THE OHIO STATE UNIVERSITY

Bioretention Cell Implementation and Performance in Northeast Ohio

Ryan Winston, PhD, P.E.

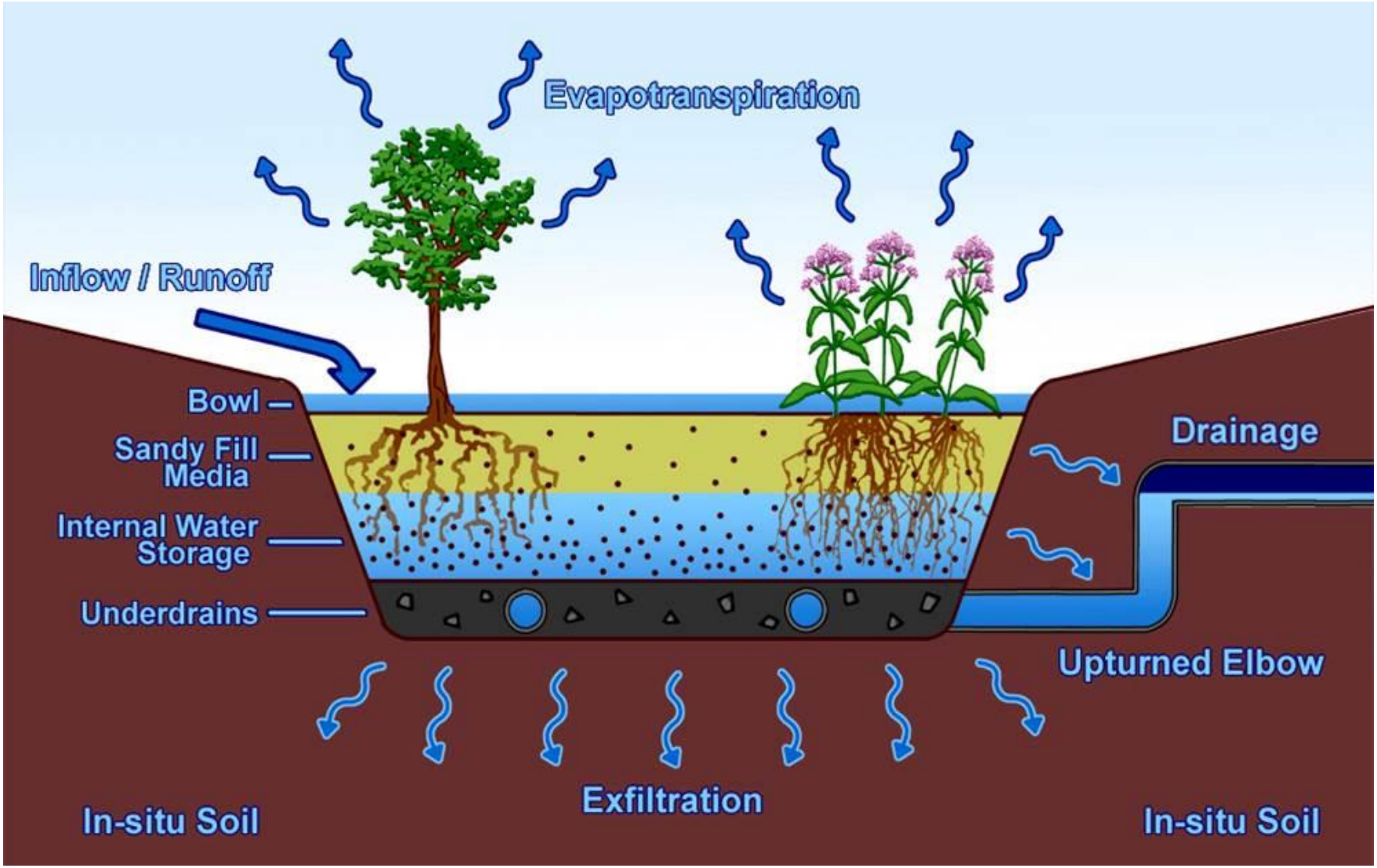
Research Scientist

Department of Food, Agricultural, and Biological Engineering

Toledo Green Infrastructure Workshop

4/14/2016

Bioretention Typical Cross-Section



Bioretention Provides…

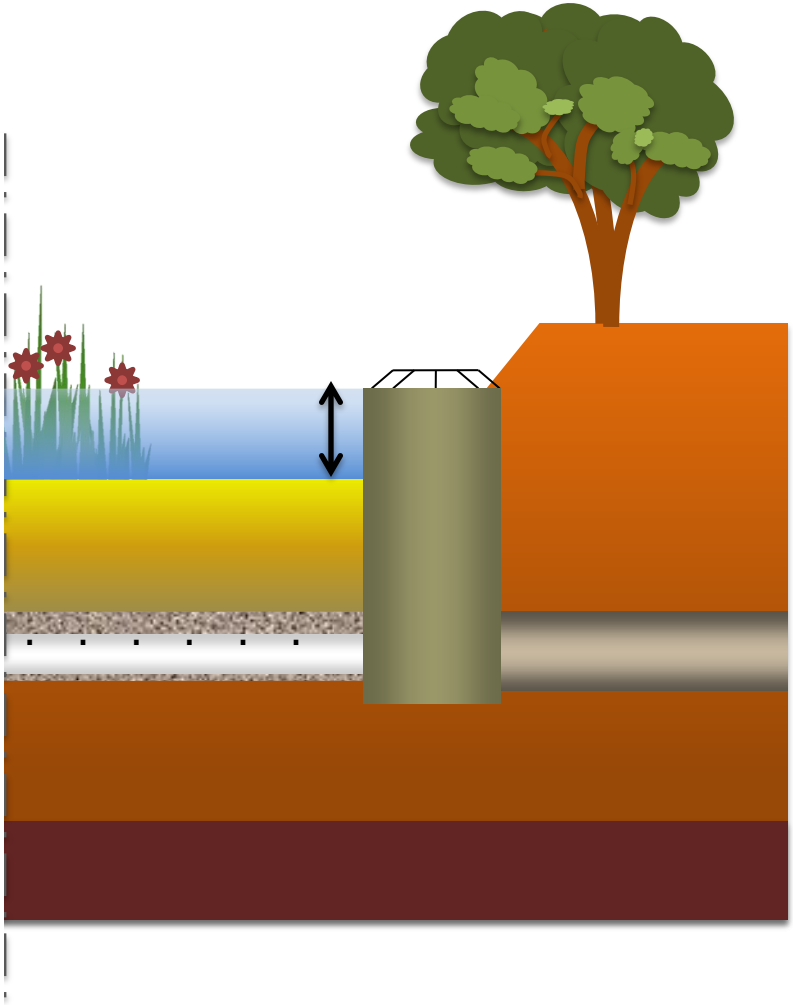
- Runoff volume reduction through exfiltration (groundwater recharge) and evapotranspiration
- Slow release of treated water through the underdrain
- Water quality improvement through filtration, sedimentation, adsorption, and plant and microbial processes
- Green space and ecological benefits

