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Expectations vs. Outcomes: Considering Performance Metrics for Stormwater Green Infrastructure

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ASCE-NJ Educator of the Year, 2018

AAEES/NJWEA Wesley Eckenfelder Memorial Breakfast
May 8, 2018


1980s


1990s
VDOT
ENVIRONMENTAL
MONITORING
SITE
RESEARCH COUNCIL
804-293-1900

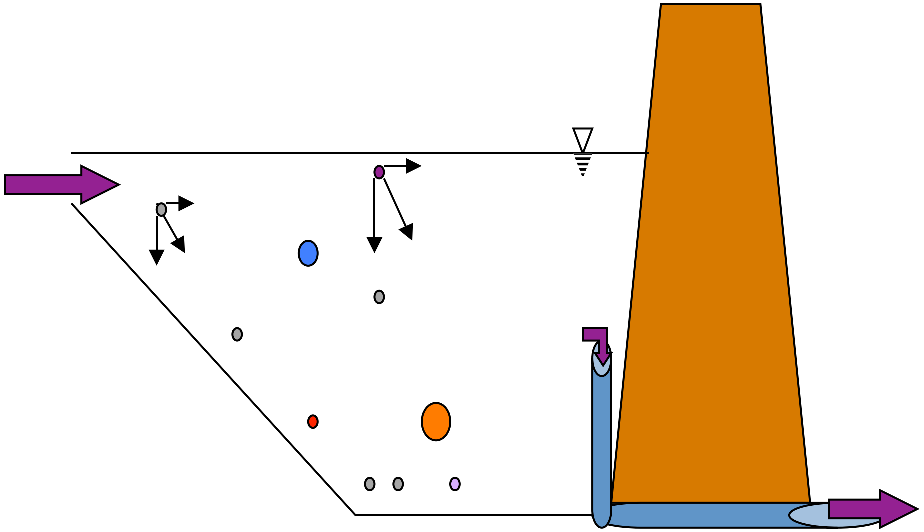

2000s


2018

1990s: NPDES Phase 1

Introduces stormwater quality treatment for large municipal separate storm sewer systems (MS4s)

The magic number: 80% TSS Removal



- Adopted from CZARA (1993)
- 1983 US EPA Nationwide Urban Runoff Program (NURP)
- Remove other pollutants by default

Design Objectives: Hydrologic Mitigation

Design Storm ARI	Impact Avoidance	Mitigation Requirement
≥ 100-yr, X-hr	Property damage & loss of life	Post-development peak flow rate to pre-development conditions (or some fraction thereof)
10 to 50-yr, X-hr	Flooding, stream erosion	
2-yr, X-hr	Stream erosion	

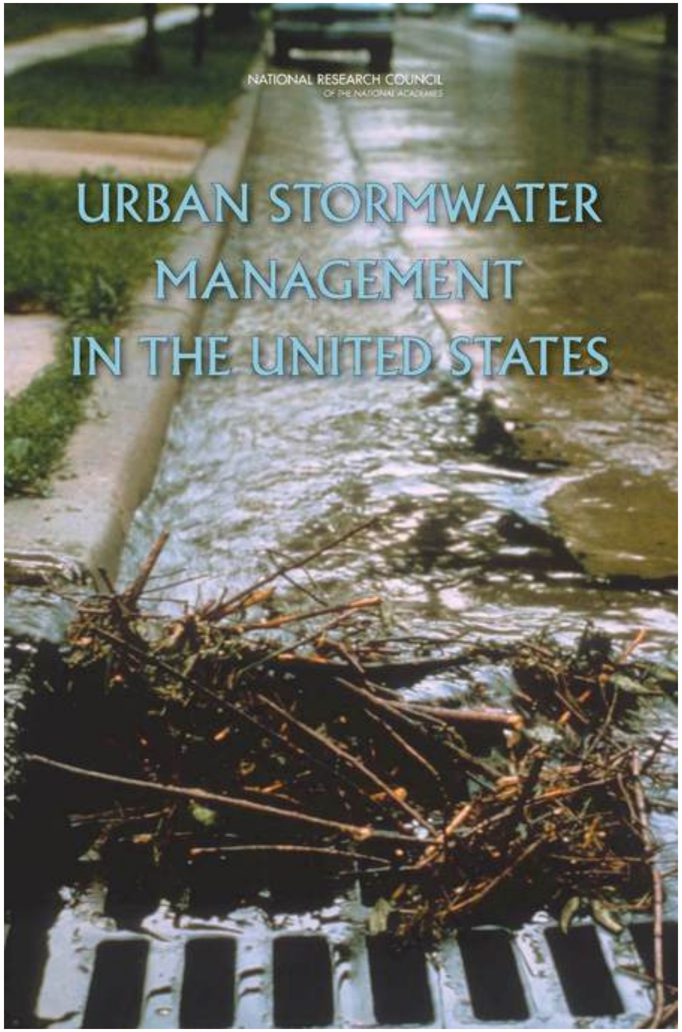
Design Objective: Minimize Stream Erosion

Leopold (1964) on natural streams:

2-yr return period flow → "bankfull" conditions → stream erosion

After ~38 years of "stormwater management", why do performance metrics and permitting objectives largely remained unchanged?

What we've learned…



"One size fits all",

end-of-pipe approaches

do not address

the wide range of hydrologic

and water quality impacts.

(National Research Council 2008)

Stormwater Quality Performance "Objectives": 80% TSS Removal

(& others by default)

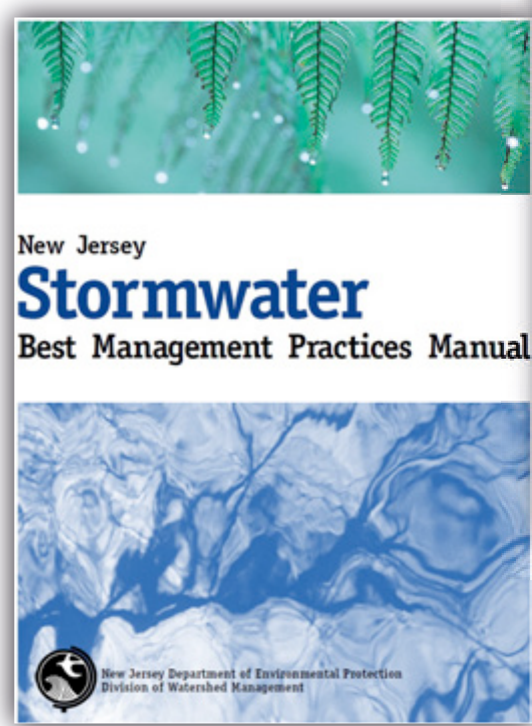


Table 4-1: TSS Removal Rates for BMPs

Best Management Practice (BMP)	Adopted TSS Removal Rate (%)
Bioretention System	90
Constructed Stormwater Wetland	90
Dry Well	Volume Reduction Only[1]
Extended Detention Basin	40 to 60[2]
Infiltration Structure	80
Manufactured Treatment Device	See N.J.A.C. 7:8-5.7(d)[3]
Pervious Paving System	Volume Reduction Or 80[4]
Sand Filter	80
Vegetative Filter	60-80
Wet Pond	50-90[5]

Section 3.3 Standard Stormwater Management Practices for Treatment

1. Can capture and treat the full water quality volume (WQv)
2. Are capable of 80% TSS removal and 40% TP removal.

Stormwater Quality Performance “Objectives”

Consider the “math”:

$$\% \ reduction = In - Out / In \times 100\%$$

$$80\% = 200 - 40 / 200 \times 100\%$$

$$60\% = 50 - 20 / 50 \times 100\%$$

Which is “better”?

What impacts the receiving environment?

INTERNATIONAL STORMWATER BMP DATABASE
www.bmpdatabase.org

Frequently Asked Questions:

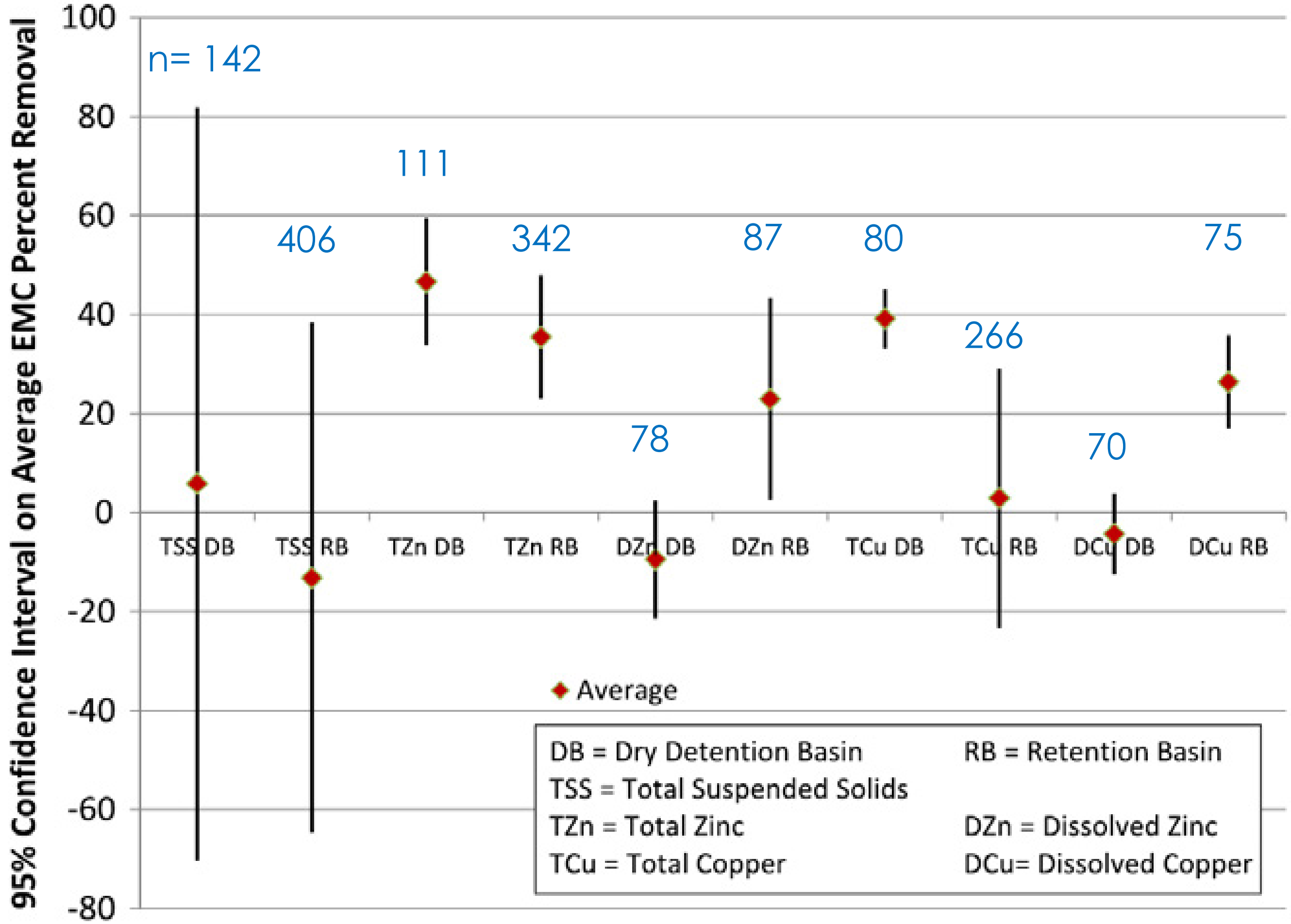
Why does the International Stormwater BMP Database Project omit percent removal as a measure of BMP performance?

