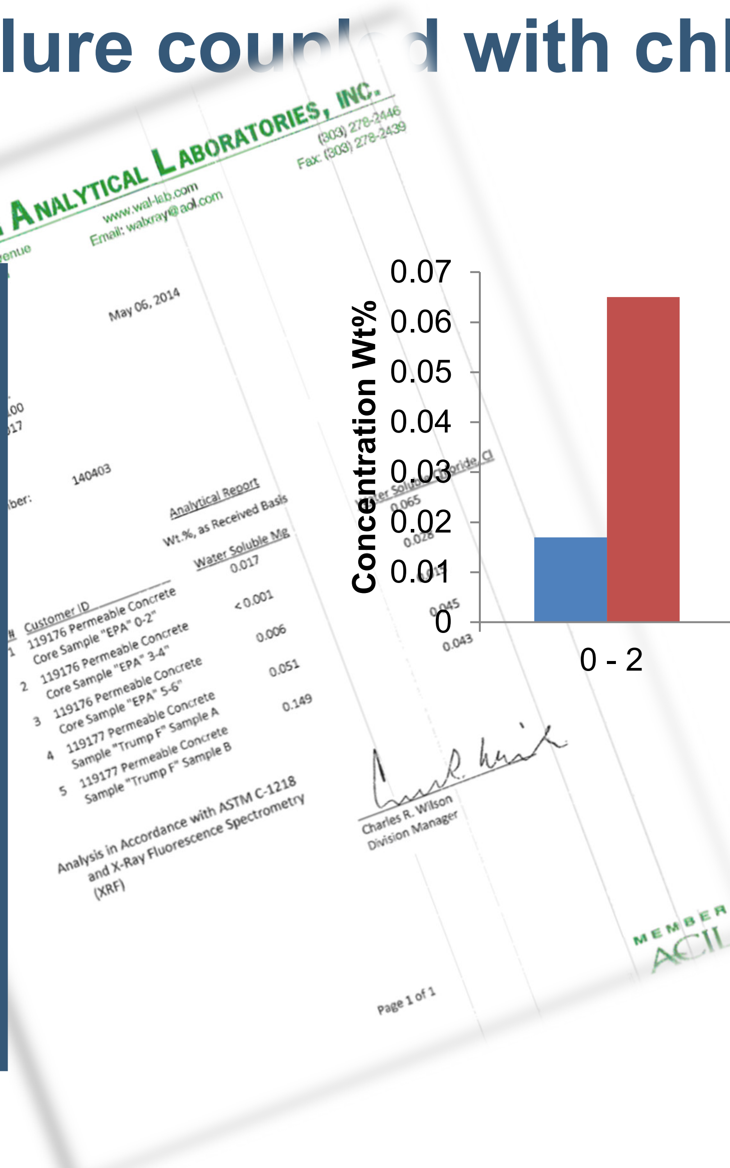
Large portions of the pervious concrete disaggregated.

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

Is structural failure coupled with chloride?



Wyoming Analytical Laboratories, Inc.

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(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	[illegible]
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

MEMBER ACIL

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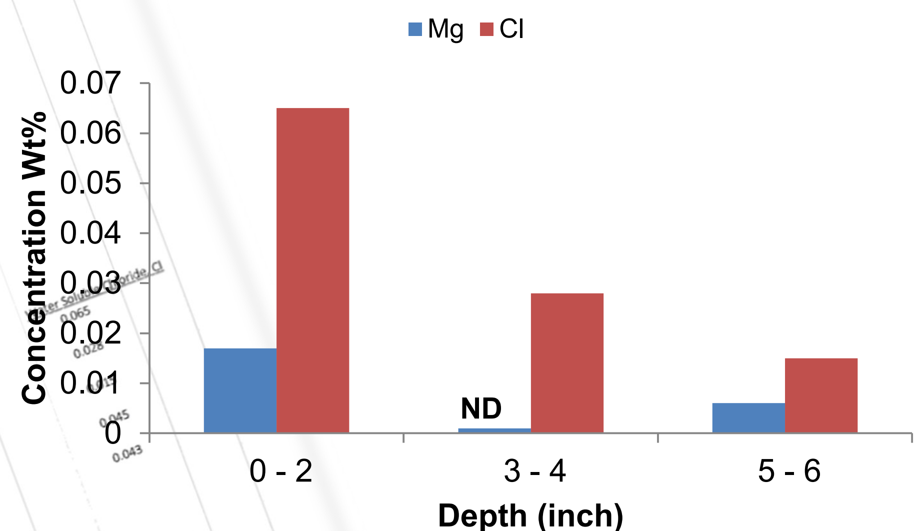

NRMCA revised O&M guidance (2015)

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

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Although the surface had disaggregated, there was still substantial material remaining.

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We have replaced the porous concrete sections with pavers.

Belgard Eco Dublin

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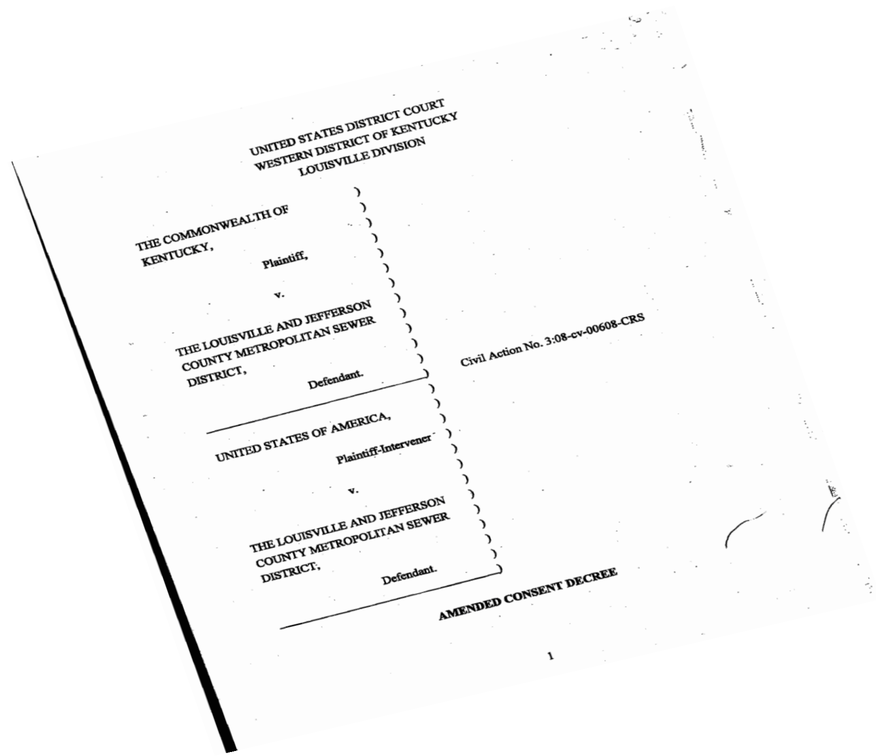
In 2011, Louisville MSD installed permeable pavement strips in parking lanes near the catch basins in the Butchertown section of Louisville.

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.

UNITED STATES OF AMERICA,
Plaintiff-Intervener
v.
THE LOUISVILLE AND JEFFERSON COUNTY METROPOLITAN SEWER DISTRICT,
Defendant.

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

AMENDED CONSENT DECREE

1

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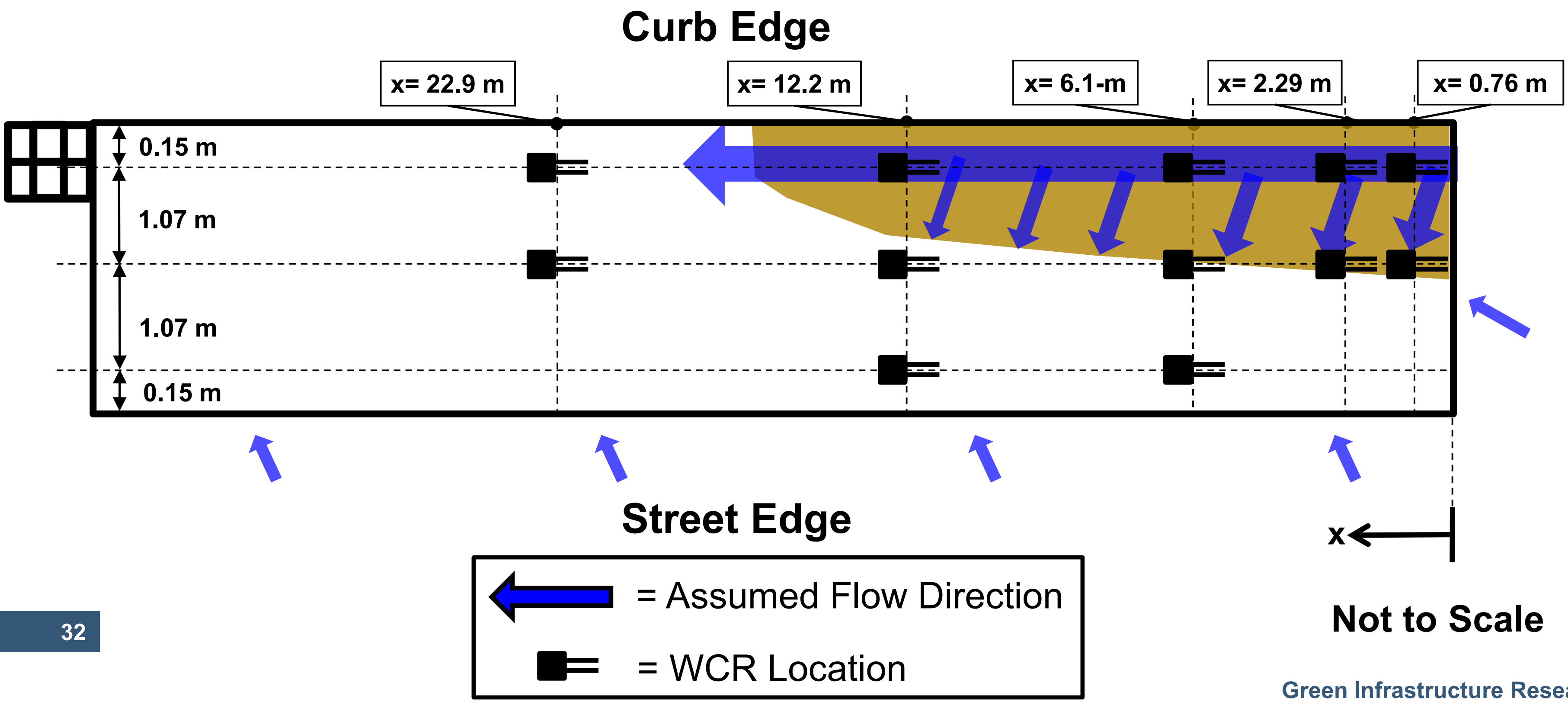
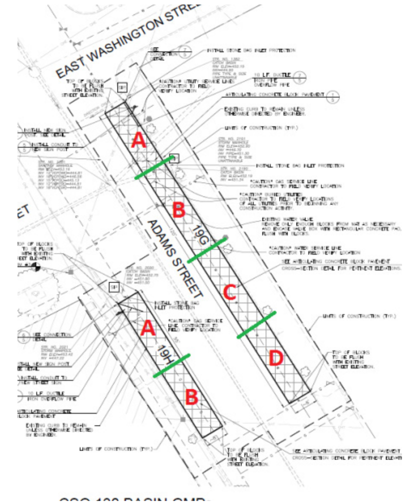
There are large variation in native soil infiltration rates at small geographic scales.