OH Bioretention Design Standard

Water Quality Volume = Runoff from first 0.75 inches of rain

- Storage provided in bowl above mulch surface
- Assumes no intra-event infiltration

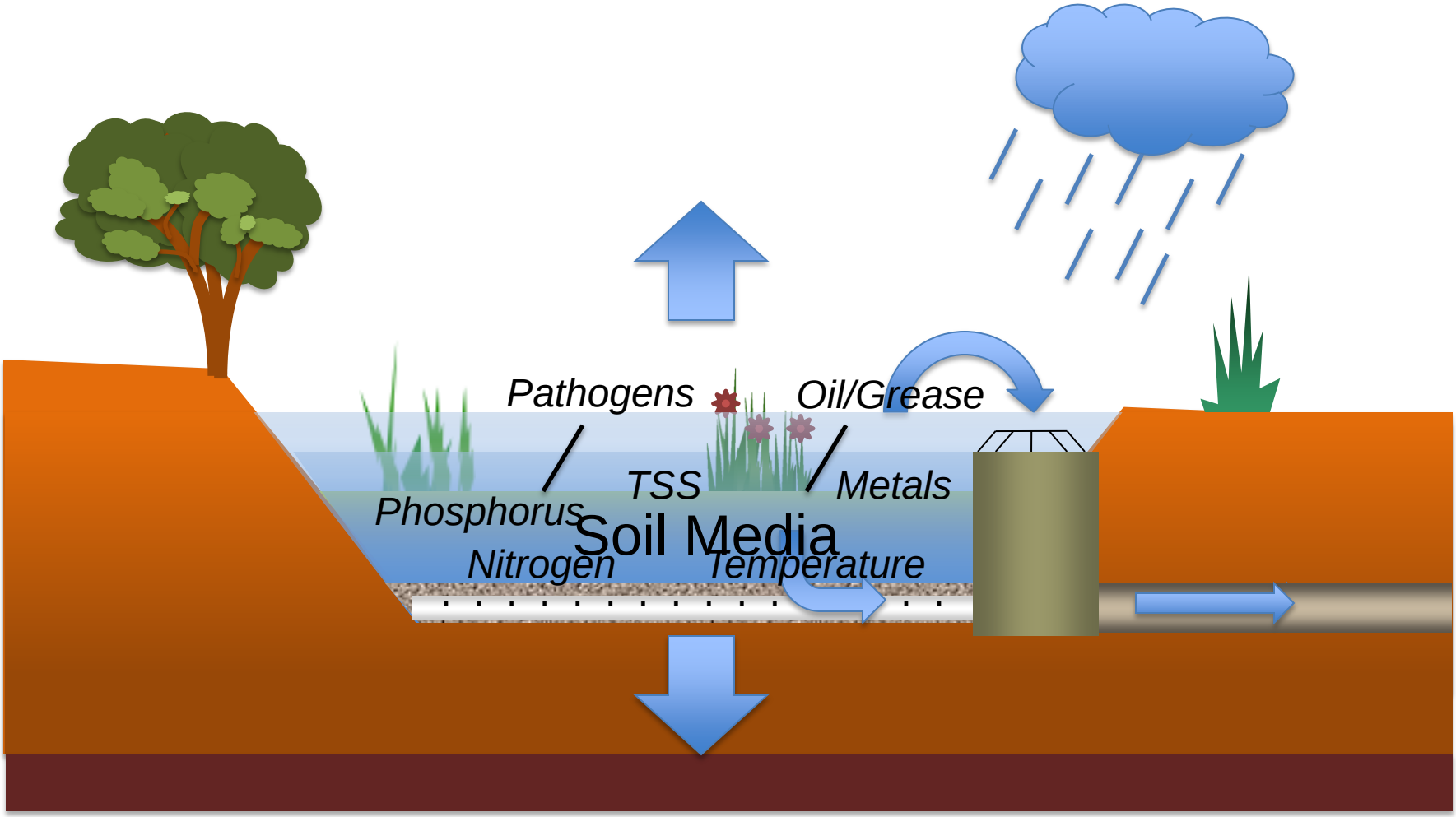
1 ft Maximum Ponding



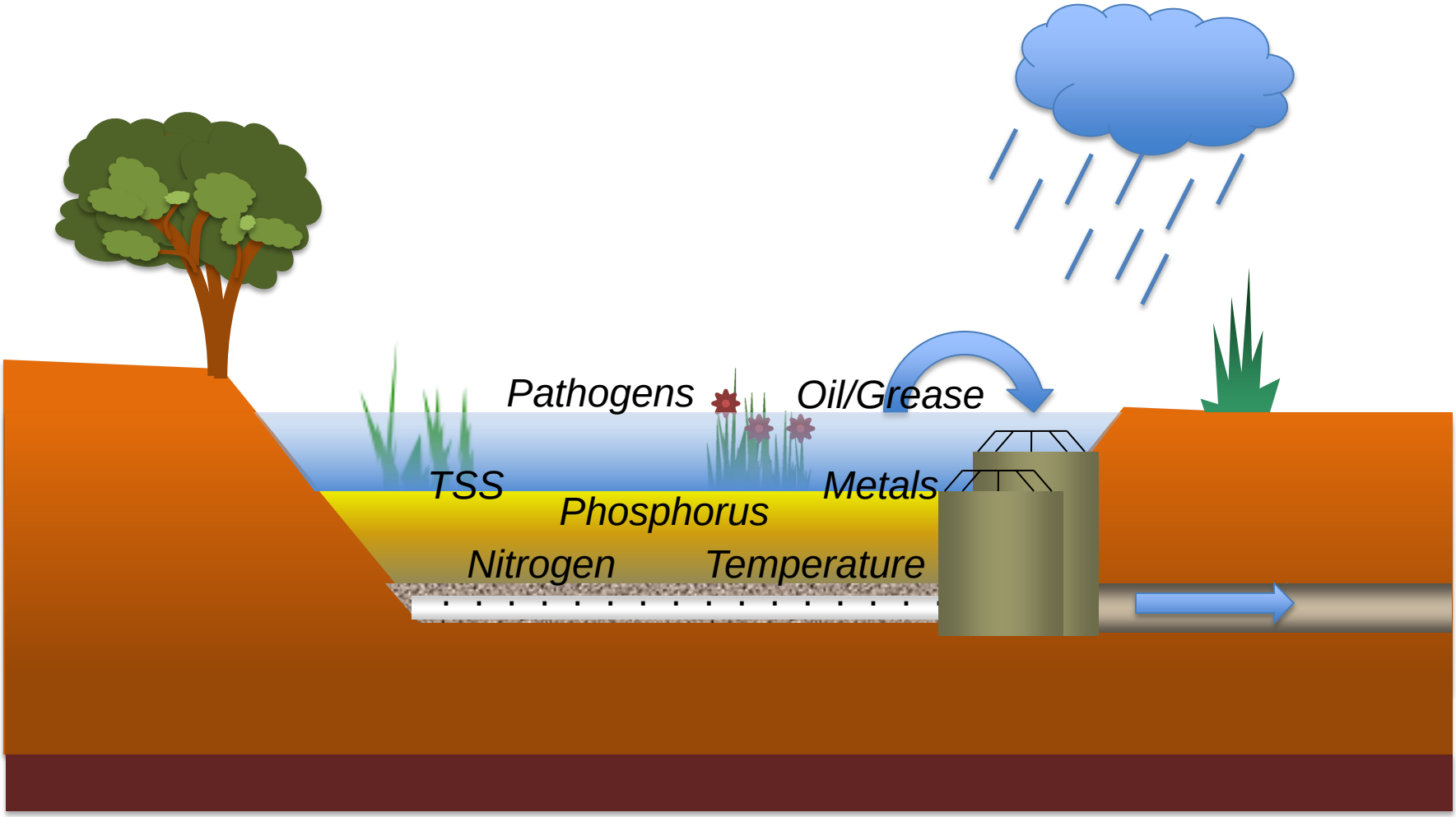