The BMP Database Project Team is frequently asked why percent removal is not used to assess best management practice (BMP) performance for the BMP database project. This paper summarizes some key shortcomings associated with percent removal as a tool to assess BMP performance. While we recognize that percent removal is an easy-to-understand concept that is attractive to many entities, we believe that the following shortcomings are significant and require an alternative measure (or measures) of BMP performance:

1. Percent removal is primarily a function of influent quality. In almost all cases, higher influent pollutant concentrations into functioning BMPs result in reporting of higher pollutant removals than those with cleaner influent. In other words, use of percent removal may be more reflective of how "dirty" the influent water is than how well the BMP is actually performing. Therefore (and ironically), to maximize percent removal, the catchment upstream should be "dirty" (which does not encourage use of good source controls or a "treatment train" design approach).

2. Significant variations in percent removal may occur for BMPs providing consistently good effluent quality. Stated differently, the variability in percent removal is almost always much broader than the uncertainty of effluent pollutant concentrations. These variations in percent removal have little relationship to the

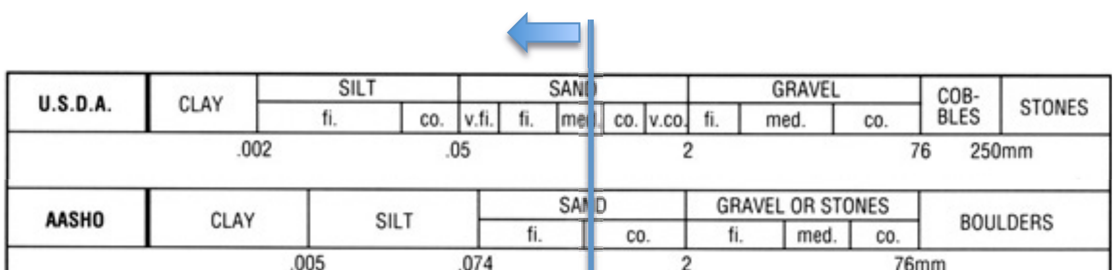
Average %-EMC Removal in Detention and Retention Basins



Fassman, E. (2012). Stormwater BMP treatment performance variability for sediment and heavy metals. *Separation and Purification Technology 84(2012) 95-103.*

Size matters

- Coarse particles caught in gutters & catchpits
- Sediment > 20 μm settles rapidly
- Sediment < 10 μm poorly removed by sedimentation (without chemical pre-treatment)



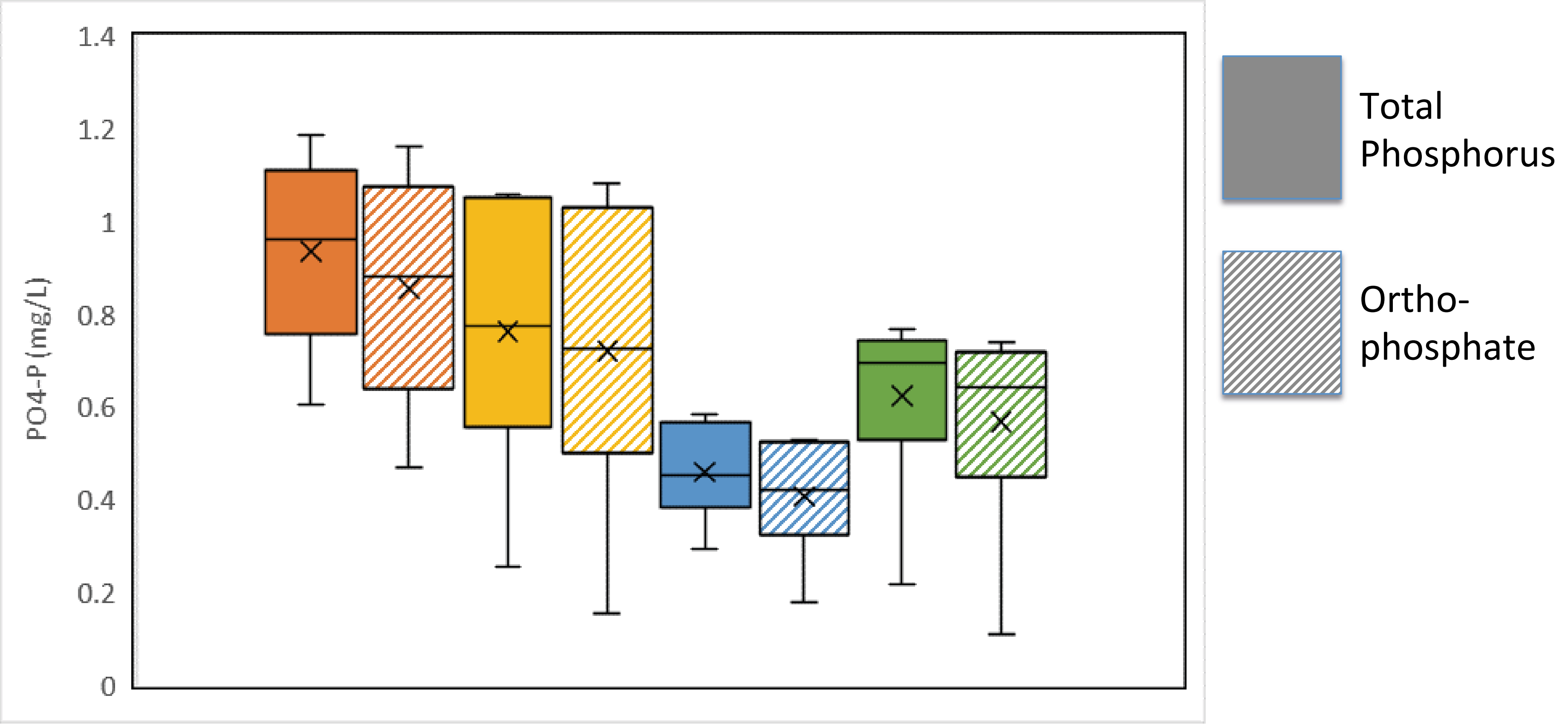
http://www.nrcs.usda.gov/Internet/FSE_MEDIA/nrcs142p2_050639.jpg

Particle-size fraction (mm)	Total Metal Concentration (mg/kg of sediment)		
	Cu	Zn	Pb
0-32	181	2080	316
32-63	197	1695	322
63-125	212	1628	334
125-250	184	1073	251
250-500	85	507	193
500-1000	26	268	323
1000-2000	21	226	36

Zanders (2005) *Sci. of the Tot. Envi.* 339(1-3): 41-7.

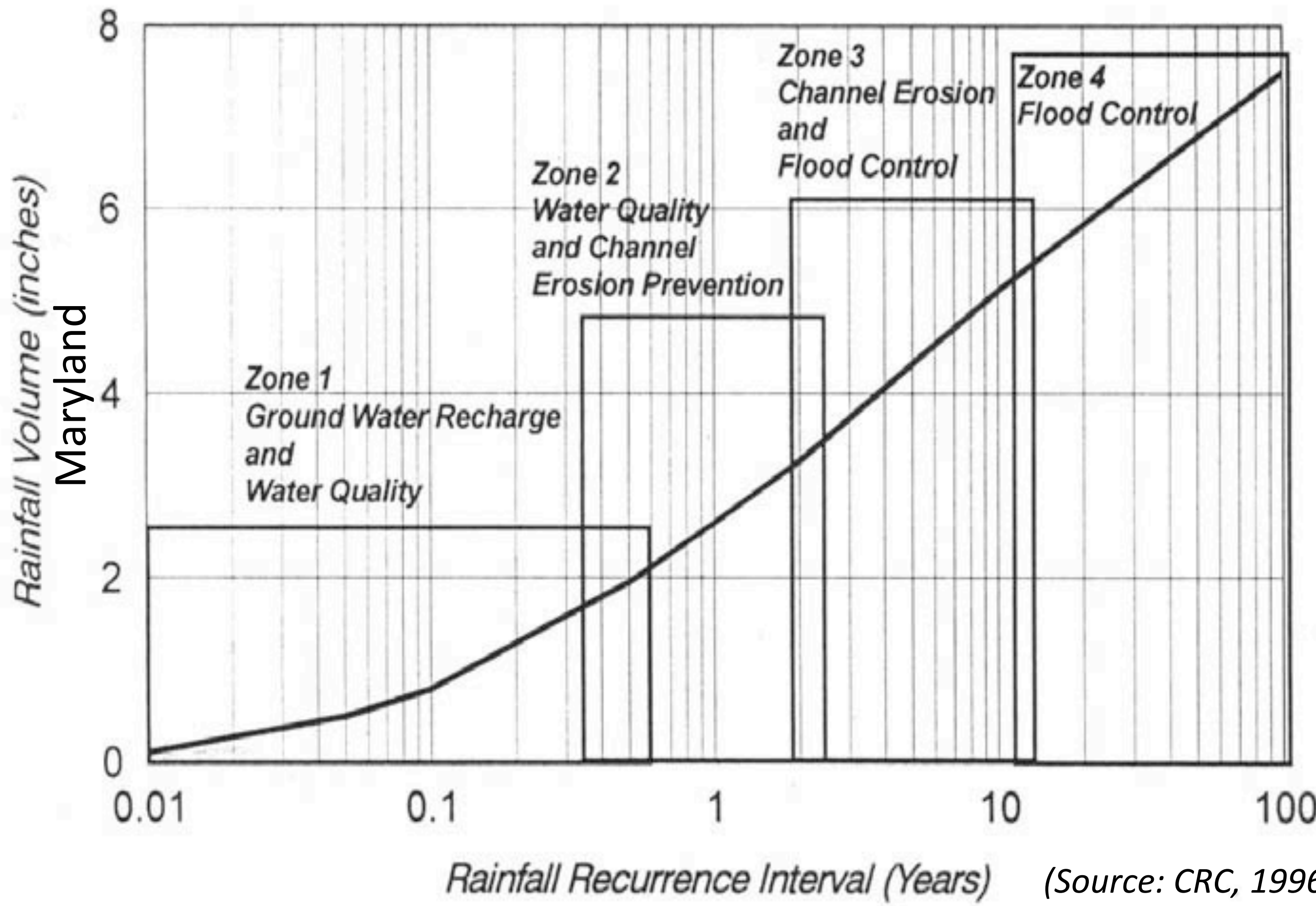
Dissolved vs. Particulate?