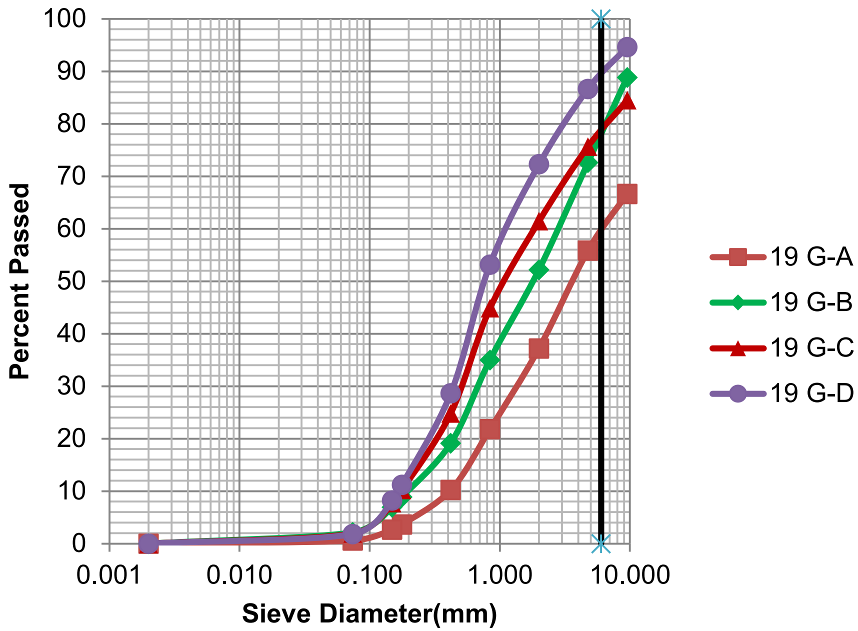
Measurement location	Expected rate from "nearby" geotechnical survey 4.3 cm/hr			
	Control 19G		Control 19H	
	Infiltration rate (cm/hr)	USDA soil texture classification (% sand/silt/clay)	Infiltration rate (cm/hr)	USDA soil texture classification (% sand/silt/clay)
Upgradient	0.114	Sandy Loam (58/34/8)	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.

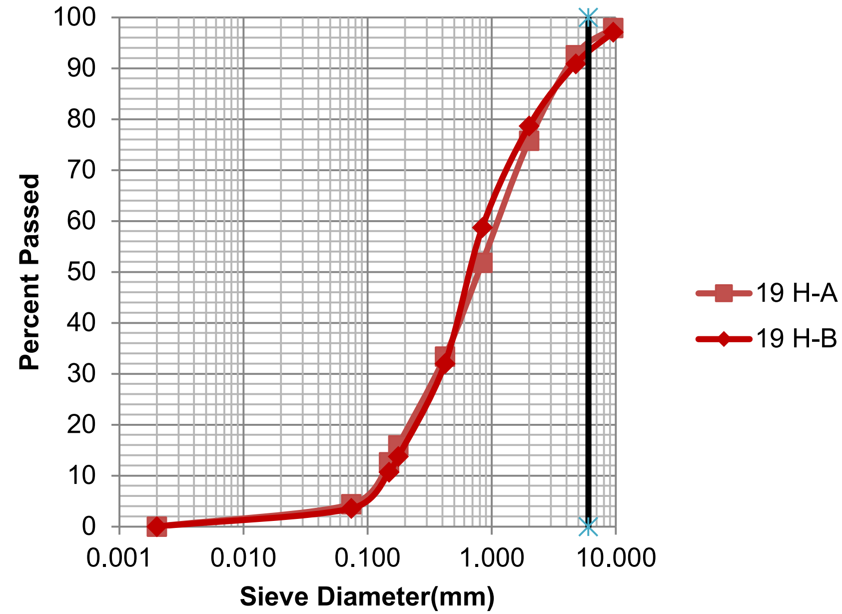


Recovered sediment particle size analysis shows initial accumulation of fines in the upgradient sections.





Mar. – May 2012
(9 in. cum. rainfall)



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

Data source:
Amirhossein Ehsaei –
University of Louisville

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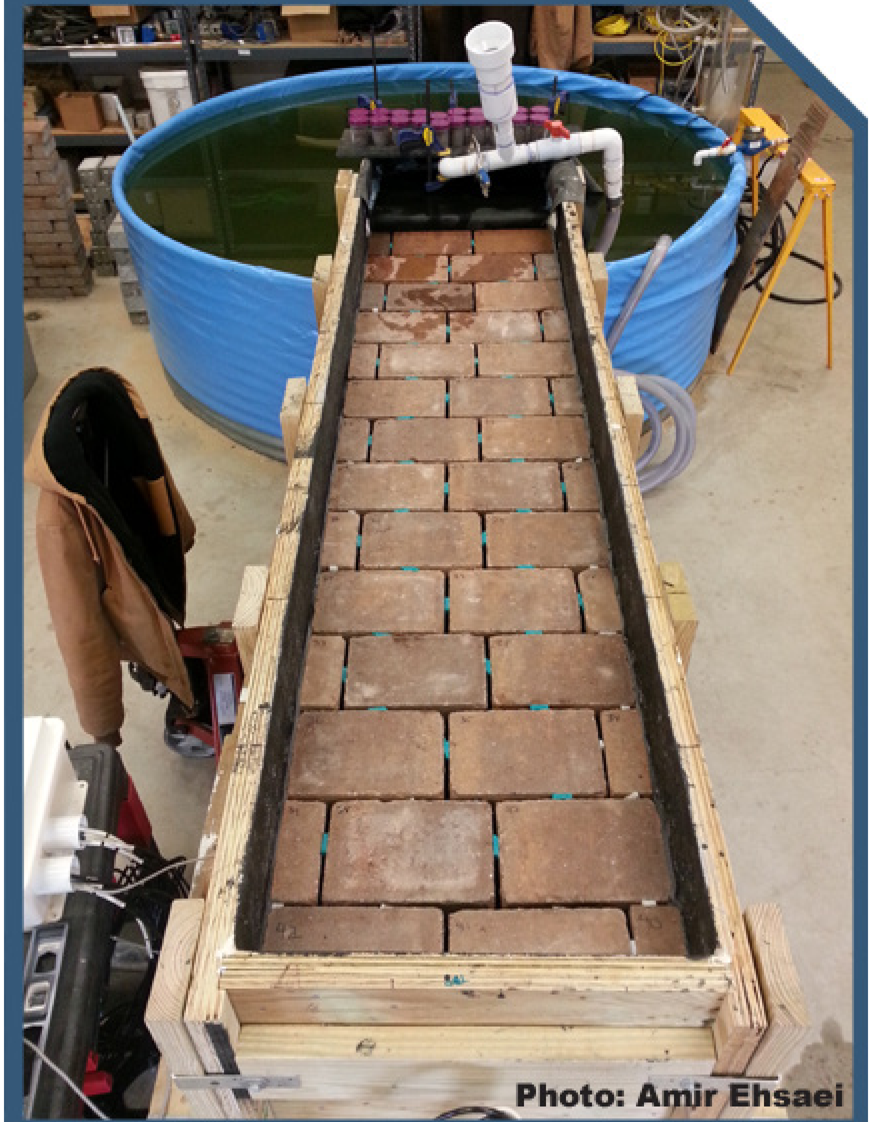
We ran some flume experiments to test the hypothesized mechanisms and influences.



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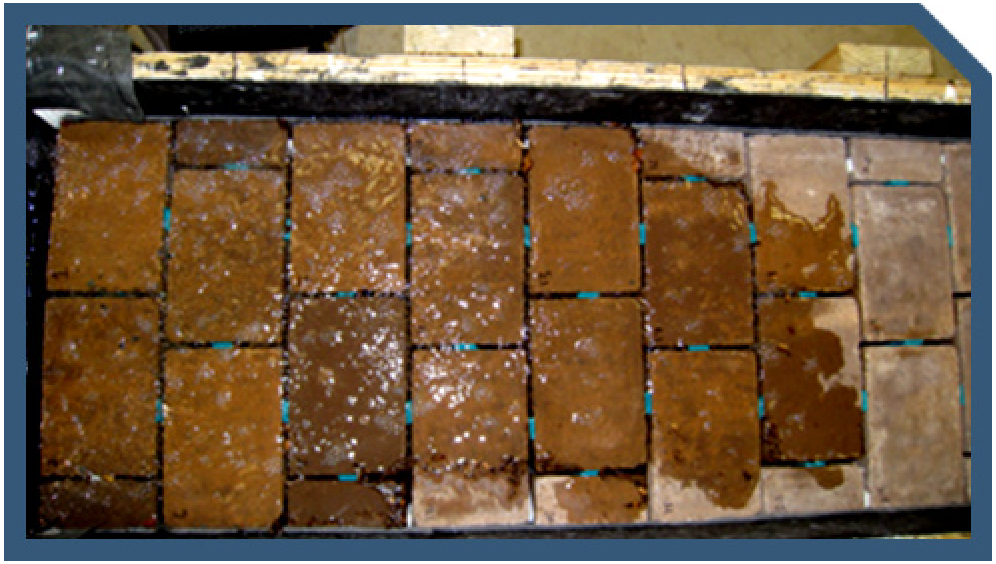
Flume tests show the progressive infiltration of the runoff that leads to the clogging.