OH Bioretention Design Standard

Media Component	Standard Specification
Sand	>80%
Fines	8 - 12%
Organic Matter	3 - 5%
P Content	15-60 mg/kg
Permeability	Drain the bowl in 24 hours

How Bioretention *Should* Work



What *Could* Happen…

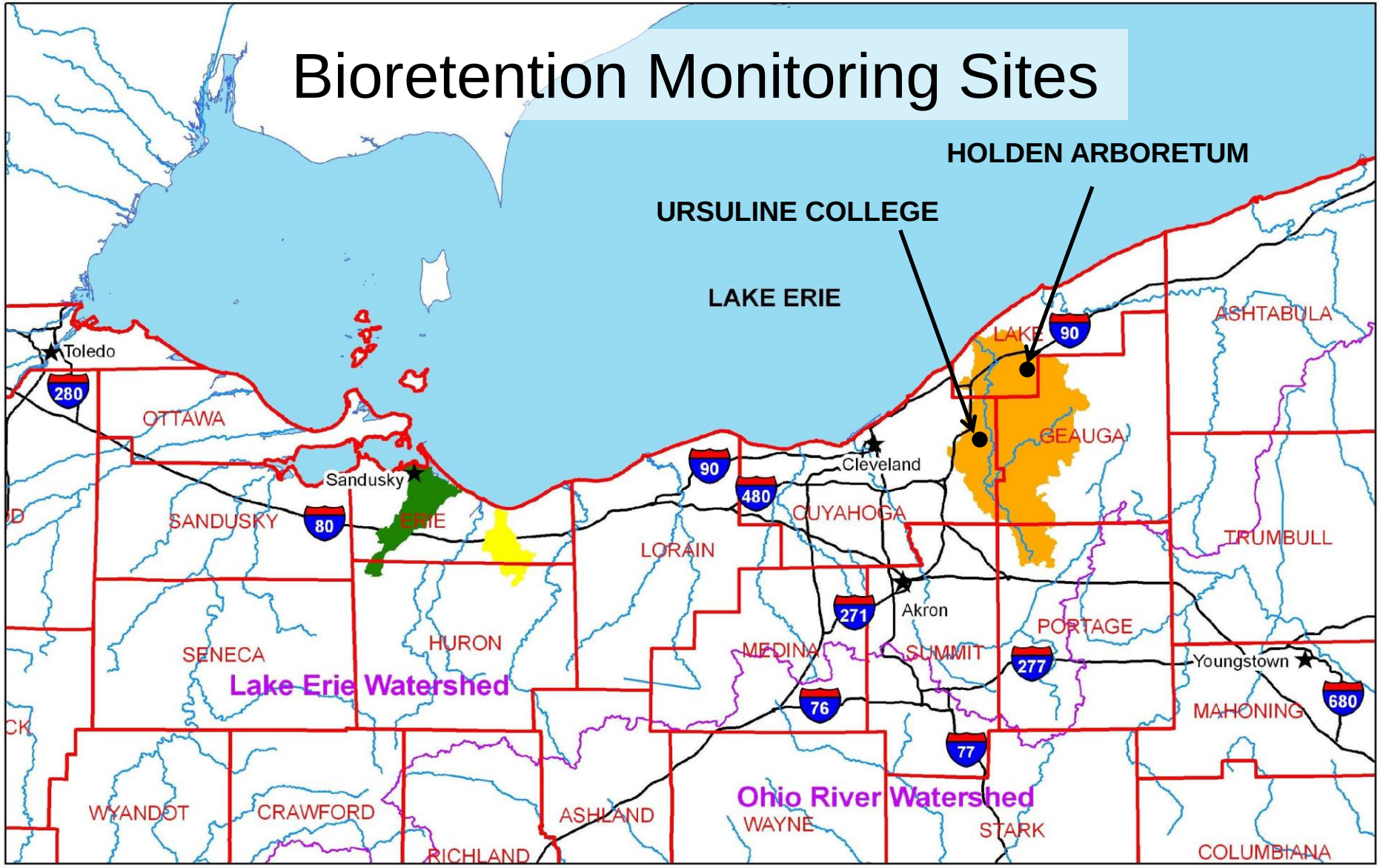


Ponding?