Example: 4 Living (Green) Roofs



A spectrum of potential impacts

Rainfall vs. Impacts

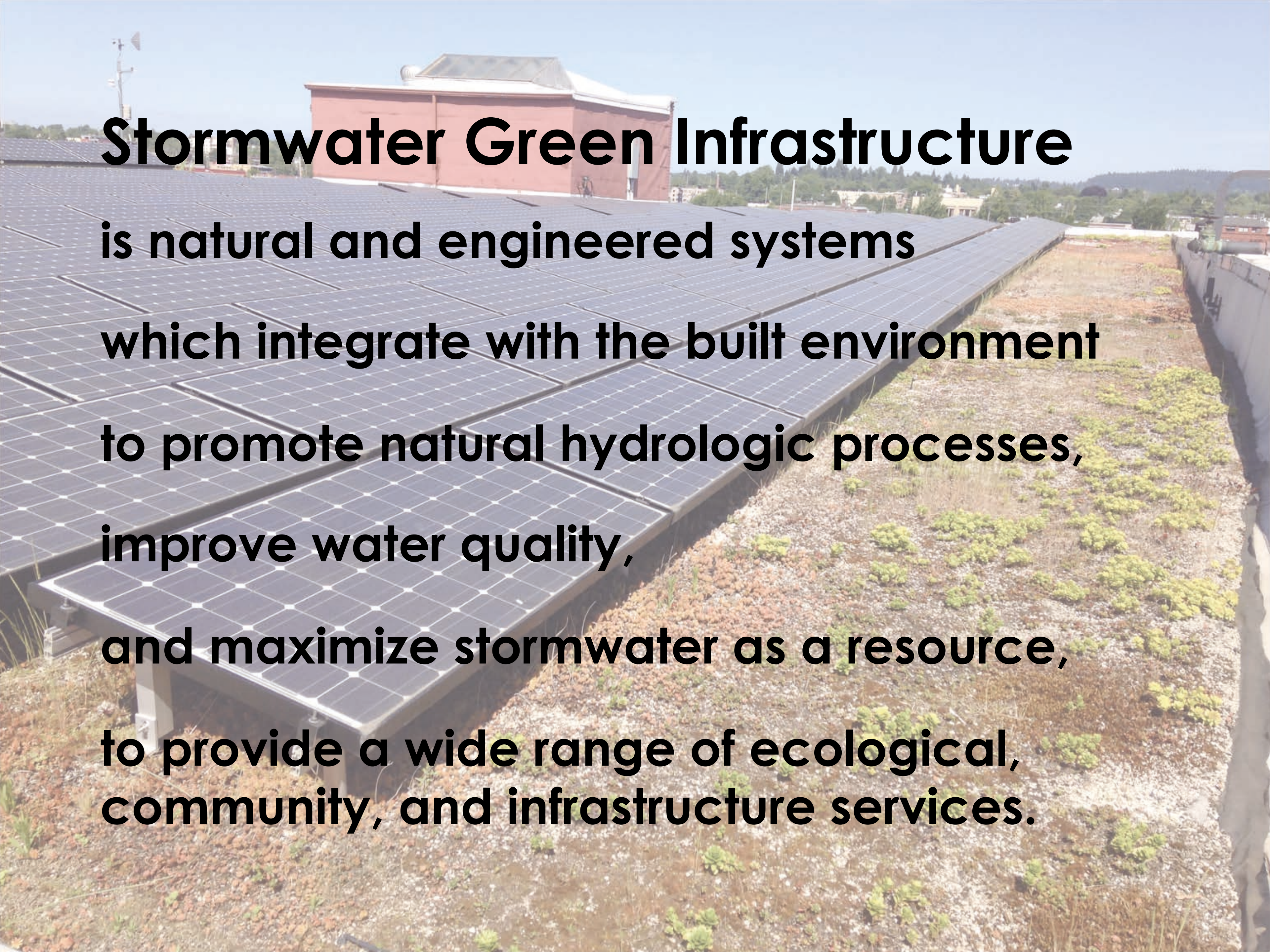


(Source: CRC, 1996)

“New” concerns: Combined Sewer Overflow Mitigation

- 2000’s Wet Weather Quality Act: drives focus on CSO mitigation, quantity control for quality improvement

https://inhabitat.com/wp-content/blogs.dir/1/files/2014/11/combined-sewage-overflow.jpg



Stormwater Green Infrastructure

is natural and engineered systems

which integrate with the built environment

to promote natural hydrologic processes,

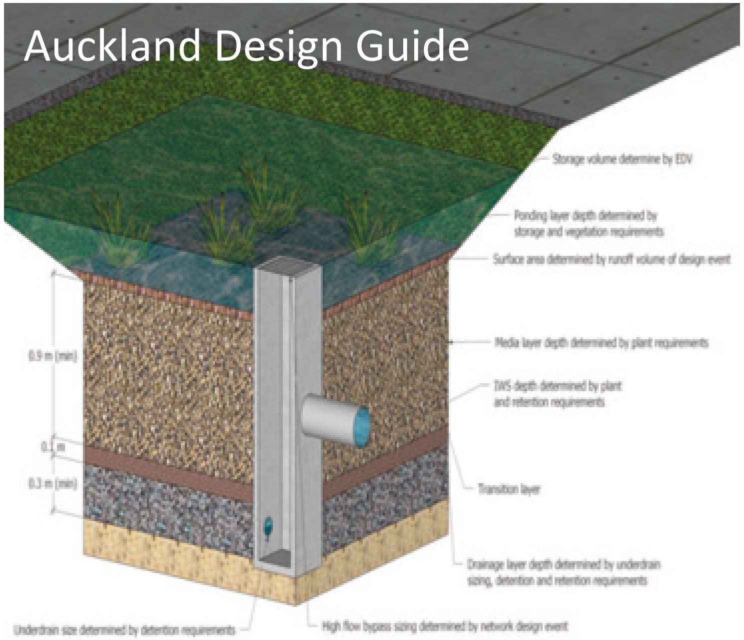
improve water quality,

and maximize stormwater as a resource,

to provide a wide range of ecological, community, and infrastructure services.

Bioretention/ Rain Gardens


Portland, OR



Auckland Design Guide

- ✓ Water quality treatment: sedimentation, filtration, sorption
- ✓ Hydrologic control: evapotranspiration, infiltration (maybe), flow through porous media

Queens


Villanova


Seattle

Swales & Bioswales

Where runoff needs to be conveyed from one location to another….

- ✓ Flow rate & some volume mitigation
- ✓ Some water quality benefit
- ✓ Reduce or eliminate buried pipes
- ✓ Aesthetic enhancement

Green (Living) Roofs

Objective: Prevent runoff generation from rooftops

NYC US Postal Service

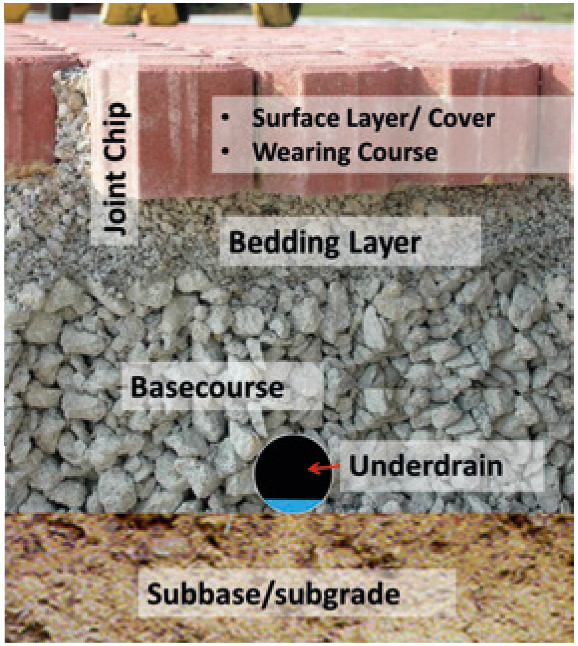
Belford Ferry

- ✓ Excellent flow & volume control

  High field capacity; Evapotranspiration; Flow through porous media

- ✓ Reduce or eliminate stormwater ponds
- ✓ Recreational space, habitat (?)
- ✓ LEED credit

Permeable Pavement



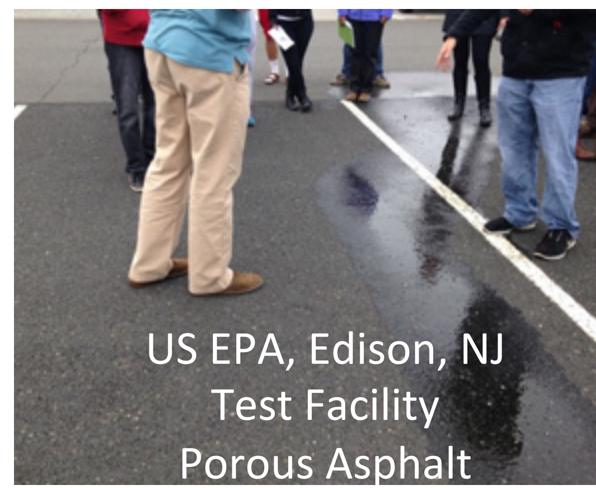
- ✓ Water quality control
- ✓ Hydrologic mitigation

Flow through porous media; storage; infiltration (maybe)

- ✓ Drive, park, load, walk

NC Arboretum, Raleigh, NC
Permeable Interlocking Pavers

Seattle High Point Neighborhood
Porous Concrete Street



US EPA, Edison, NJ
Test Facility
Porous Asphalt

Roof Runoff SCMs

Rainwater Harvesting & Reuse

- ✓ Confined space
- ✓ Flow control (?)
- ✓ CSO mitigation

Bioretention Planters

Spoiled for Choice?