Photos: Amir Ehsaei
University of Louisville

The flume tests showed the same pattern of accumulated sediment as observed in the field.

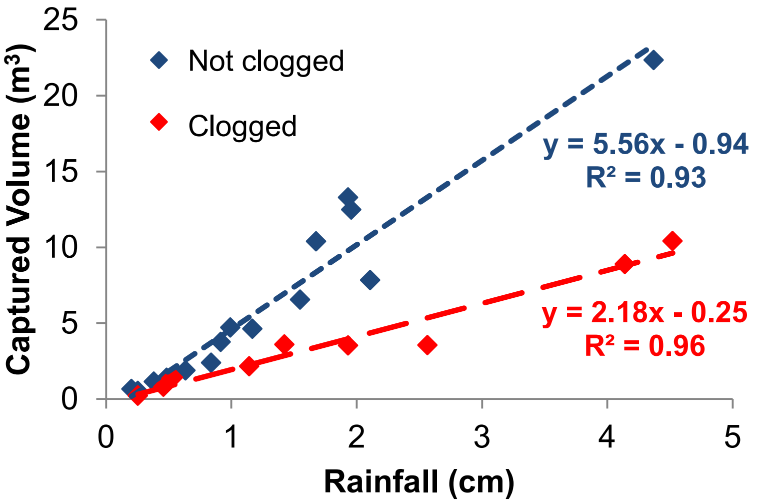
Inorganic material near up gradient edge

Organic material near down gradient edge

Photos: Amir Ehsaei
University of Louisville

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.



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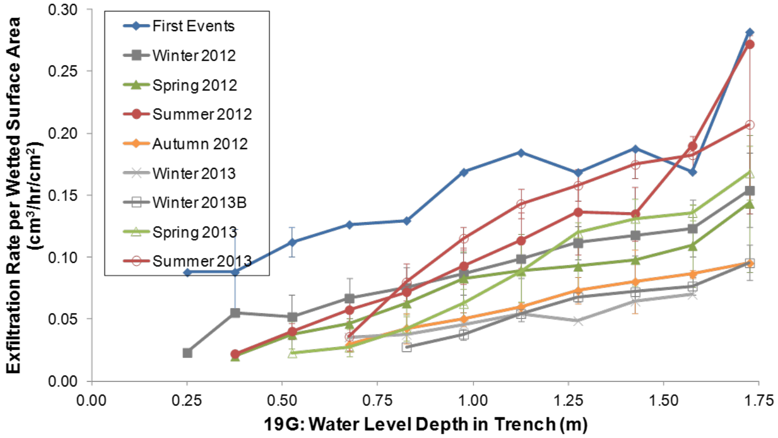
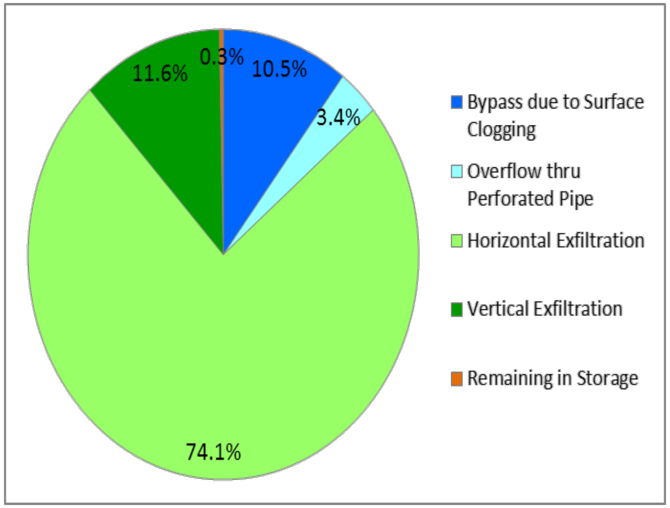
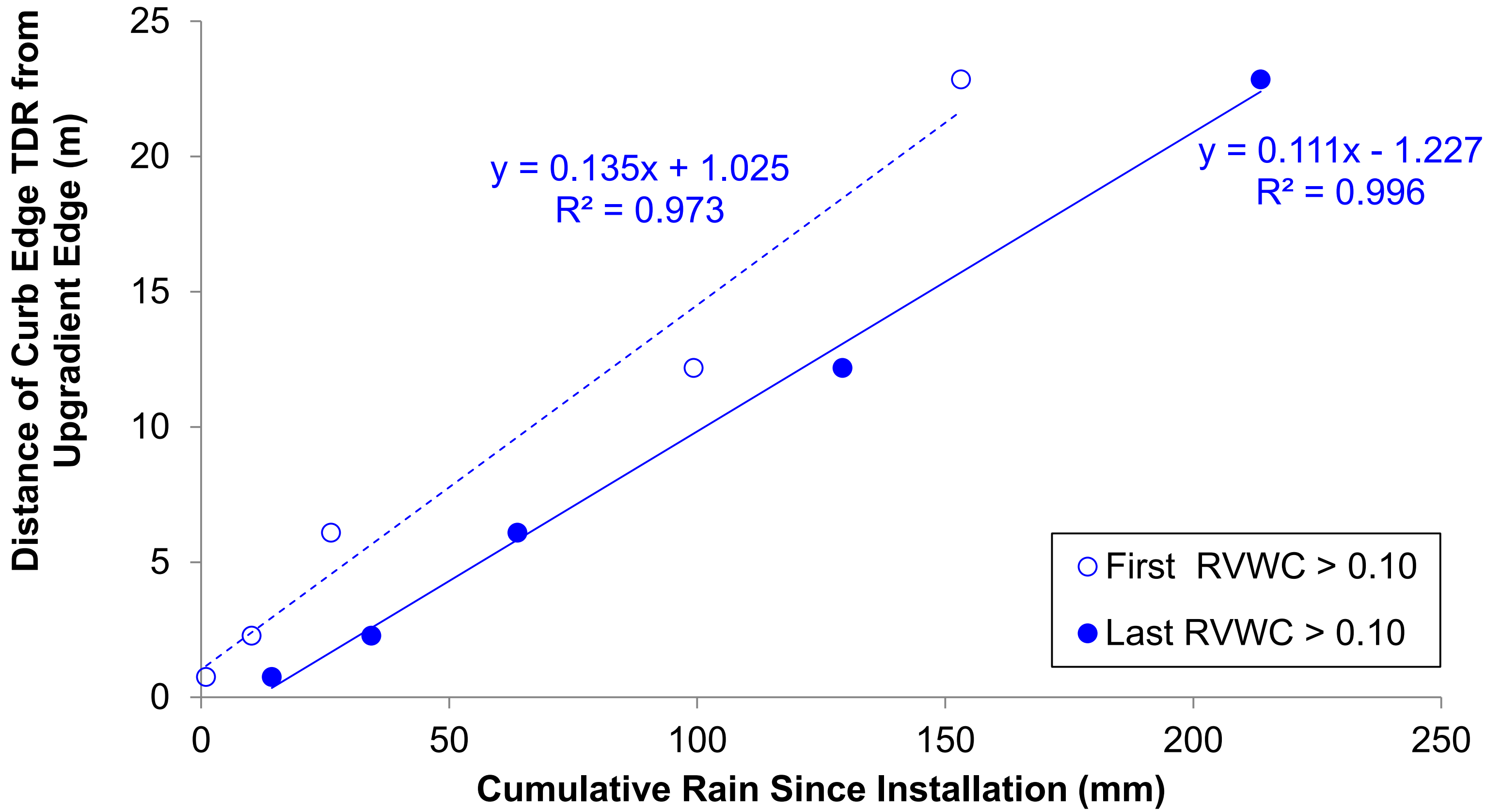
Findings:

- 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.



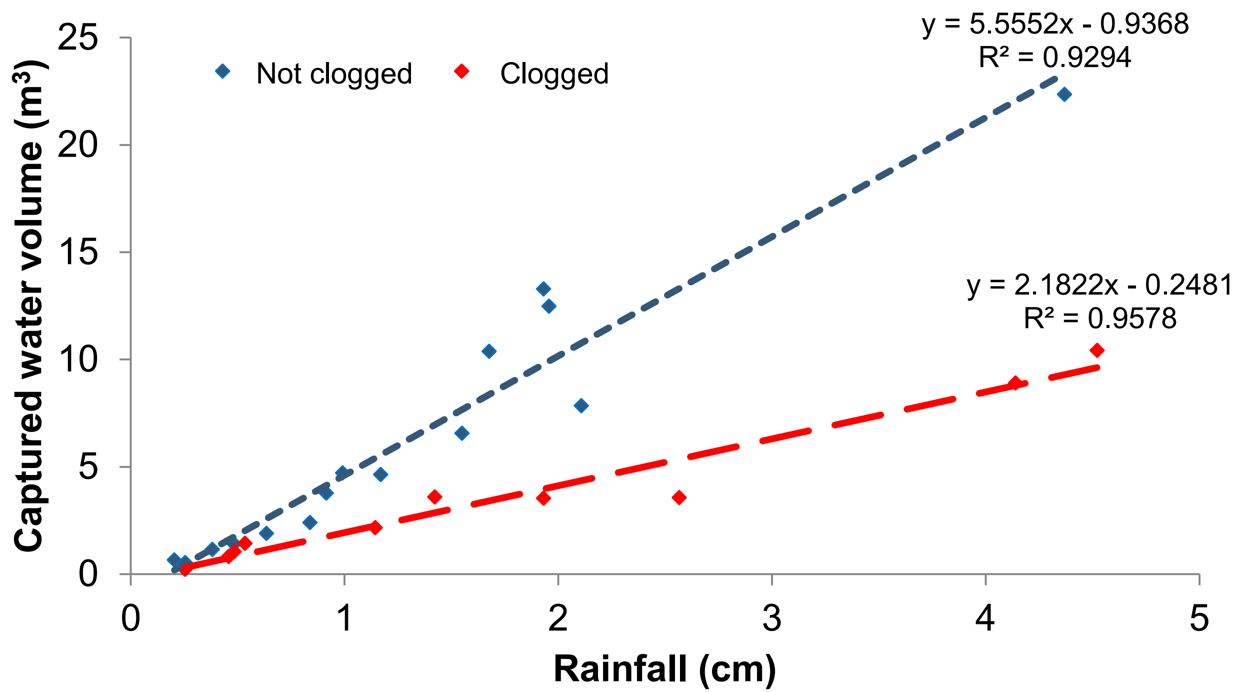


Installed instruments can be used to determine the control's longitudinal clogging rate.