National Estuarine Research Reserve System (NERRS) Science Collaborative: Evaluating Stormwater Solutions in Ohio's Lake Erie Basin

- NOAA Funds administered by the University of New Hampshire
- Research addressing local coastal management problems
- Researchers and intended users work together

Bioretention Monitoring Sites



Watersheds:

- Old Woman Creek Watershed
- Pipe Creek Watershed
- Chagrin River Watershed

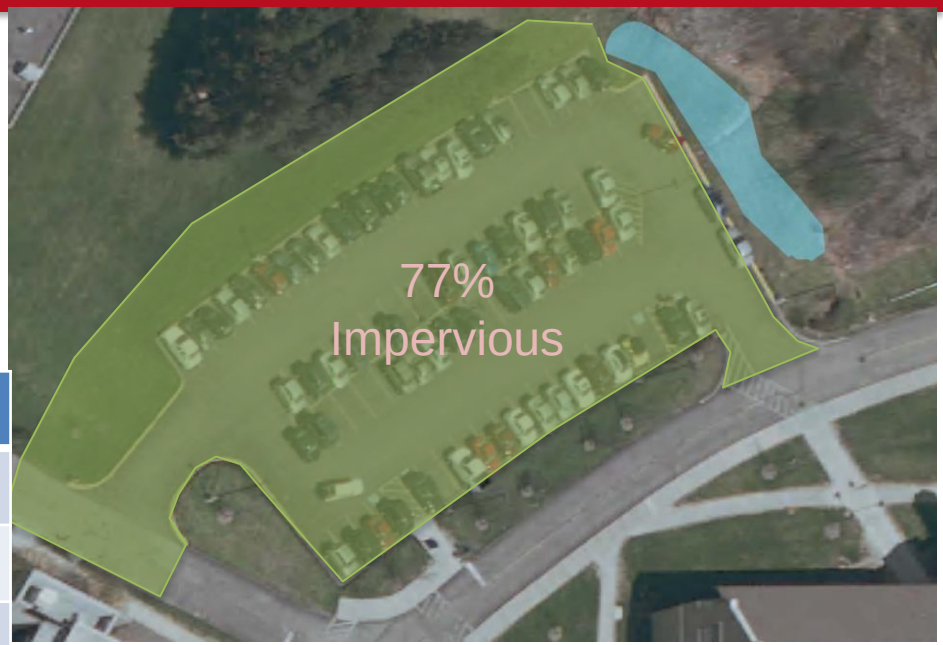
- County Boundary
- Lake Erie Tributary Area
- Streams
- Interstates

0 10 20 40 Miles

Chagrin River Watershed Partners, Inc.
P.O. Box 229
Willoughby, Ohio 44096-0229
440.975.3870

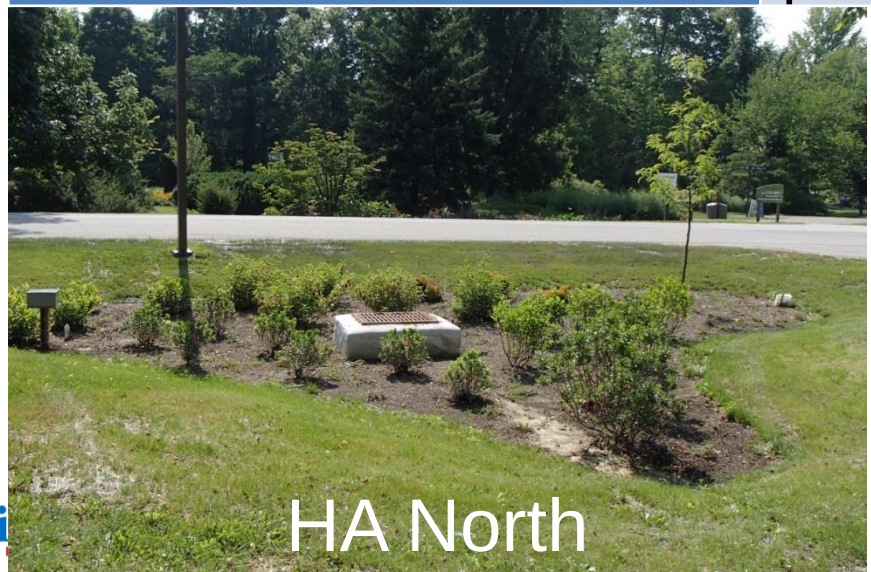
Ursuline College (UC) Cell

Characteristics	UC
Catchment area	0.89 acres
Imperviousness	77%
Bioretention surface area	1960 ft^2
Media characteristics	87% sand, 4% silt, 9% clay
Vegetation	Forbs & perennial grasses