- Many GI technologies
- Flow control mechanisms differ
- Water quality treatment mechanisms differ

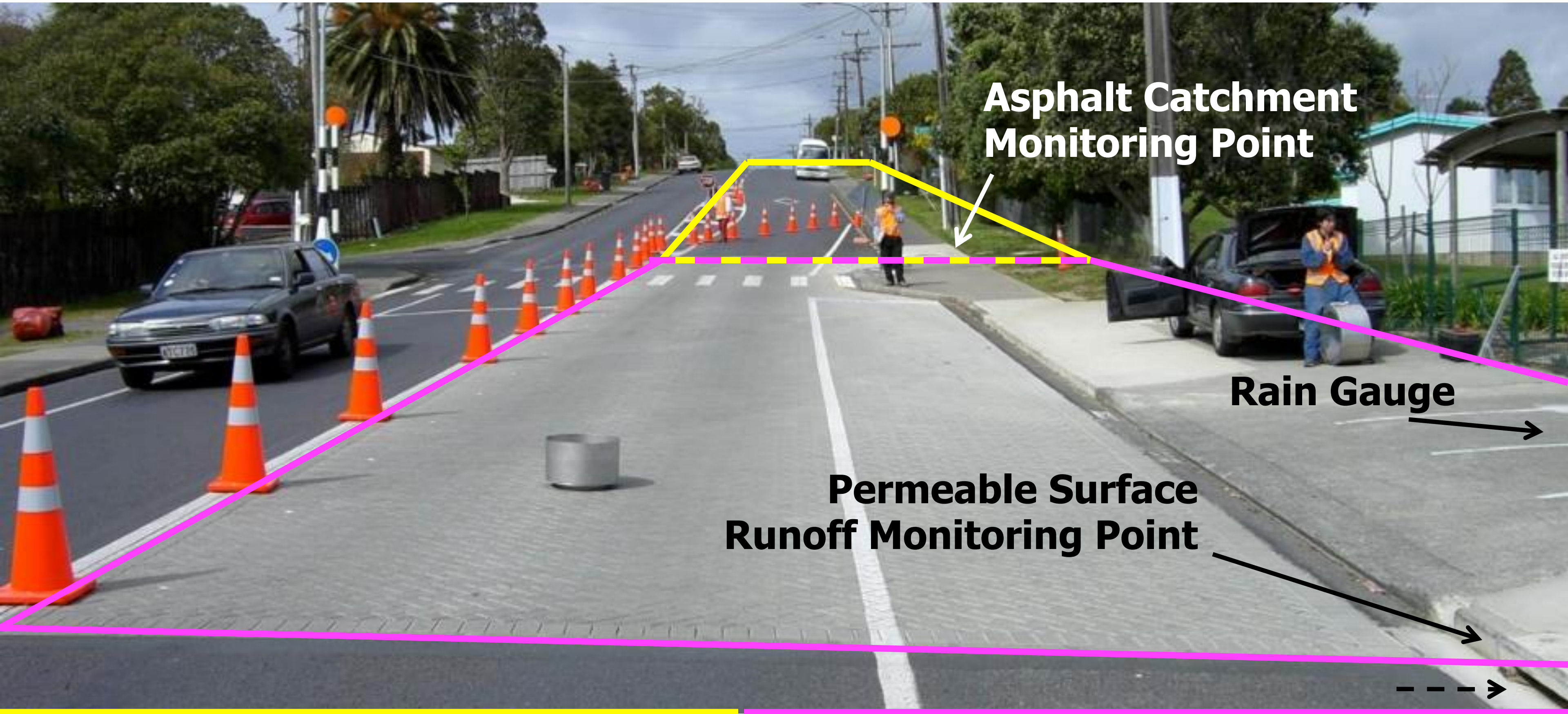
Where we are (broadly):
Use green infrastructure to the maximum extent practicable

Where we should be:
Match form to function.
Treatment trains.

Embrace new knowledge with “new” metrics

Hydrologic Mitigation	Water Quality
• Flow frequency analysis • Flow duration curves	• Probability plots / frequency analysis • Receiving water capacity
Design storms → continuous simulation	% Removals → effluent quality

Permeable Pavement Hydrology



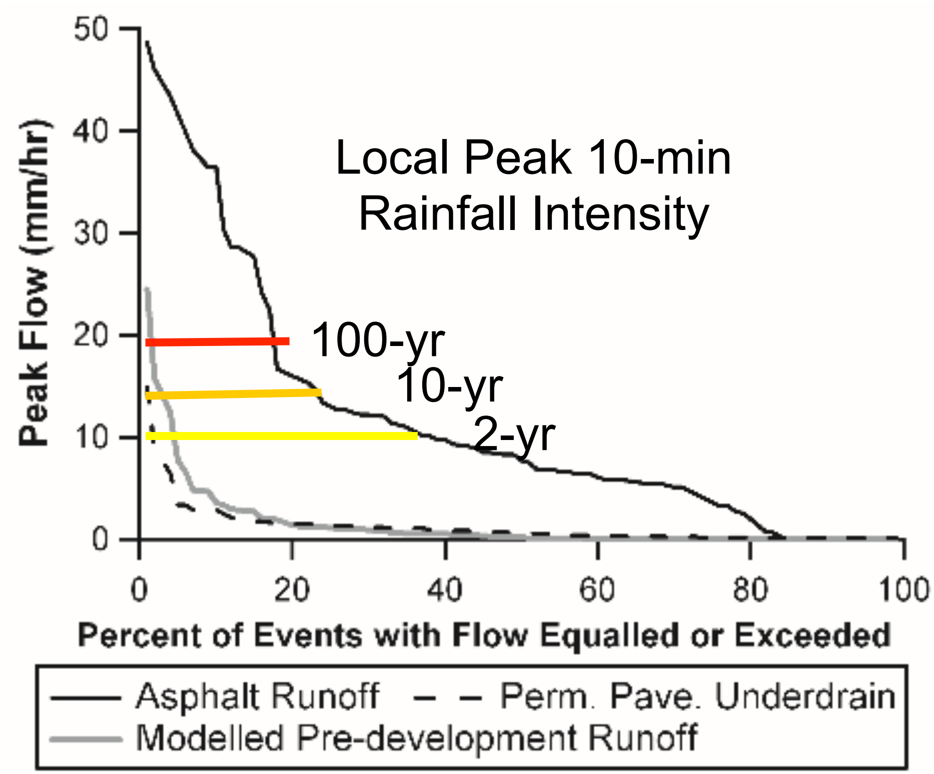
Asphalt Catchment
850 m^2 asphalt road, footpath, grass

Permeable Pavement Catchment
200 m^2 permeable pavement
195 m^2 sidewalk, driveway, grass

Fassman, E.A., Blackbourn, S. (2010). Urban Runoff Mitigation by a Permeable Pavement System over Impermeable Soils. *Journal of Hydrologic Engineering* **15**(6): 475-485.

Flow Frequency Analysis vs. Event–Based Assessment

81 storms

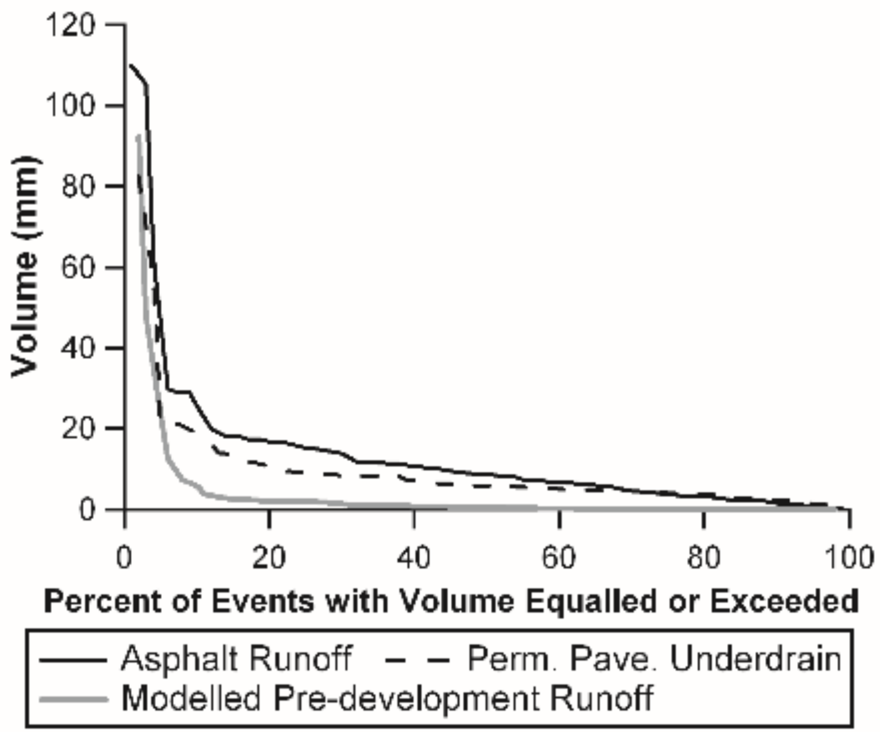


No. of Storms	Storm Depth (mm)	Average Peak Flow (mm/h)		
		Pre*	Asph	Perm
36	2 – 7**	0.0	3.0	0.2
10	7 - 10	0.1	9.5	0.8
24	10 - 20	1.0	9.5	1.2
5	20 - 30	3.3	13.3	1.3
3	30 - 50	6.6	28.6	3.4
3	50 - 150	12.4	46.0	6.5

* Modelled using regulatory approach.
** Best estimate. Storms < 7 mm not accurately measured.

Fassman, E.A., Blackbourn, S. (2010). Urban Runoff Mitigation by a Permeable Pavement System over Impermeable Soils. *Journal of Hydrologic Engineering* **15**(6): 475-485.

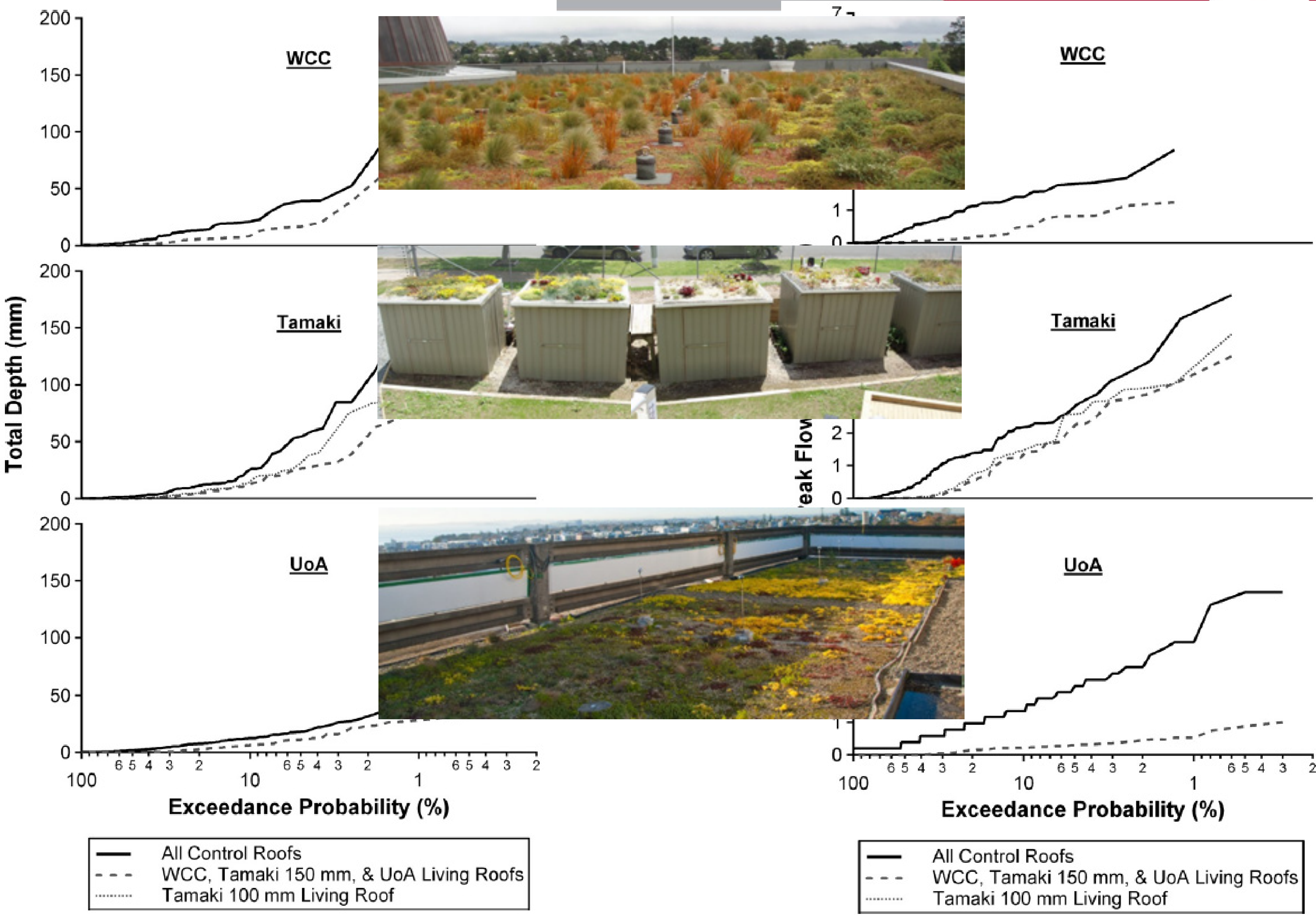
Discharge Volume Frequency Analysis vs. Event-Based Runoff Coefficient