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

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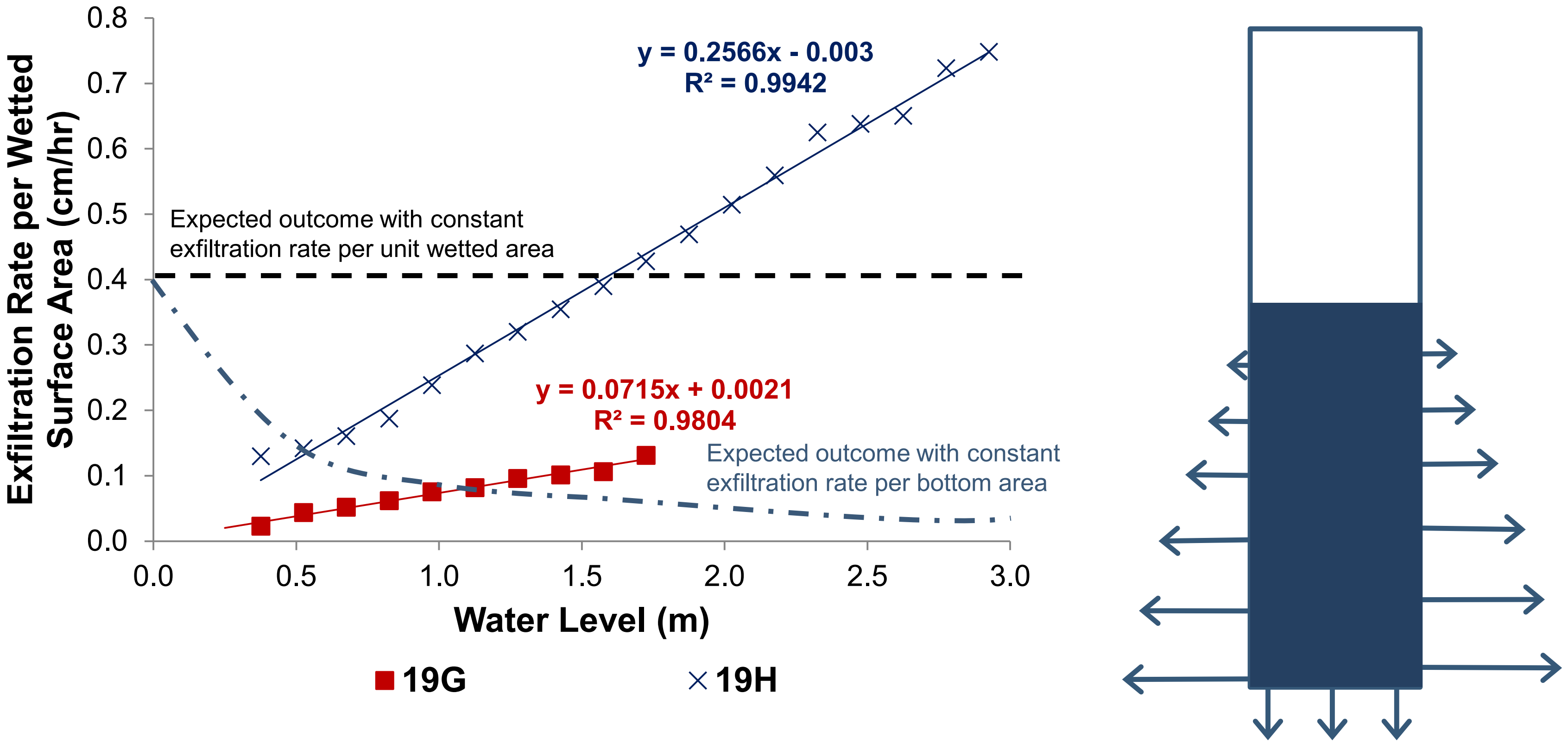
Constant exfiltration across wetted perimeter or base is not supported by the measurements.



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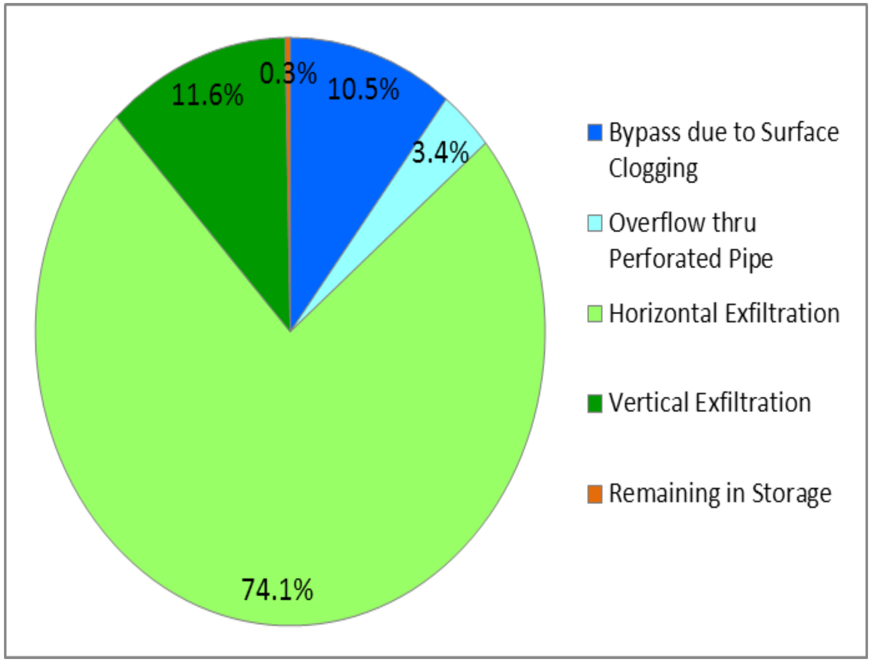
Modeling the fate of runoff showed that most of the captured water exfiltrated laterally through the side walls.

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.



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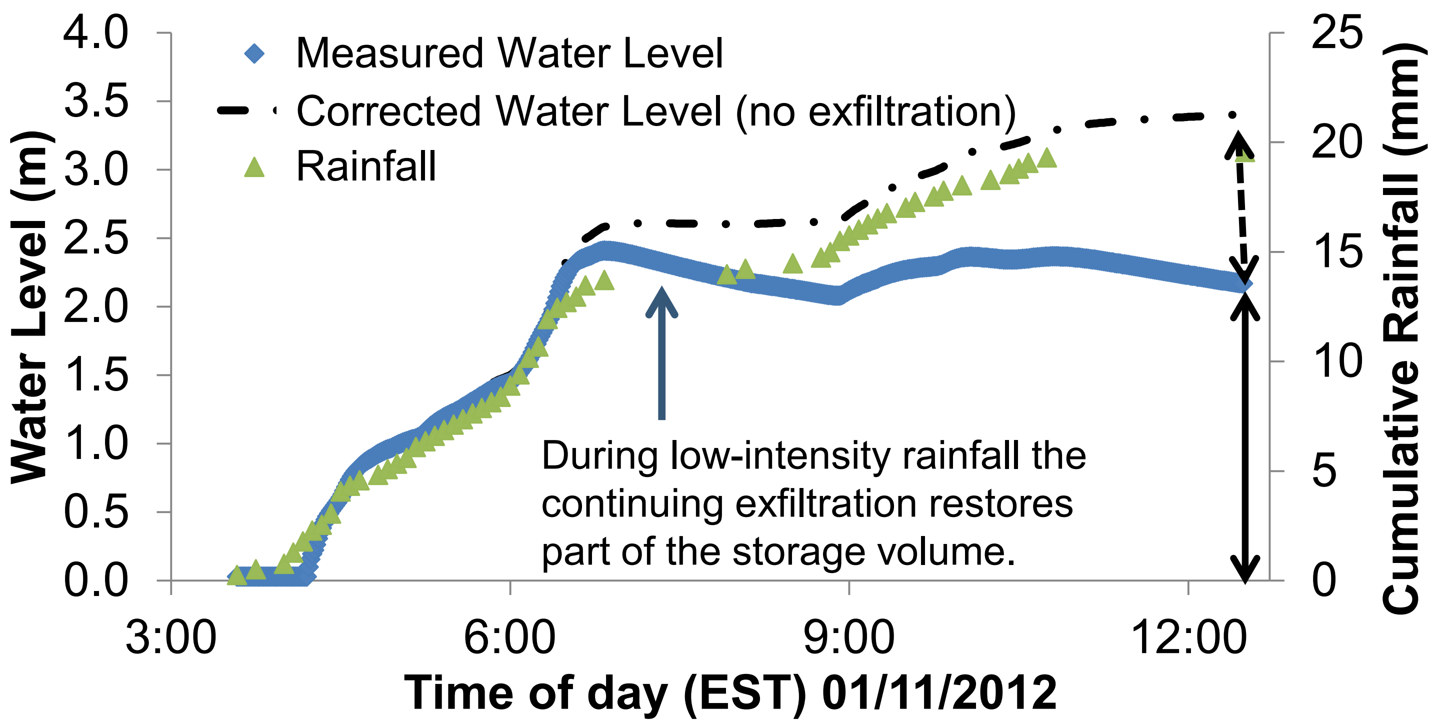
Intra-event exfiltration can be significant



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

Research at Fort Riley ….