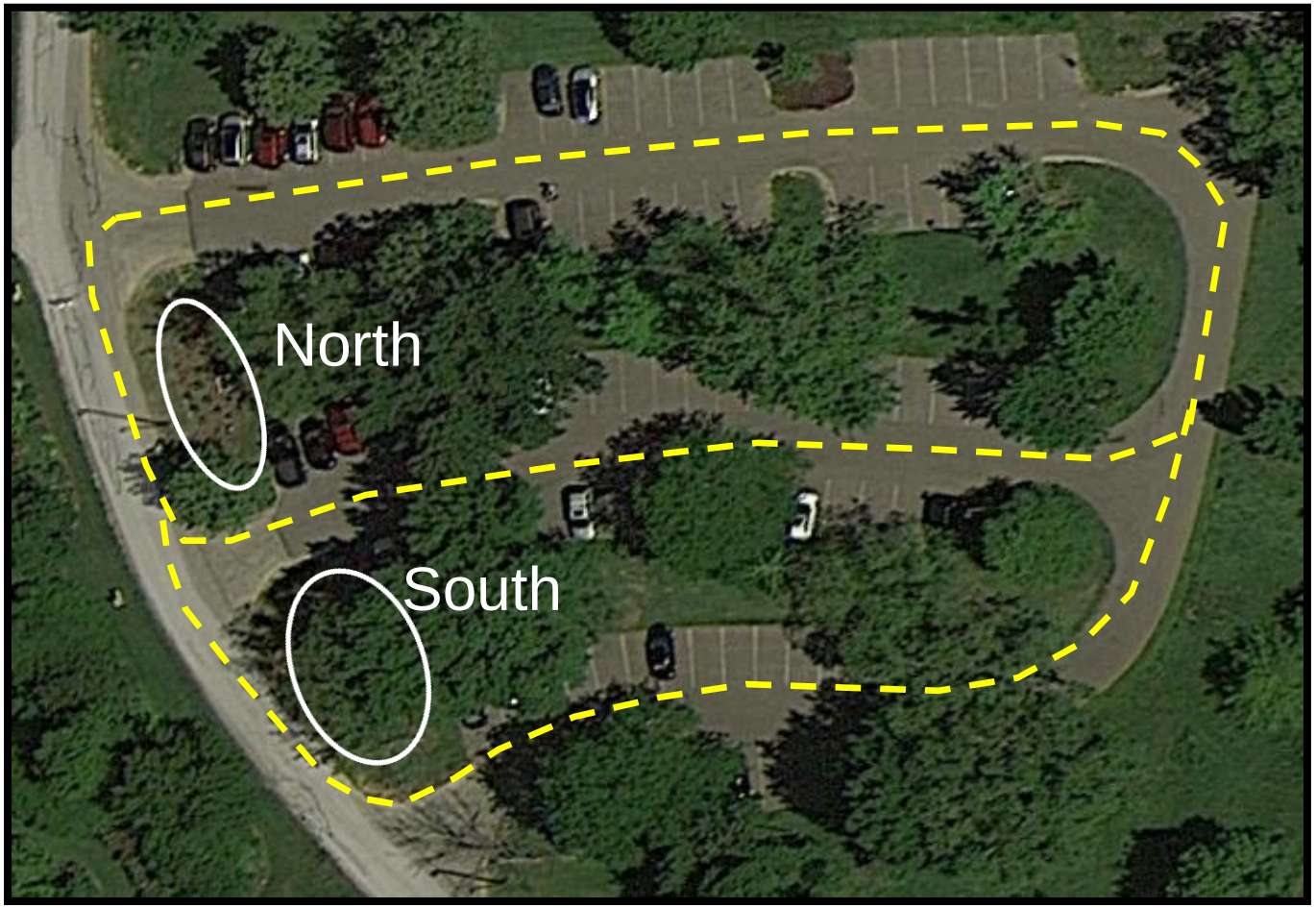


Holden Arboretum (HA) cells

Characteristics	HA South	HA North
Catchment area	0.48 acres	0.67 acres
Imperviousness	58%	
Bioretention surface area	610 ft^2	850 ft^2
Media characteristics	88% sand, 2% silt, 10% clay	
Vegetation	Forbs and perennial grasses	Shrubs/trees



HA Catchments



Design Characteristics

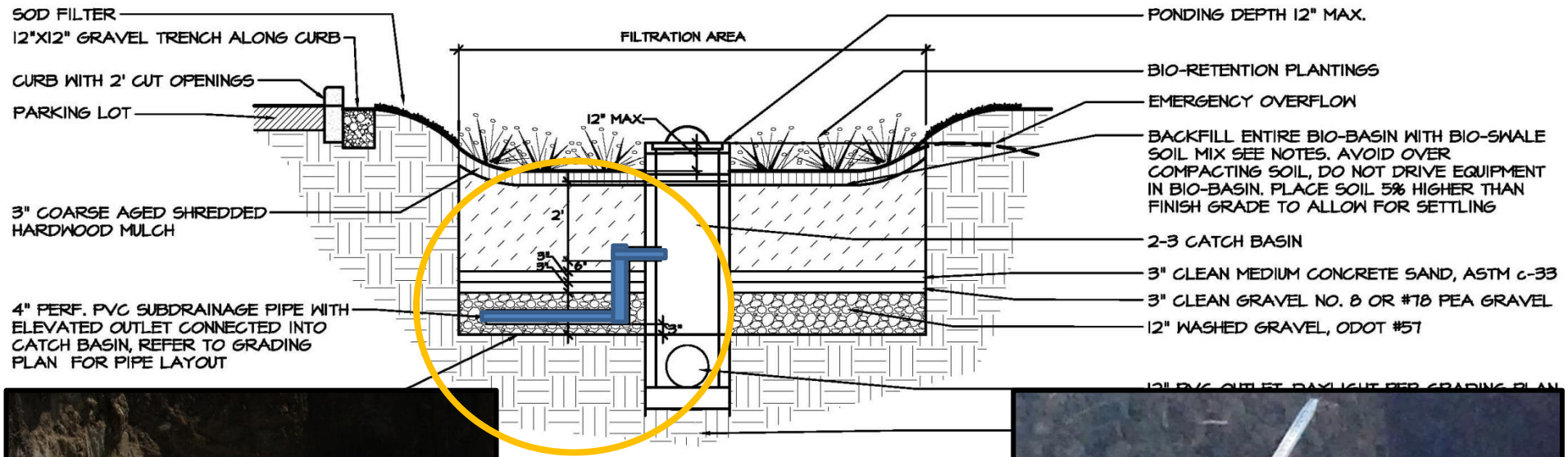
Ohio Design Event = 0.75 in

Cell	Media Depth (in)	Gravel Layer Depth (in)	Avg. Bowl Depth (in)	BRC SA: Watershed SA	Runoff Depth Captured without Overflow (in)
UC	24	12	12	6.2%	1.16
HA South	33	12	15	5%	1.78
HA North	36	12	16	5%	1.76