Field-Measured Runoff Coefficients

%-ile	Asphalt Catchment "C"	Permeable Pavement Underdrain "C"
0.10	0.48	0.29
0.25	0.60	0.43
0.50	0.85	0.49
0.75	0.94	0.57
0.90	0.98	0.63

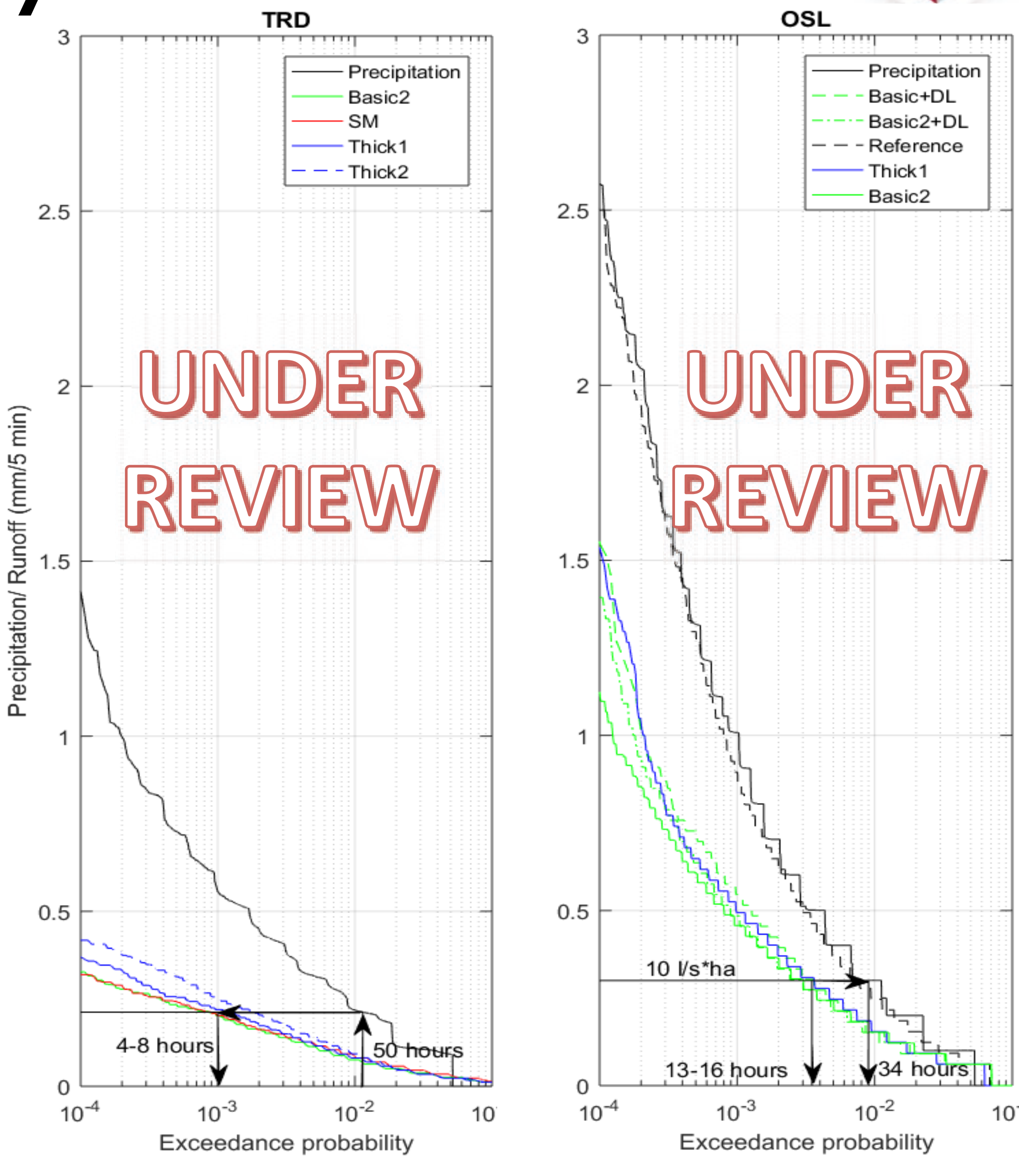
Fassman, E.A., Blackbourn, S. (2010). Urban Runoff Mitigation by a Permeable Pavement System over Impermeable Soils. *Journal of Hydrologic Engineering* **15**(6): 475-485.



Fassman-Beck et al. (2013) *Jrnl. of Hydrology*

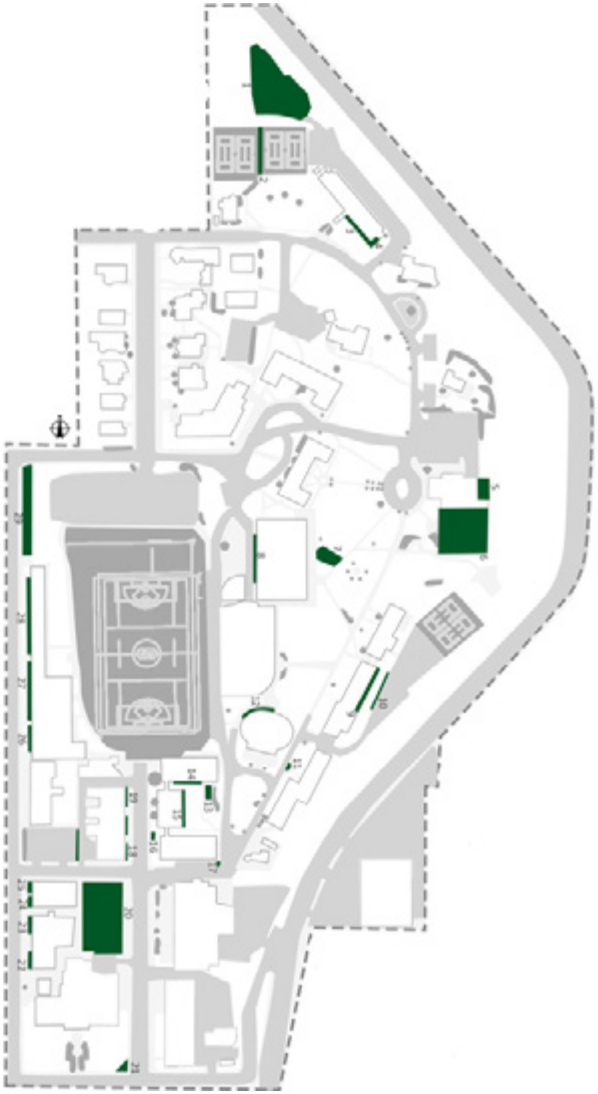
Flow Duration Analysis
Green Roofs

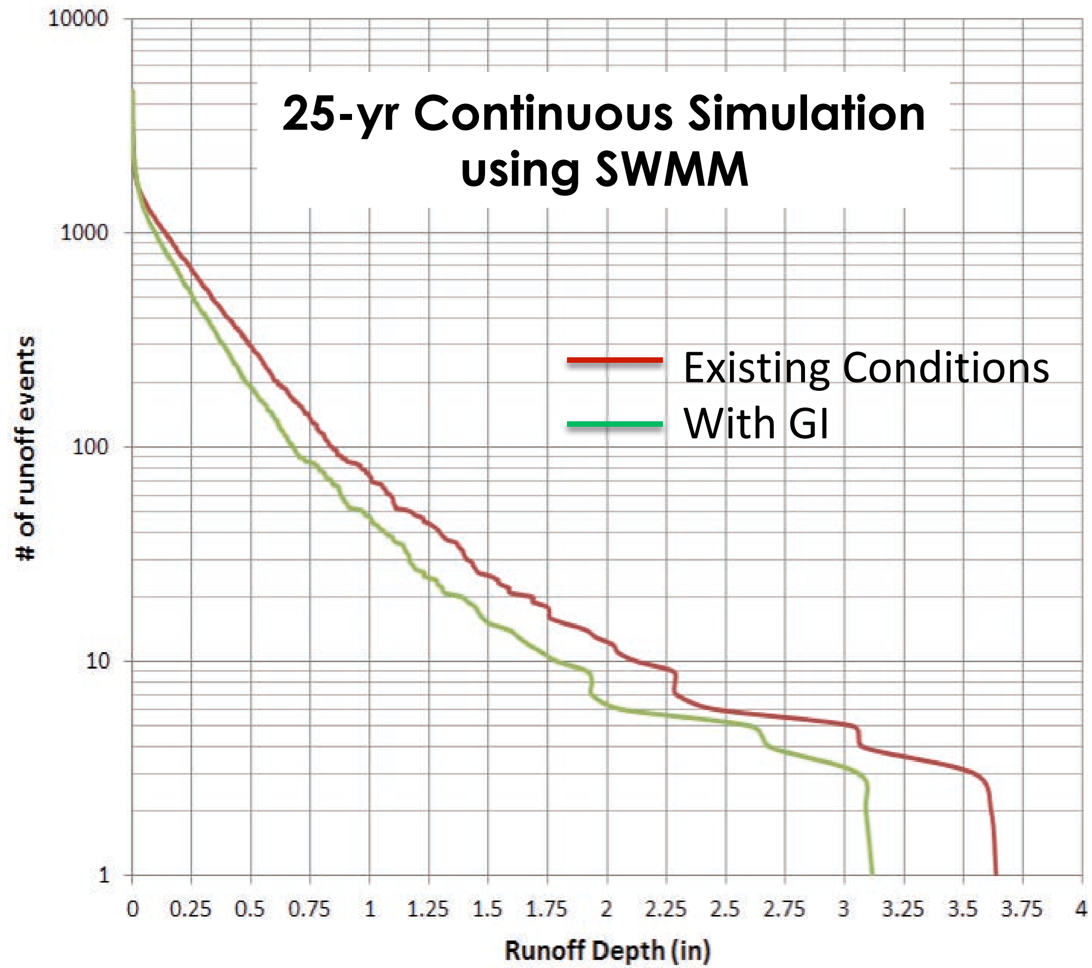
- Demonstrate compliance (or exceedance) with allowable discharge rates under all conditions
- Duration and magnitude of exceedance of combined sewer capacity