Photo: Chris Otto

EPA United States Environmental Protection Agency

Research at the K-5 school includes interaction with the STEM program

Photo: Maria Childs, Fort Riley Public Affairs

https://www.army.mil/article/174165/fort_riley_students_go_beyond_the_classroom_to_learn_science_of_water

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Monitoring Clogging of the Permeable Pavement

- Previous EPA research provides a foundation for predicting the clogging mechanism and progression.
- This site is providing us an opportunity for confirmatory monitoring, evaluation of alternate instrumentation to determine maintenance time, confirmation that the clogging depends on rainfall, and evaluation of maintenance practices.

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Measuring infiltration locations

https://www.campbellsci.com/tb4-l

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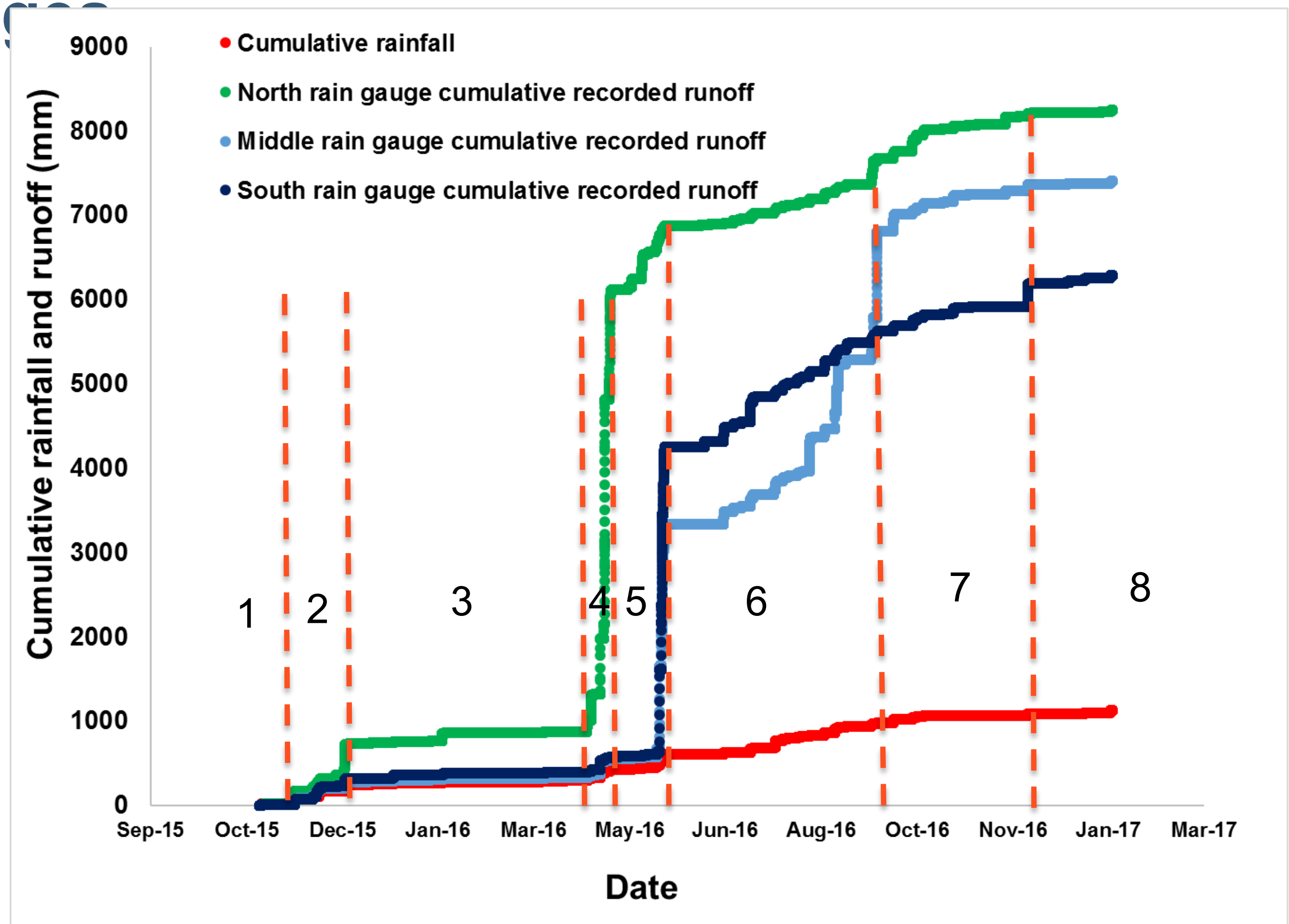
Clogging investigation by buried rain gauges

Clogging investigated using buried tipping bucket rain gauges



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Tipping bucket rain gauges recording, normalized to rainfall

Period	Status	Start	End	North rain gauge (mm)	Middle rain gauge (mm)	South rain gauge (mm)	Roof's rain gauge (mm)	North rain gauge ratio	Middle rain gauge ratio	South rain gauge ratio
1	Pre-clogged	10/29/2015	11/17/2015	175	83	75	77	**2.27**	1.08	0.97
2		11/17/2015	12/13/2015	558	199	246	169	**3.3**	1.18	1.46
3		12/13/2015	4/17/2016	546	123	151	123	**4.45**	1	1.23
4		4/17/2016	4/30/2016	5168	220	184	120	**43.01**	1.83	1.53
5		4/30/2016	5/25/2016	658	1106	1034	87	**7.6**	**12.77**	**11.94**
6	Clogged	5/25/2016	8/31/2016	593	3620	3867	427	1.39	**8.48**	**9.06**
7		8/31/2016	9/30/2016	416	1746	271	88	**4.72**	**19.84**	**3.08**
8	Unsuccessful maintenance	9/30/2016	01/17/2017	489	289	600	108	**4.53**	**2.67**	**5.55**

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Documenting Exfiltration Pathways

- The research effort is helping us to understand how water exits the storage gallery to make room to capture the next event.

- We are attempting to monitor lateral exfiltration, document head dependence, and changes in both as the parking lot ages.

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Near fie

SITE PLAN

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Interaction of Captured Water with the Groundwater

- Collecting runoff and infiltrating water in a concentrated area should affect the groundwater hydrology – so we are monitoring near-field groundwater levels.
- Infiltrating the runoff water will affect groundwater chemistry. We are testing for this as well.
- We are also documenting water chemistry during the vadose zone migration.

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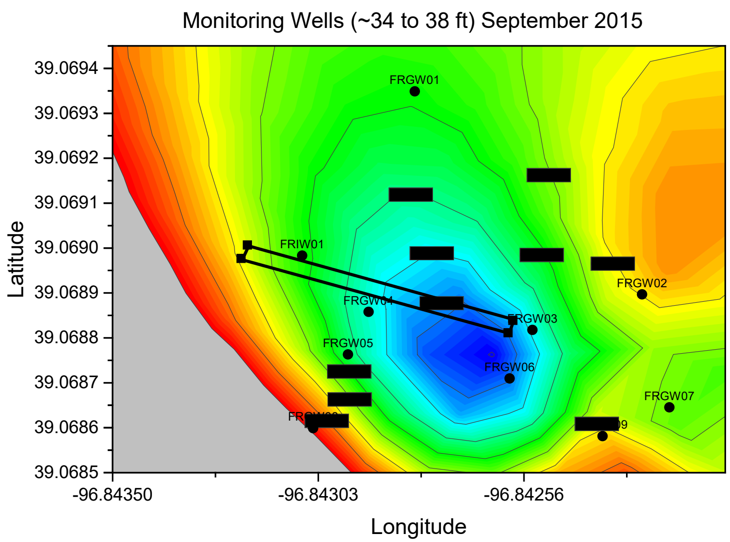
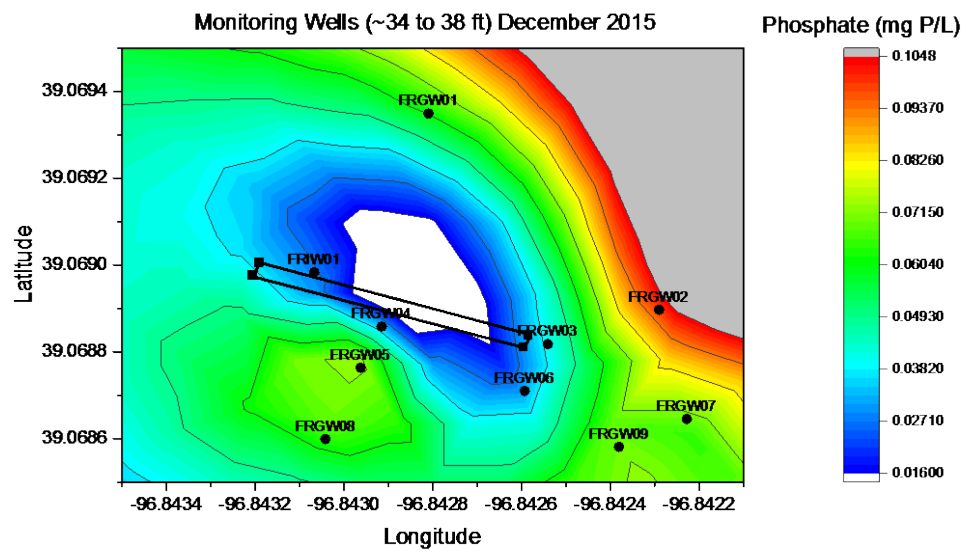
Analytes of interest

Field analysis	Laboratory analysis	
pH	ICP-OES Total Metals	Iodide
Temperature	ICP-OES Dissolved Metals	Phosphate
Dissolved Oxygen	ICP-MS Total Metals	Sulfate
Specific Conductivity	Total Nitrogen	O, H Stable isotopes of water
ORP	Nitrate + Nitrite	DOC
Alkalinity	Ammonia	DIC
Dissolved Ferrous Iron	Bicarbonate	Low level volatile organic compounds‡
Dissolved Sulfide	Bromide	Organic compounds (SVOC)‡
Turbidity	Chloride	
TDS	Fluoride	

‡ Region 7 is assisting with collecting and analyzing these samples.