Typical = 12 in

Typical = 5%

Internal Water Storage (IWS) Zone



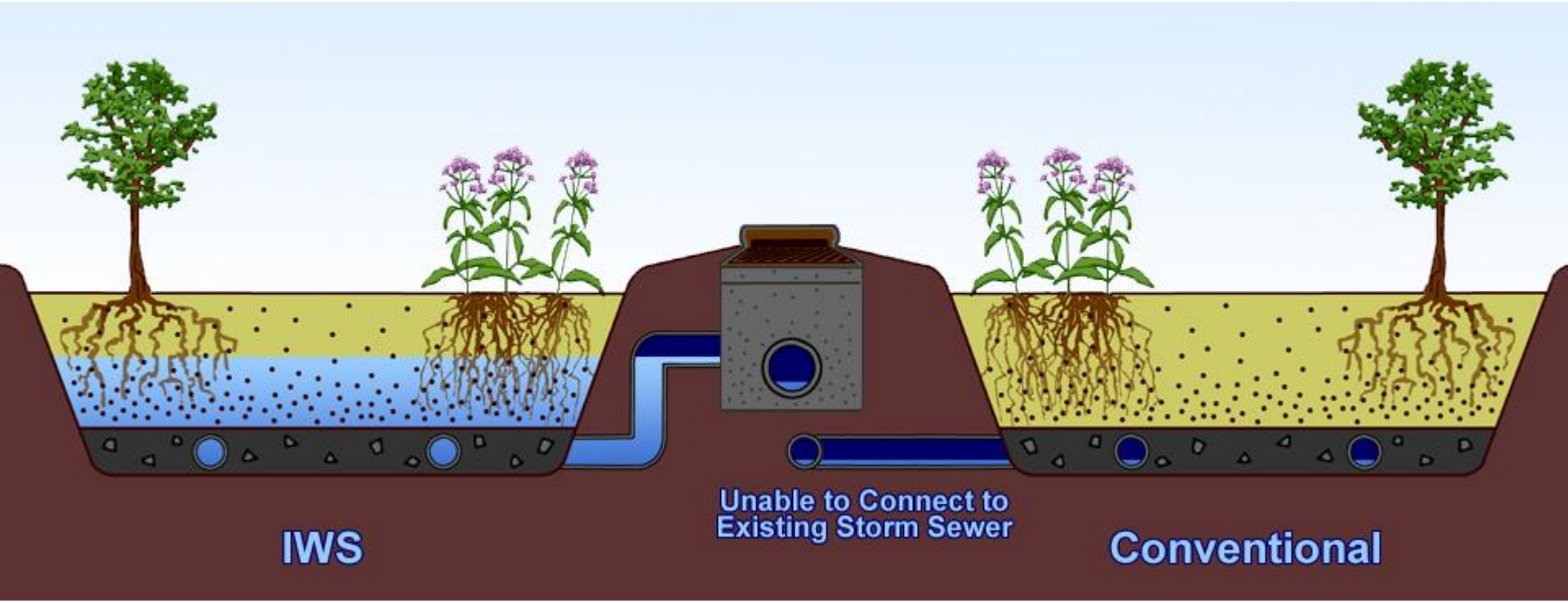
Ursuline: 24 in

Holden N: 18 in

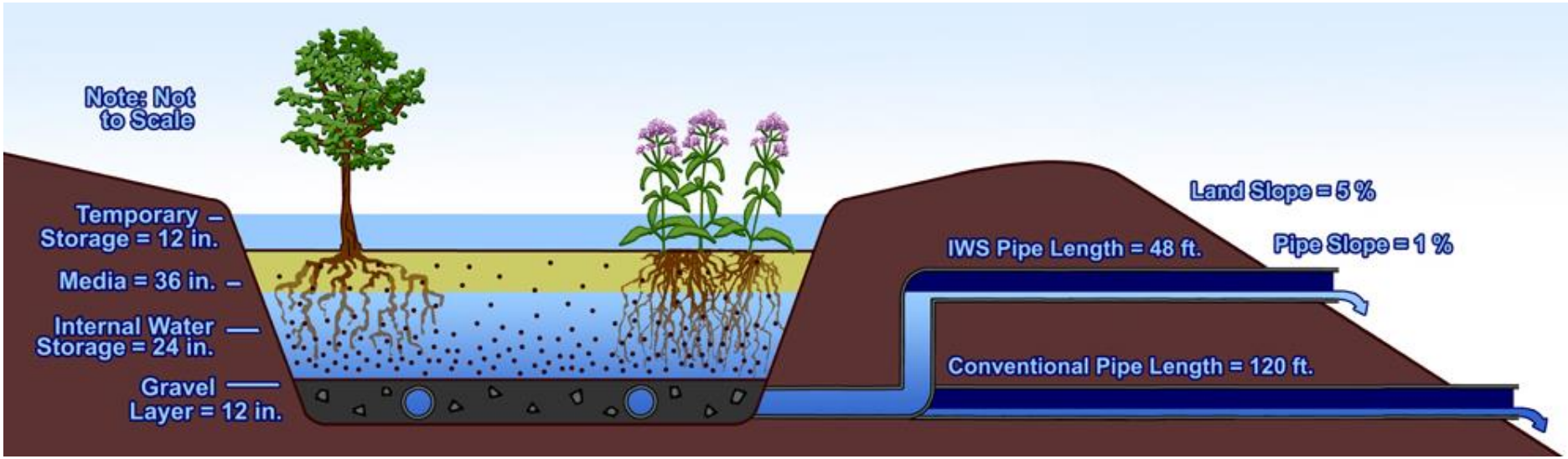
Holden S: 15 in

What Could be Improved Here?

Retrofit Ease / Cost Savings



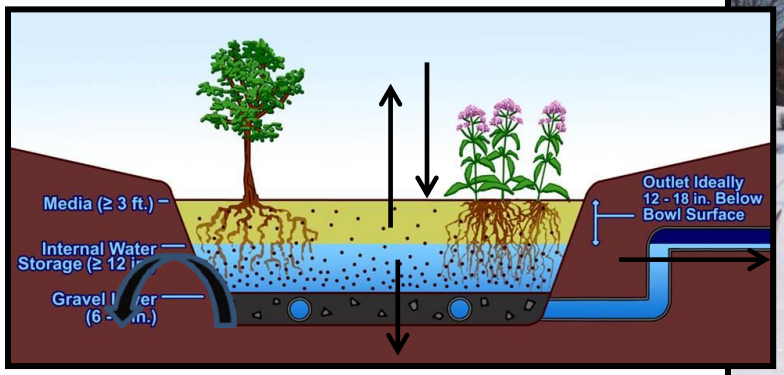
Retrofit Ease / Cost Savings



Hydrologic Monitoring

Quantify the water balance:

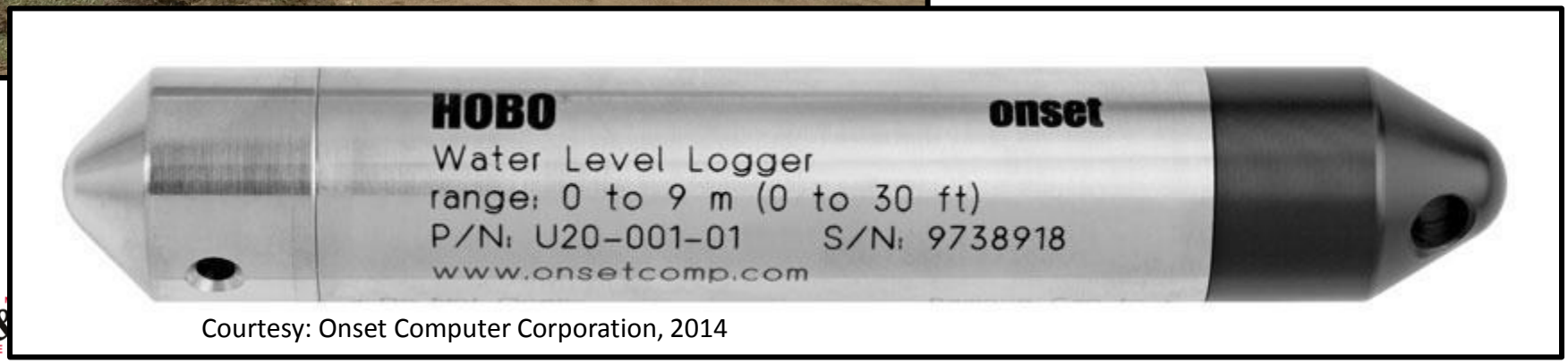
- Rainfall
- Evapotranspiration + Exfiltration
- Drainage
- Overflow



Soil Testing

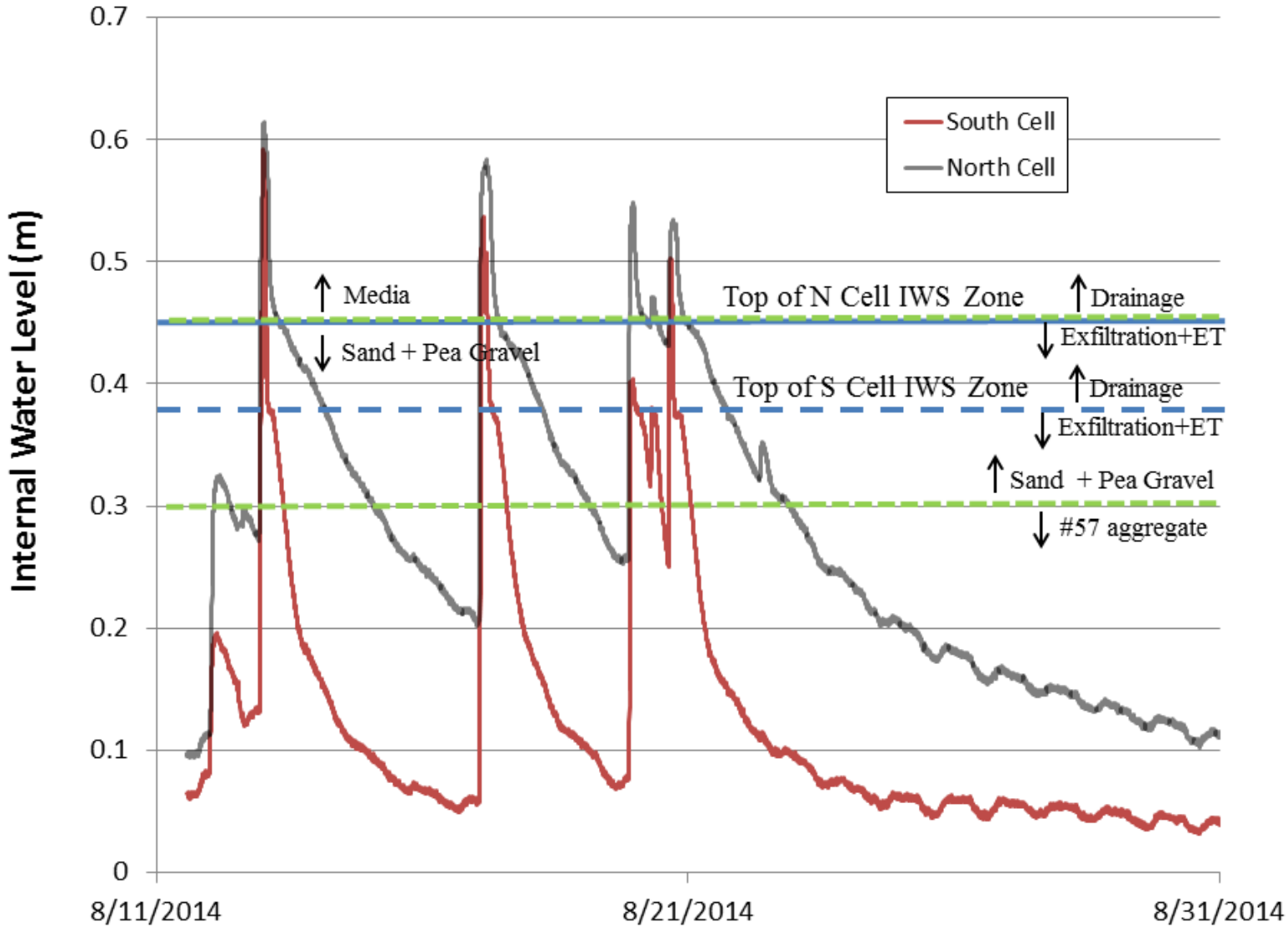
Site	Mapped Soil	Subgrade Soil Texture	Measured Kfs (in/hr)
Holden Arboretum	Platea (North) Pierpont (South)	Silty Clay Loam	South – 0.02, 0.04 North – 0.02, 0.02
Ursuline College	Mahoning	Clay/Fill	0.02, 0.02, 0.03