Data and analysis courtesy of Birgitte Gisvold Johannessen, Ph.D. Candidate, Norweigan University of Science and Technology

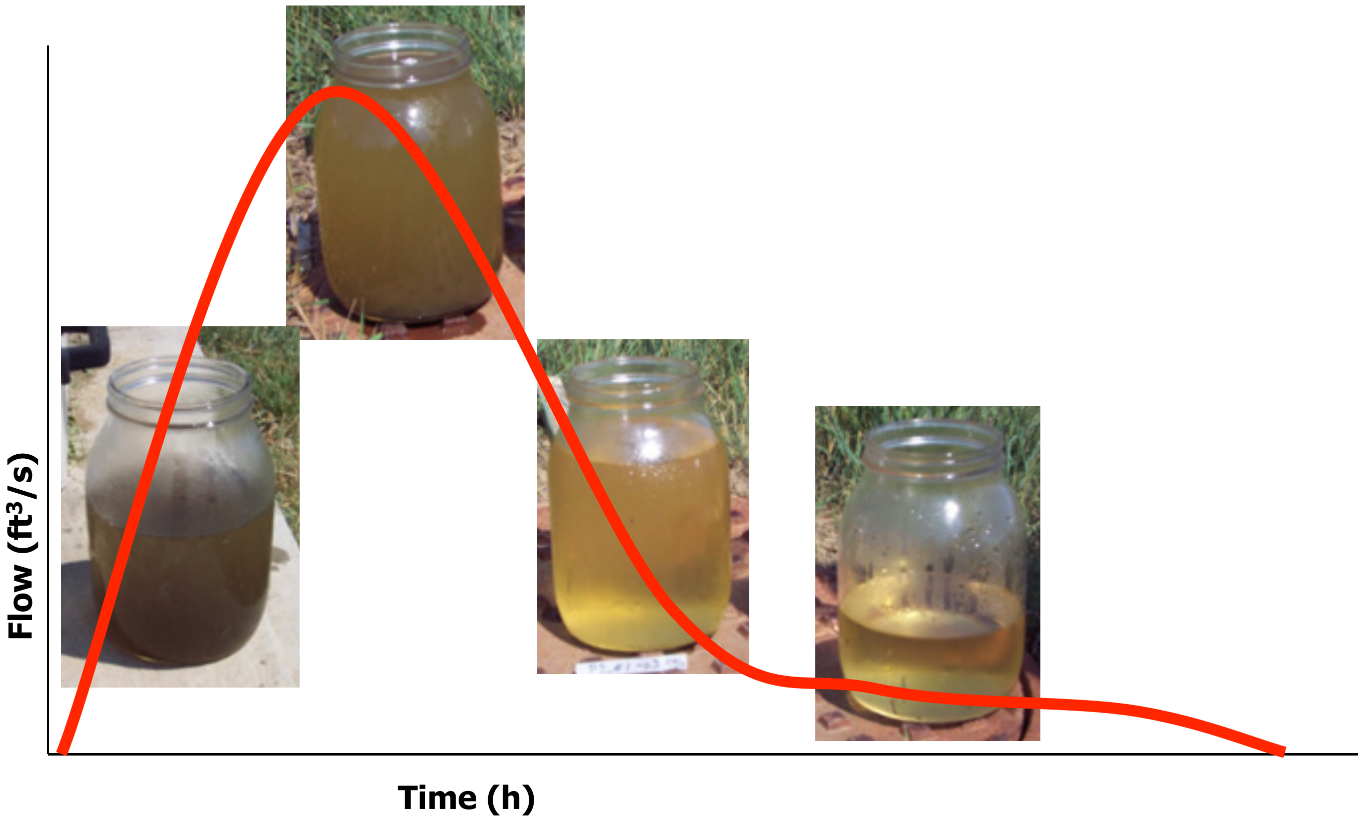
2015 USEPA Campus RainWorks Challenge: Stevens 2nd Pl. Master Plan





Challenges of stormwater quality

Alternatives to the 80% "Rule"



Runoff Samples from Residential Subdivision in Denver, c.2003

BMP Database

www.bmpdatabase.org

International Stormwater BMP Database

Home | Get Data | Submit Data | Documents | Guidance | About

Madison Water Pump House Rain Garden, City of Madison

Welcome! The International Stormwater Best Management Practices (BMP) Database project website features a database of over 600 BMP studies, performance analysis results, tools for use in BMP performance studies, monitoring guidance and other study-related publications. **New to the site?** Start Here

News

- 2016 BMP Performance Summaries
- 2016 Studies Now Available
- Stream Restoration Database
- Agricultural BMP Database Version 2.0 Now Available
- 2014 BMP Database Release
- 2014 BMP Performance Summaries
- 2013 Advanced Analysis
- National Stormwater Quality Database Has A New Home

Related Databases & Research

- Stream Restoration Database
- National Stormwater Quality Database
- Agricultural BMP Database
- Chesapeake Bay Research Portal

Urban Stormwater Research Reports

- 2016 BMP Performance Summaries
- 2014 Statistical Appendices
- 2012 Manufactured Device Performance Analysis Summary
- 2012 Volume Reduction in Bioretention
- 2012 Database Overview
- 2012 Chesapeake Bay BMP Performance Summary

Retrieve Urban Stormwater BMP Performance

- BMP Study Retrieval Tool
- BMP Map Tool
- BMP Category Reports
- Online Statistical Analysis Tool
- Download Access Database

Contacts | Policies | Disclaimer

Accounting for variability?

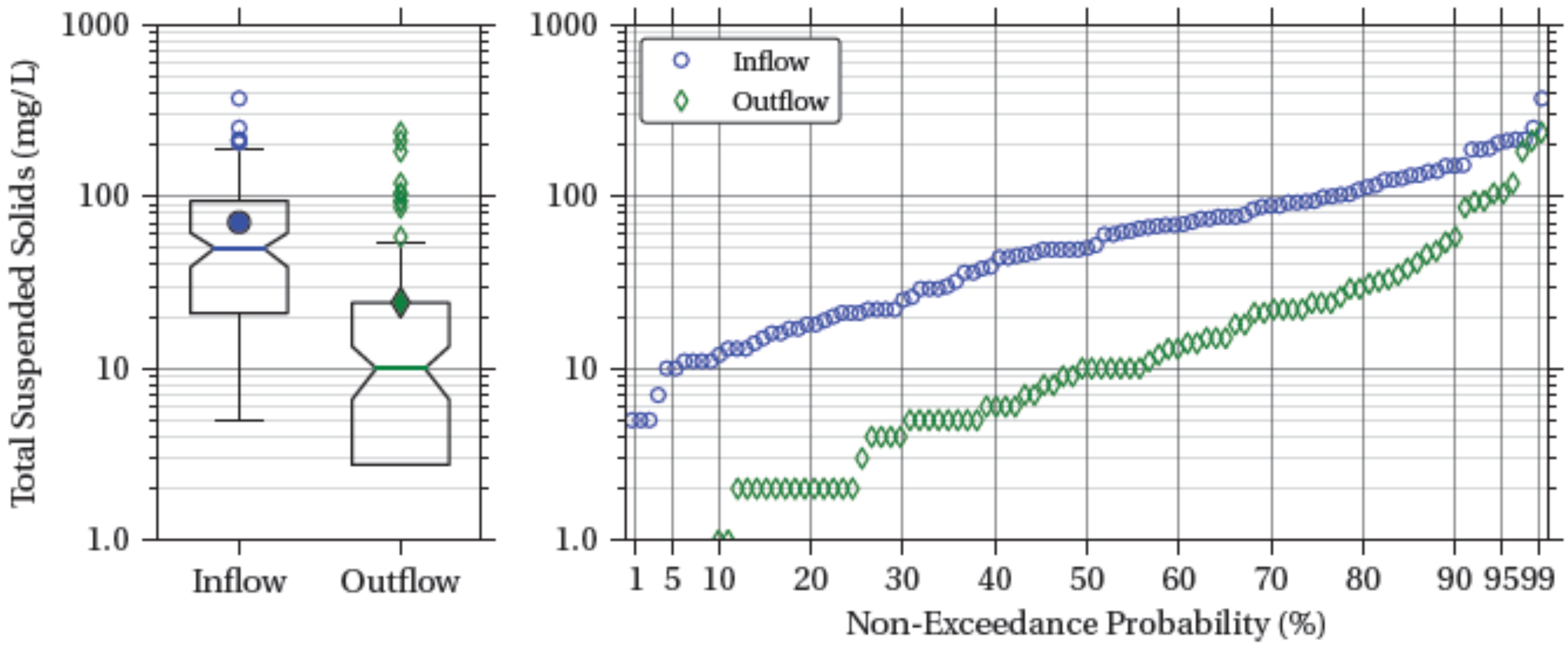


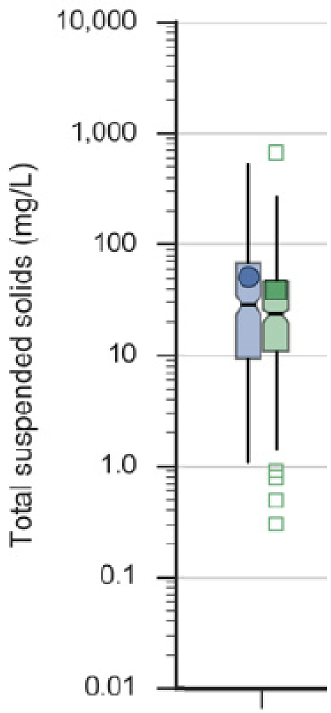
Figure 2.1: Box and Probability Plots of Total Suspended Solids at Bioretention BMPs