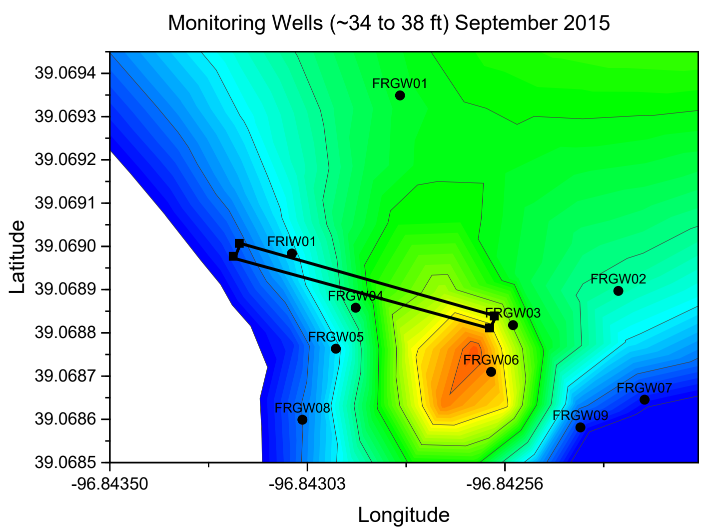
Early indicators suggest that the infiltrating water alters the subsurface phosphate



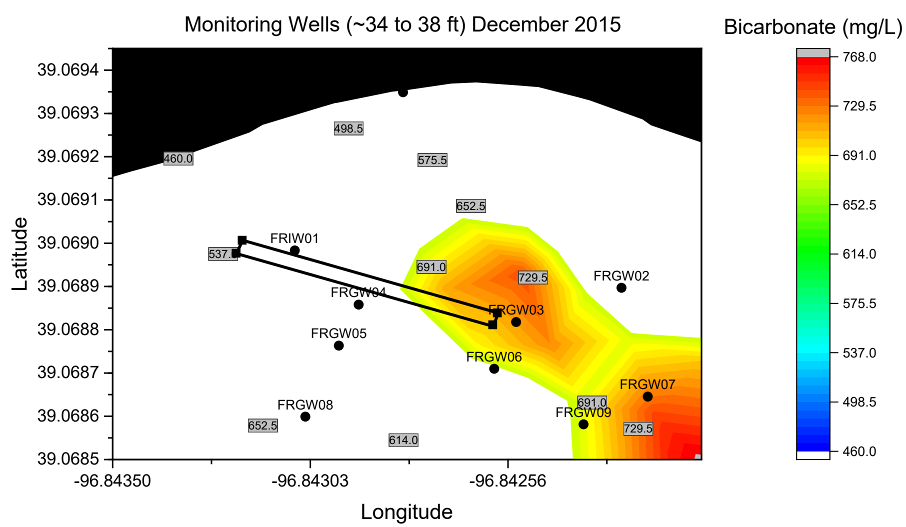


It appears that the exfiltrate carries carbonate from [illegible] gate.

September 2015



December 2015



34 to 38 ft BGL

EPA
United States
Environmental Protection
Agency

Office of Research and Development
National Risk Management Research Laboratory
Water Systems Division
Water Resources Recovery Branch

United States Environmental Protection Agency

EFFECTIVENESS

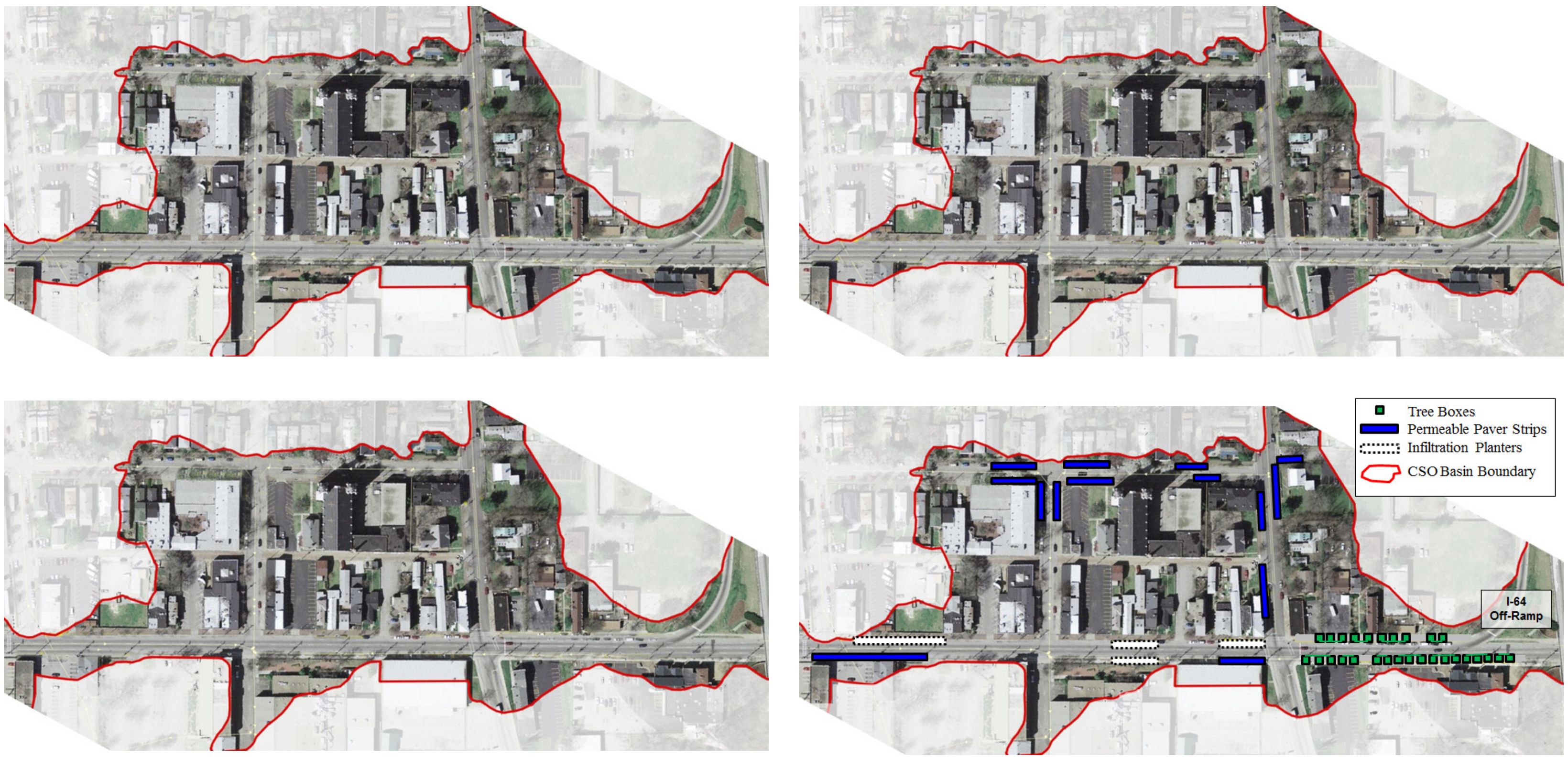
EPA
United States
Environmental Protection
Agency

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

Control | Impact

Before

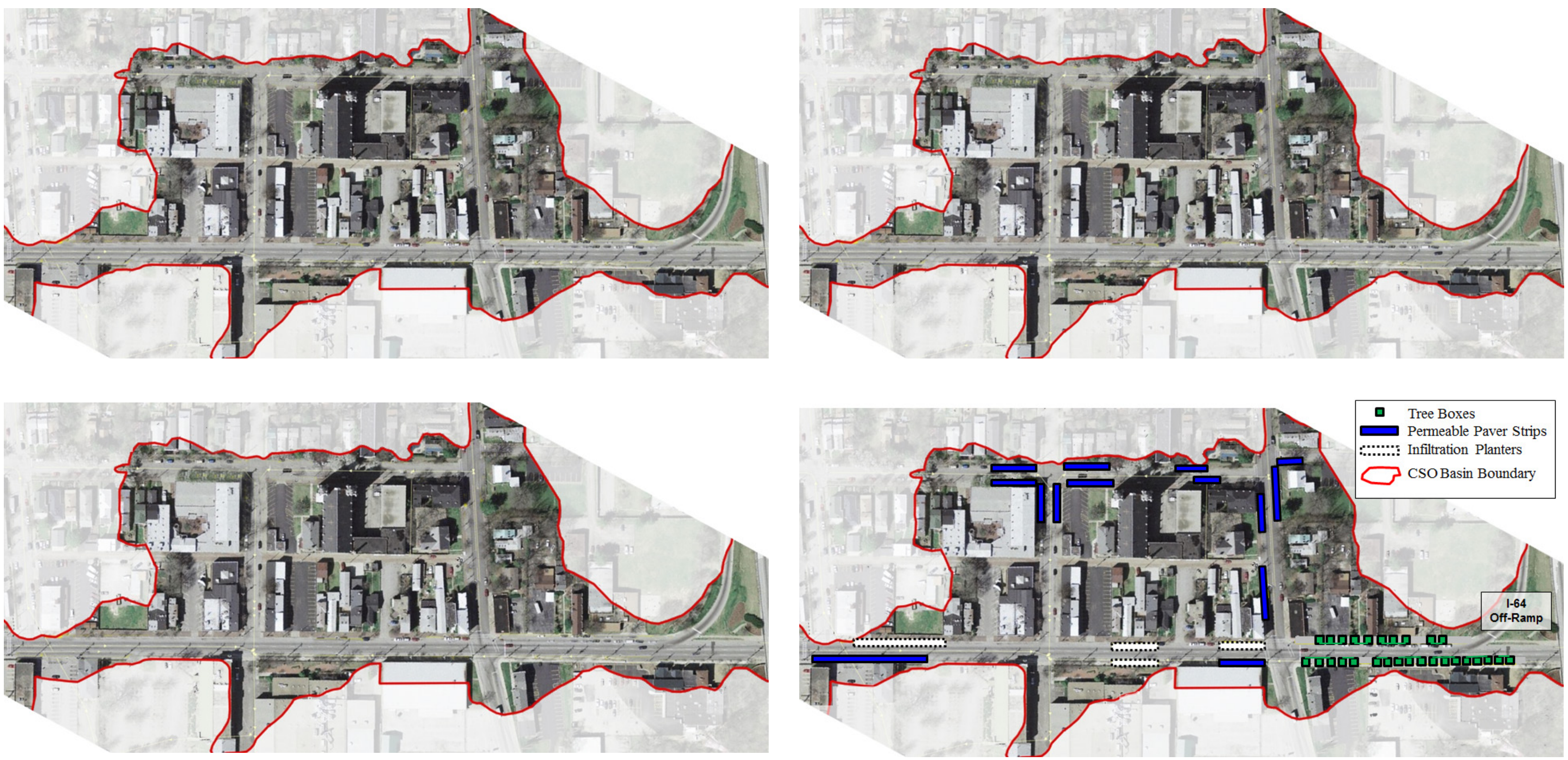
After



Plan “B” created a virtual sewershed for comparison.