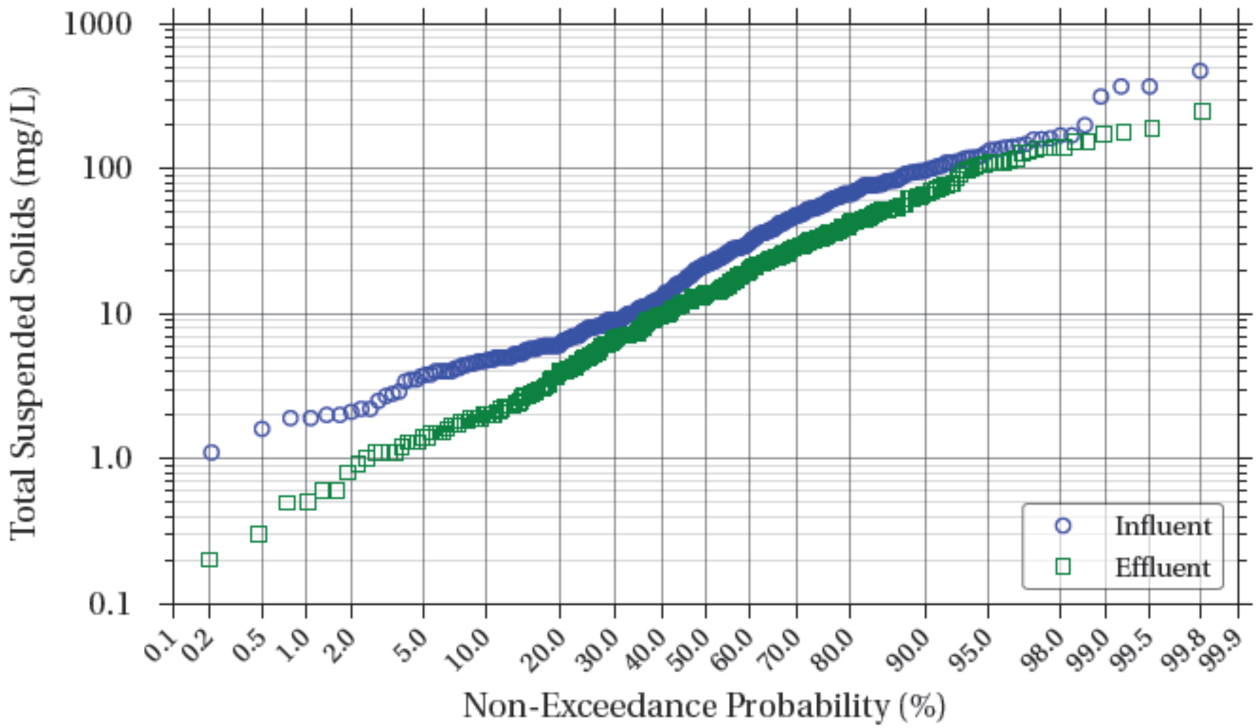
Int'l BMP Database

Geosyntec Consultants & Wright Water Engineers, May 2011

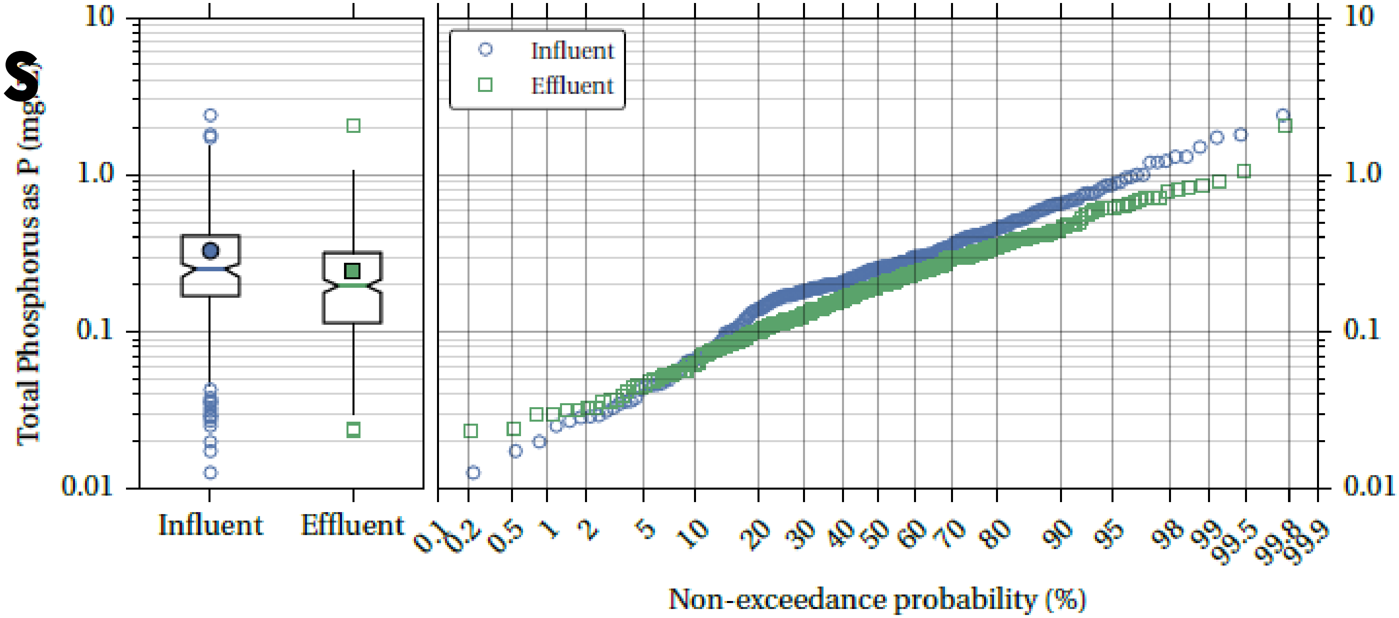
Swale TSS Performance

NJ DEP awards “credit” for 50% TSS removal if design complies with minimum guidelines in stormwater manual (Sect 9.12)

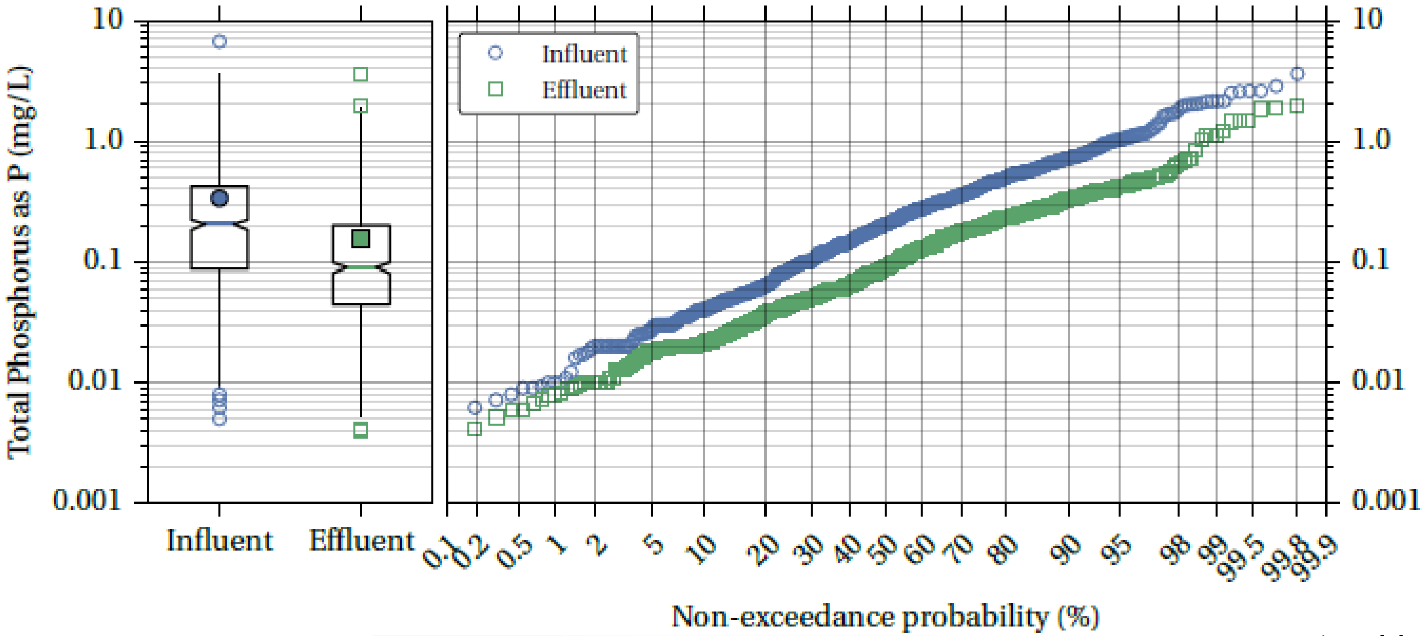




Total Phosphorus

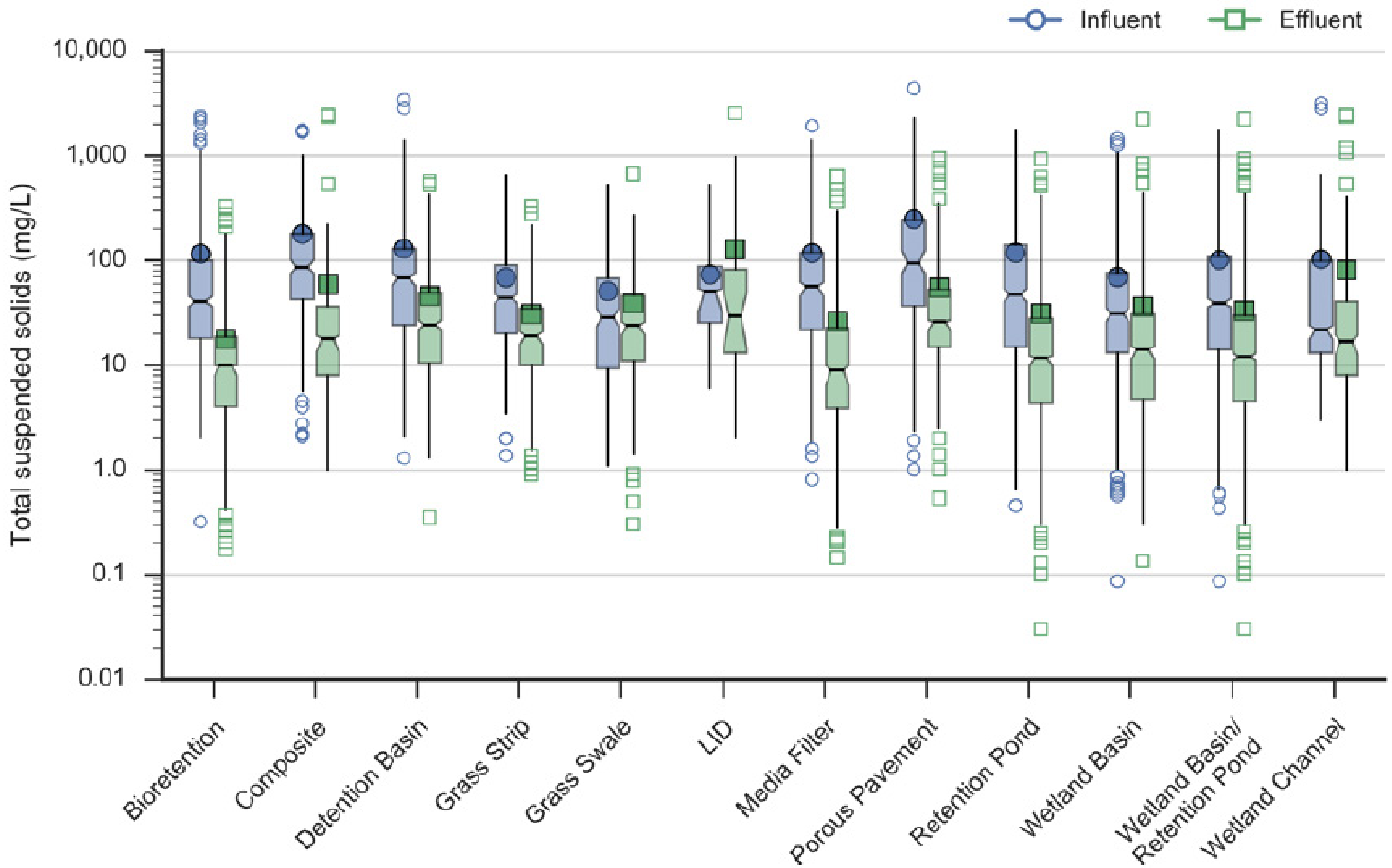


Detention Basin



Retention Basin

Example Data Analysis: TSS Box & Whisker Plots



Wright Water Engineers and Geosyntec. (2017). Int'l Stormwater BMP Database 2016 Summary Statistics. www.bmpdatabase.org.

Statistical Performance Summary: TSS

BMP Category	BMPs		EMCs		25th		Median			75th	
	In	Out	In	Out	In	Out	In	Out	Difference	In	Out
Bioretention	25	25	520	463	18.0	4.0	40.6 (36.0, 46.0)	10.0 (8.0, 10.0)	◆◆◆	99.2	18.5
Composite	10	10	202	174	42.4	8.0	85.7 (75.0, 101.3)	18.0 (12.8, 19.2)	◆◆◆	178.8	36.5
Detention Basin	32	33	411	436	24.1	10.5	68.0 (57.4, 76.2)	24.3 (21.8, 27.0)	◆◆◆	129.0	49.6
Grass Strip	19	19	361	282	20.0	10.0	44.0 (39.0, 48.0)	19.0 (15.5, 21.0)	◆◆◆	90.0	35.0
Grass Swale	24	24	442	418	9.2	11.0	28.6 (23.0, 35.0)	24.0 (19.0, 26.0)	◇◇◆	67.5	46.7
LID	3	3	131	62	25.5	13.0	51.0 (32.0, 54.0)	29.5 (15.0, 49.3)	◇◇◇	87.5	82.0
Media Filter	25	25	400	377	22.0	3.9	56.4 (46.0, 61.9)	9.0 (6.4, 10.0)	◆◆◆	120.0	22.8
Porous Pavement	9	9	404	248	36.8	15.0	93.7 (75.0, 126.0)	26.0 (20.6, 27.0)	◆◆◆	243.0	53.2
Retention Pond	56	56	923	933	15.0	4.3	47.2 (40.0, 54.0)	11.7 (10.0, 12.3)	◆◆◆	139.8	28.0
Wetland Basin	22	22	492	486	13.1	4.7	31.0 (26.4, 35.5)	14.1 (11.6, 15.2)	◆◆◆	75.9	31.0
Wetland Basin/ Retention Pond	78	78	1415	1419	14.0	4.5	38.9 (35.6, 43.6)	12.0 (11.1, 13.0)	◆◆◆	110.3	29.6
Wetland Channel	12	12	199	178	13.0	8.0	22.0 (18.0, 24.0)	17.0 (13.0, 19.0)	◇◆◆	98.4	40.5

Inflow-Outflow Concentration Differences	Interpretation
◆◇◇	95% confidence intervals around influent/effluent medians do not overlap.
◇◆◇	P-value of the Mann-Whitney test is less than 0.05.
◇◇◆	P-value of the Wilcoxon test is less than 0.05.

Wright Water Engineers and Geosyntec. (2017). Int'l Stormwater BMP Database 2016 Summary Statistics. www.bmpdatabase.org.

Promising developments?

PHILADELPHIA WATER Stormwater Plan Review

Guidance Manual

Stormwater Management Guidance Manual V3.0 | Stormwater Management Guidance Manual V2.1

In conjunction with the update to Philadelphia's Stormwater Regulations on July 1, 2015, Philadelphia Water has engaged in extensive revisions to create the Philadelphia Stormwater Management Guidance Manual, Version 3. The goals of this revision include:

- Daylighting and clarifying inte
- Identifying design requiremen
- Creating a singular resource f

What is the Stormwater Managemen

The Stormwater Regulations require 15,000 square feet (5,000 in certain also trigger portions of the Stormwat projects. The Stormwater Managem community, designed to help the app

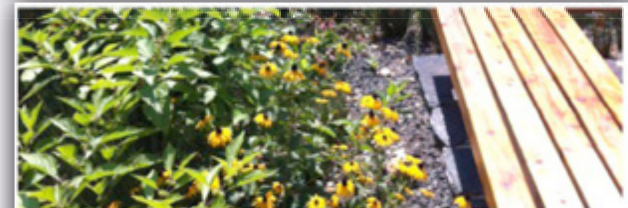
Requirement

The Water Quality requirement stipulates infiltration of the first 1.5 inches of runoff from all directly connected impervious area (DCIA) within the limits of earth disturbance. This volume of stormwater runoff is referred to as the Water Quality Volume (WQv). If infiltration is feasible on the project site, the Water Quality requirement must be met by infiltrating 100% of the WQv through stormwater management practices (SMPs).

In the past, 85% TSS removal has been used as a standard. DEQ is no longer using that standard because it is not reflective of the actual field performance of SCMs. Most SCMs do not remove 85% of TSS, especially at lower concentrations of TSS in the influent.

A-2. SCM Credit Table

SCM	Role	% Annual Runoff Treated if 100% Sized	% Treated Runoff to Fates			$EMC_{effluent}$ (mg/L)	
			HSG	ET&I	Effluent	TN	TP
Bioretention per MDC	Primary	94	A	90	10	0.58	0.12
			B	71	29		
			C	36	64		
			D	14	86		
Bioretention per MDC but without IWS (retrofits and special cases only)	Primary	94	A	51	49	1.20	0.12
			B	20	80		
			C	11	89		
			D	9	91		
Bioretention with design variants per Hyper Tool	Primary	Tool Output	Tool Output			0.58 / 1.20	0.12



North Carolina
Stormwater Control Measure Credit Document

Aug. 2017

Where we started

What's available now

- Water quality treatment performance as %-removals.
- Large storm peak flow control
- End-of-pipe SCMs

- Empirical evidence. Lots of it.
- Frequency distributions, advanced statistics
- Hydrograph analysis
- Green Infrastructure SCMs

kimedia Commons images

I invite you to Stevens' Living Laboratory

Generating evidence-based criteria for the future of urban stormwater management.

Education & Outreach

1870

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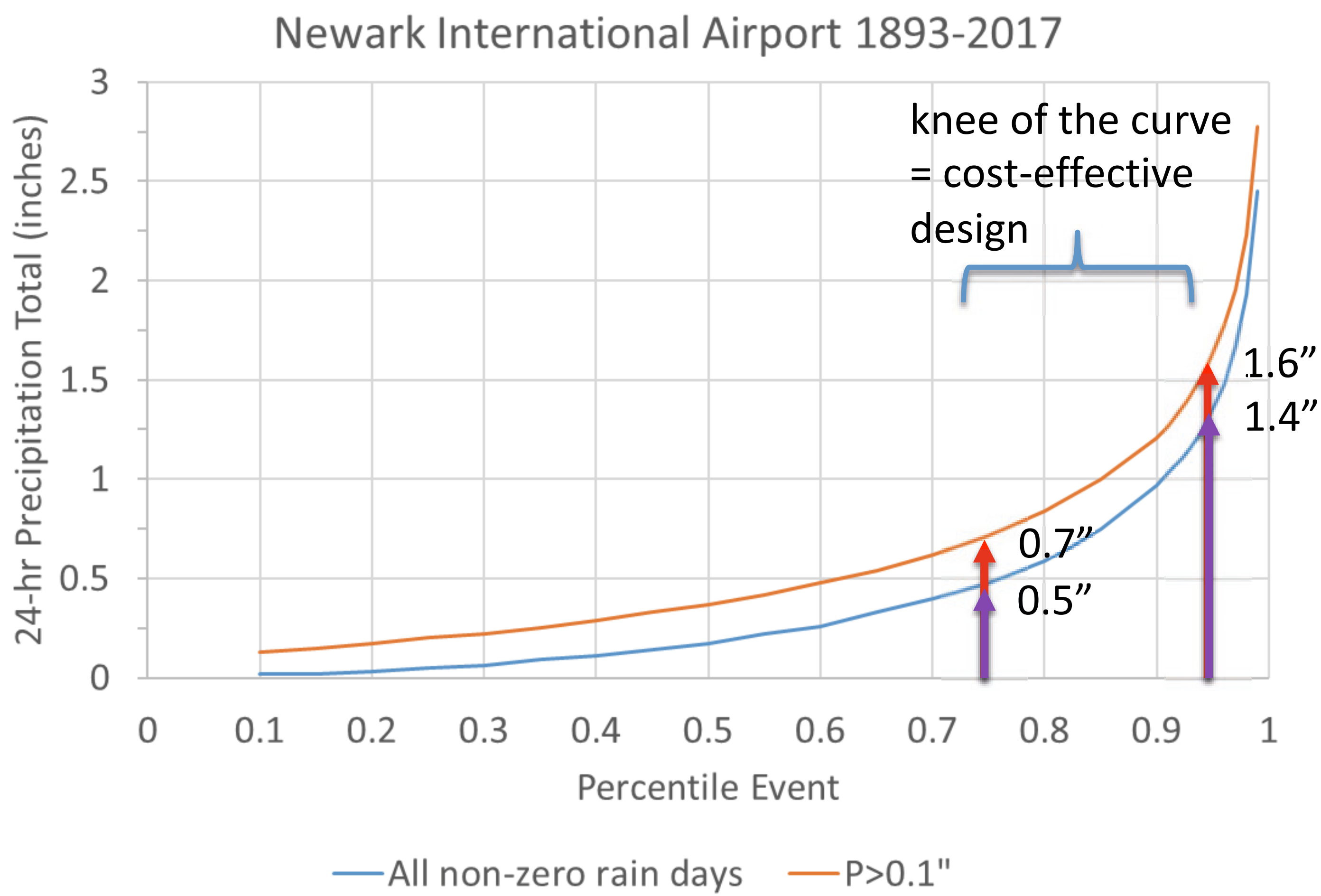
efassman@stevens.edu

Guo & Urbonas (1996): "Maximized Detention Volume"



NJ data from https://www.ncdc.noaa.gov/cdo-web/