Modeled (InfoWorks) | **Measured**

Before / **After**



United States Environmental Protection Agency

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	• $X_{3,1}, X_{3,2}, X_{3,3}$ . . .	• $X_{4,1}, X_{4,2}, X_{4,3}$ . . .

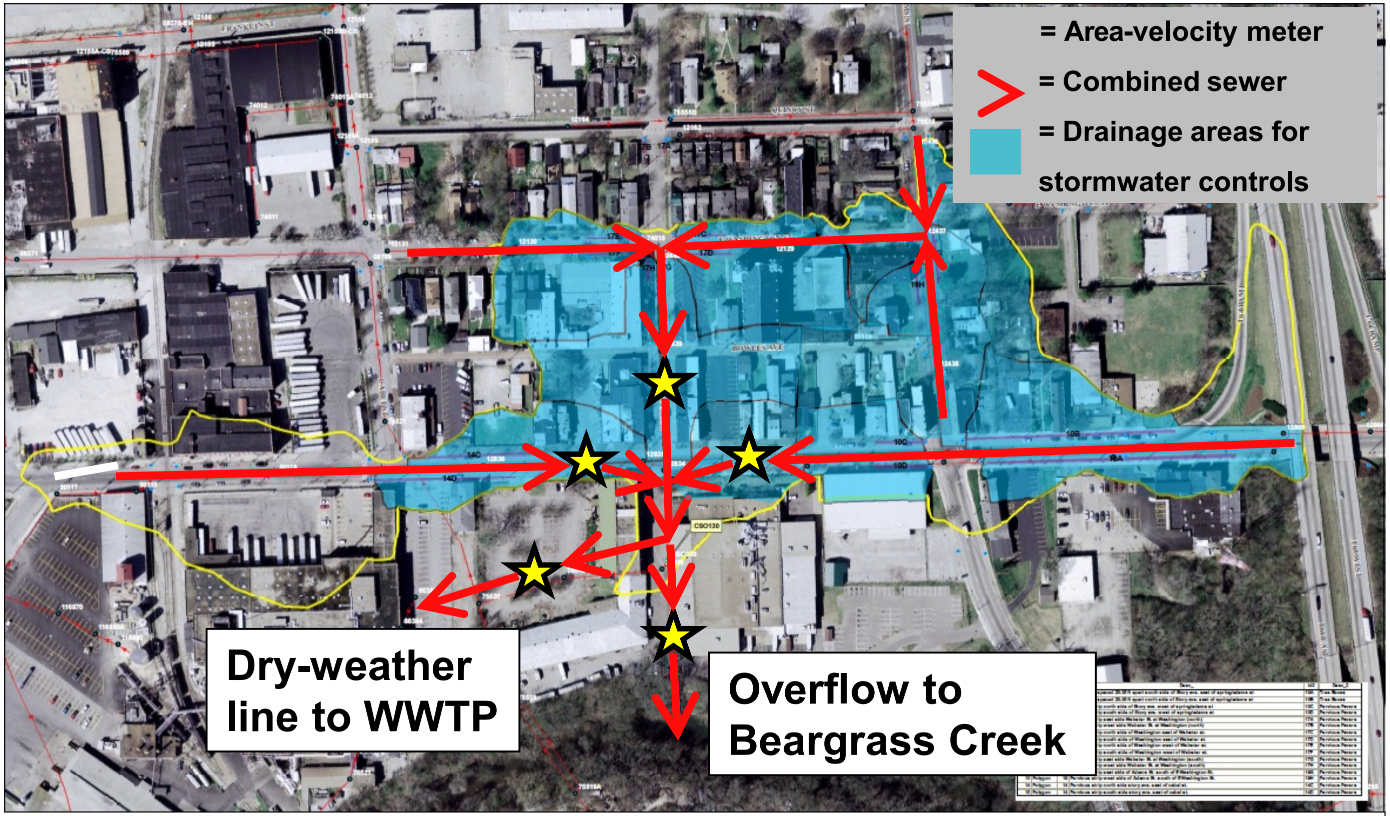
EPA United States Environmental Protection Agency

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.

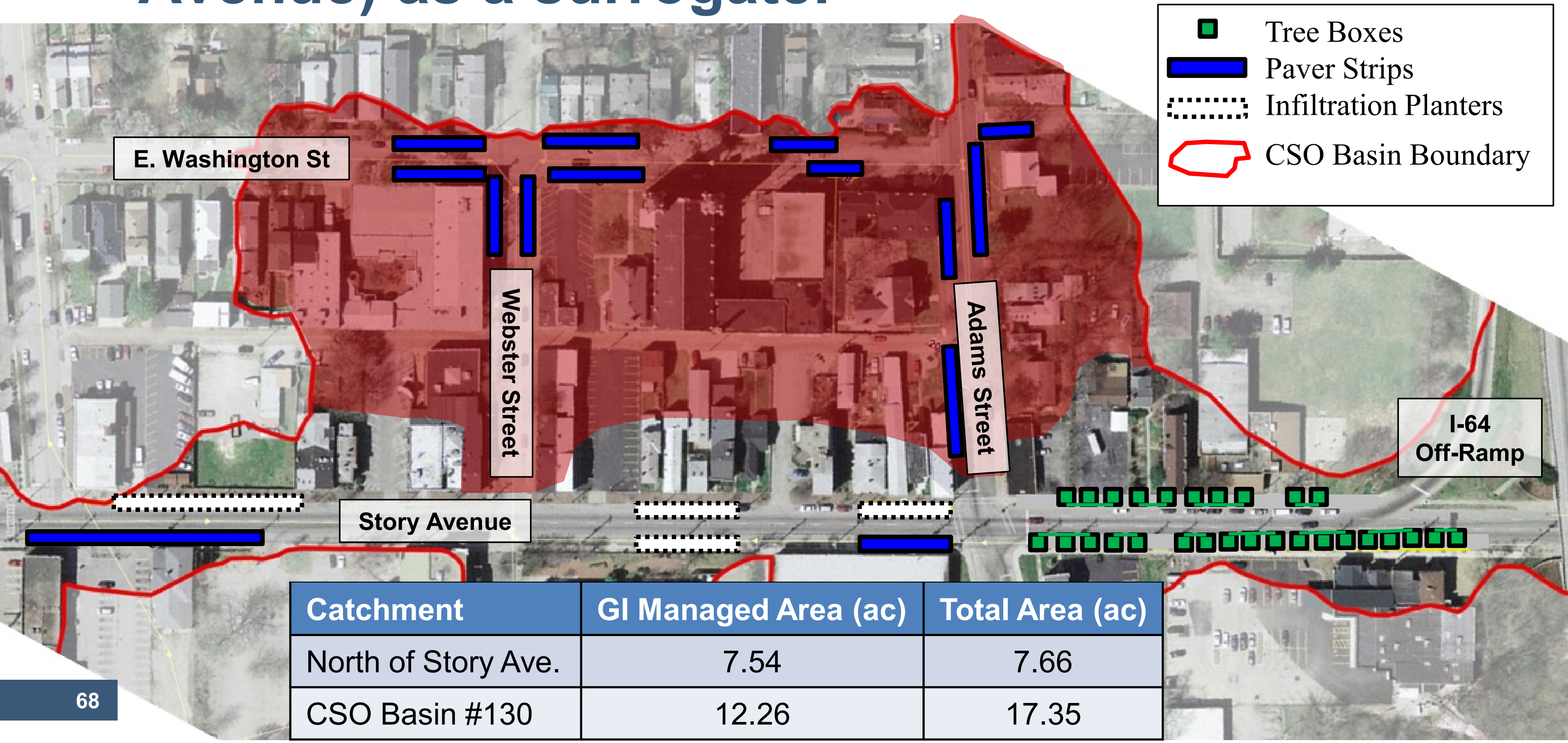
The flow meters separated the basin into 4 catchments, and catch basins were used to define 29 subcatchments.

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



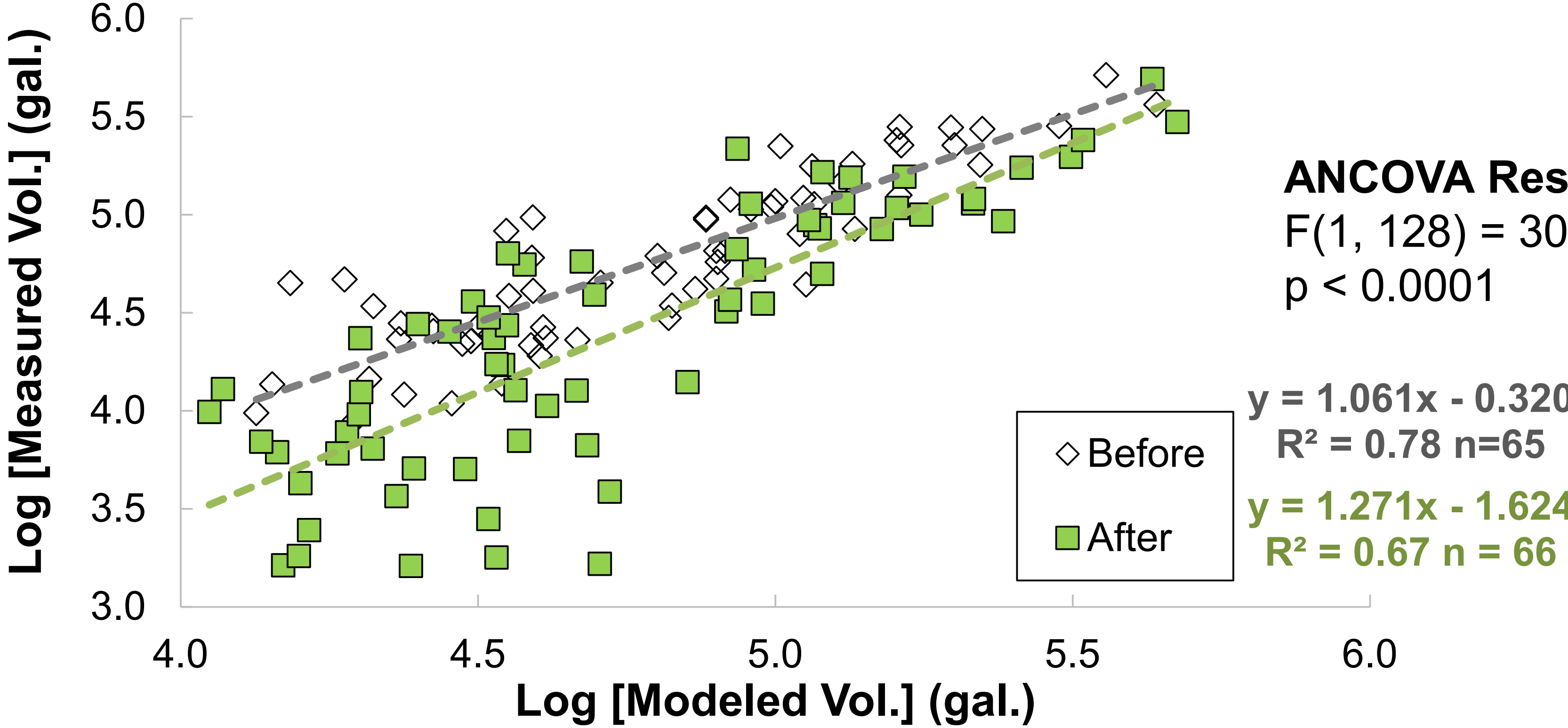
EPA United States Environmental Protection Agency

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.

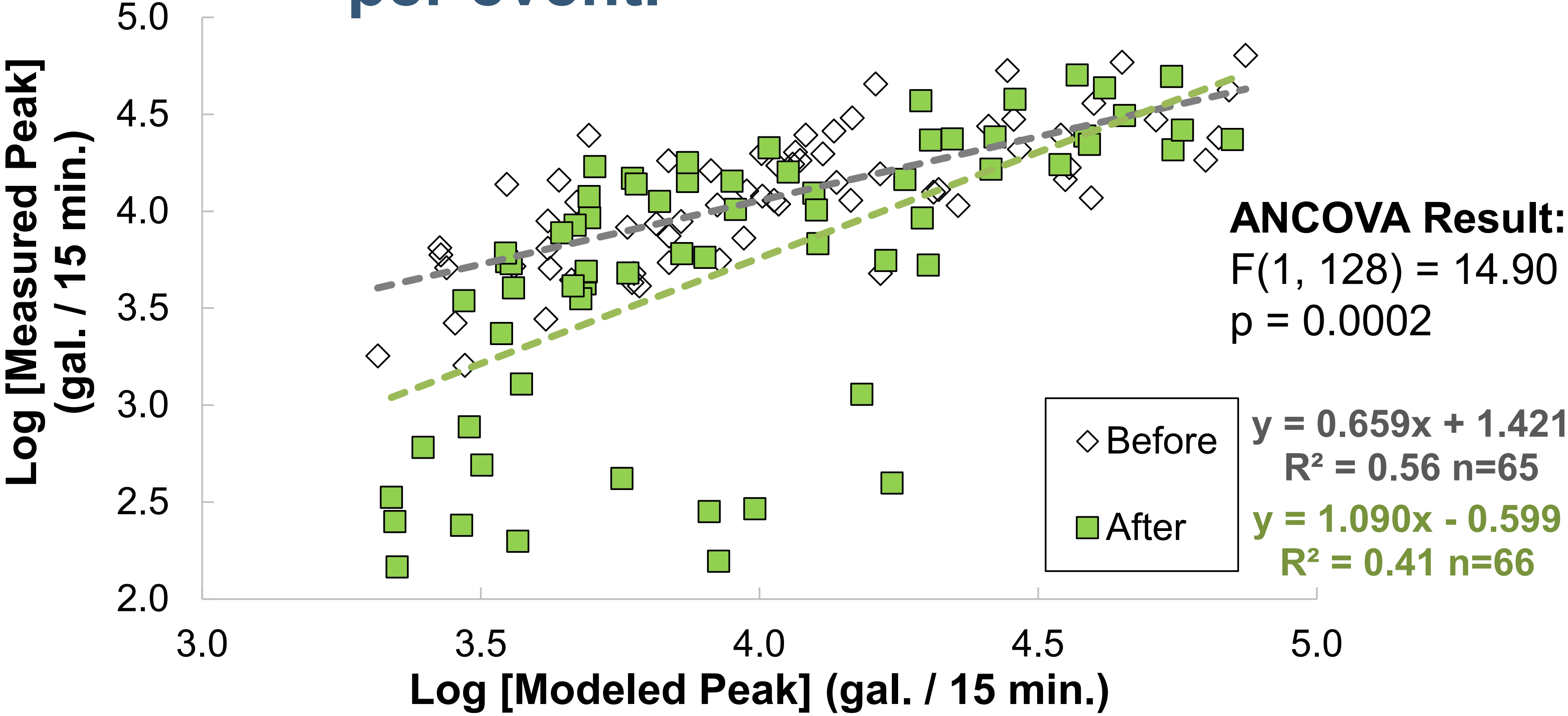


ANCOVA Result:
$F(1, 128) = 30.84$
$p < 0.0001$

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

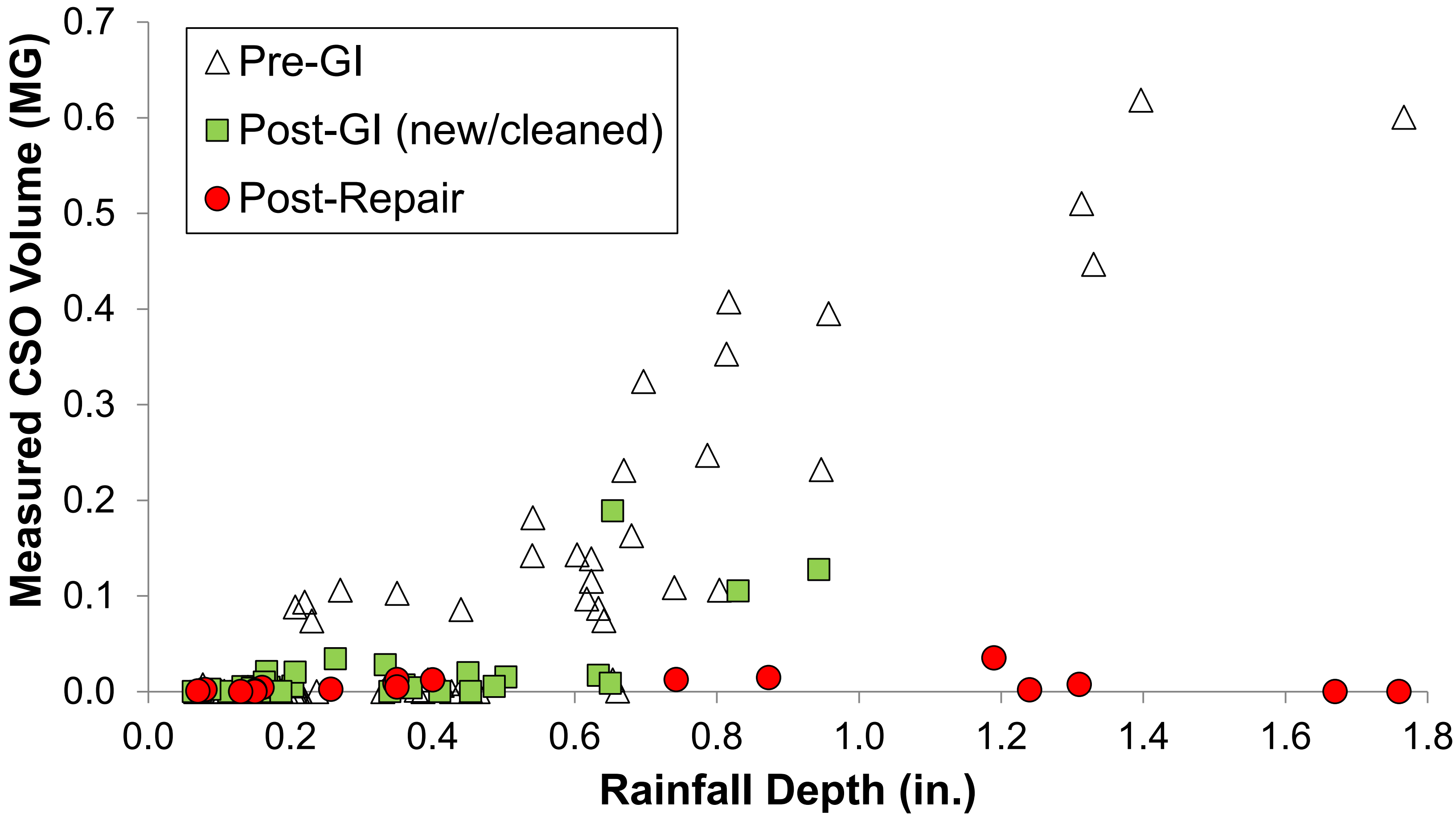
Using the BACI approach, GI also significantly reduced peak flow rates per event.



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)

Sneak preview of upcoming research

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