Monitoring Post-Construction Drawdown

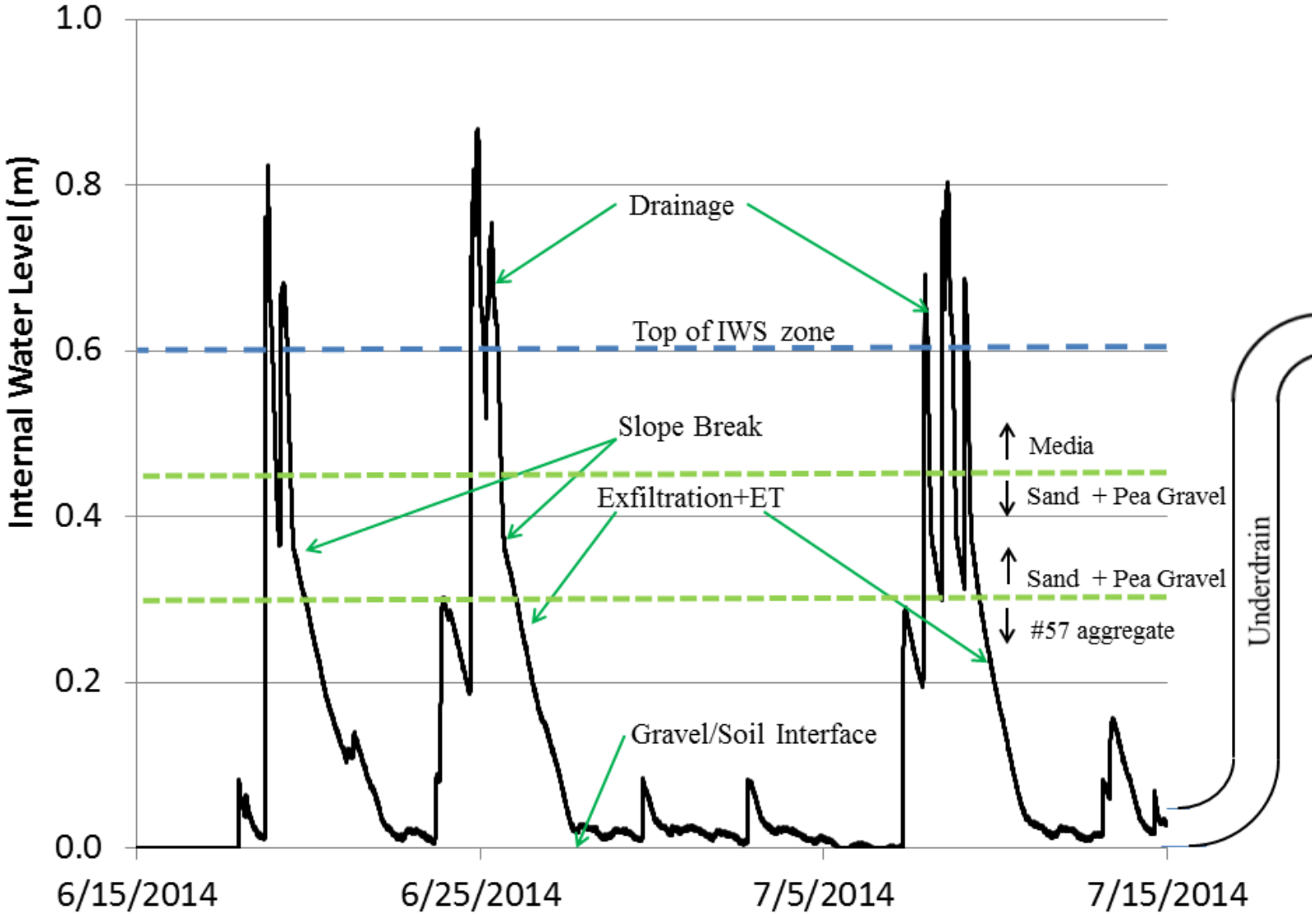


Courtesy: Onset Computer Corporation, 2014

HA Water Table

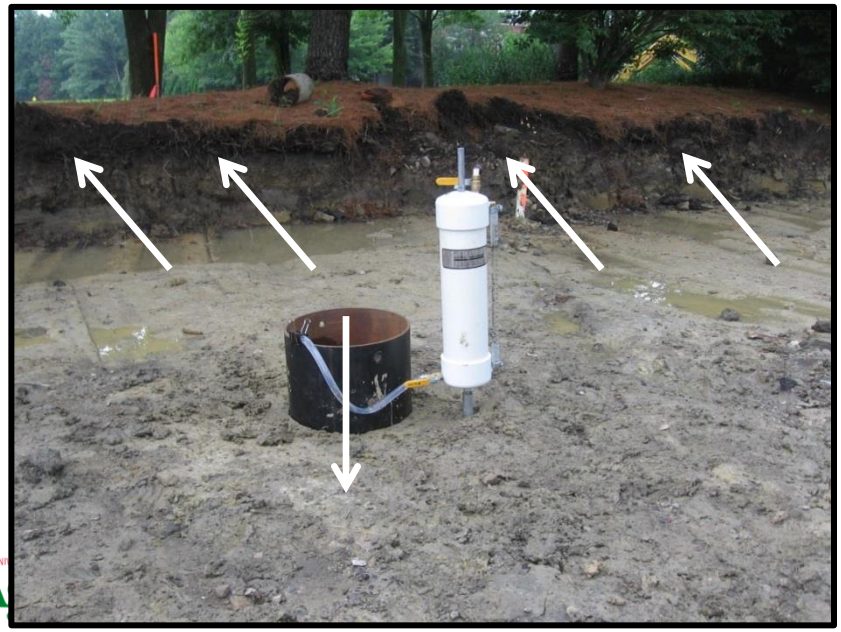


Ursuline Water Table



Post-Construction Drawdown

Site	Pre-Construction Kfs (in/hr)	**Average** Measured Drawdown Rate (in/hr)
Holden North	0.02, 0.02 →	0.067
Holden South	0.02, 0.04 →	0.078
Ursuline	0.02, 0.02, 0.03 →	0.17



Single ring tests:

- Provide estimates of vertical soil hydraulic conductivity

Drawdown Rates:

- Include lateral exfiltration, greater driving head for exfiltration, and minor ET

Heterogeneity of Soils

Source: Bathke and Cassel (1991), SSSAJ

	Landscape position			
Horizon	Interfluve	Shoulder	Linear	Footslope
A	0.30	0.17	0.04	0.11
AT†	0.0003	0.53	0.06	101.78
B1 (Bt1)	0.34	114.12	0.51	2.5
B1T	1.14	6.24	0.63	55.33
B2 (Bt2)	0.69	–	0.18	0.37
B2T	0.04	–	0.28	0.59
BC	0.04	1.35	0.92	–
C	–	0.63	–	–

† Horizon designations followed by T indicate samples taken from the transition area of the contiguous horizons.

Take Home Message

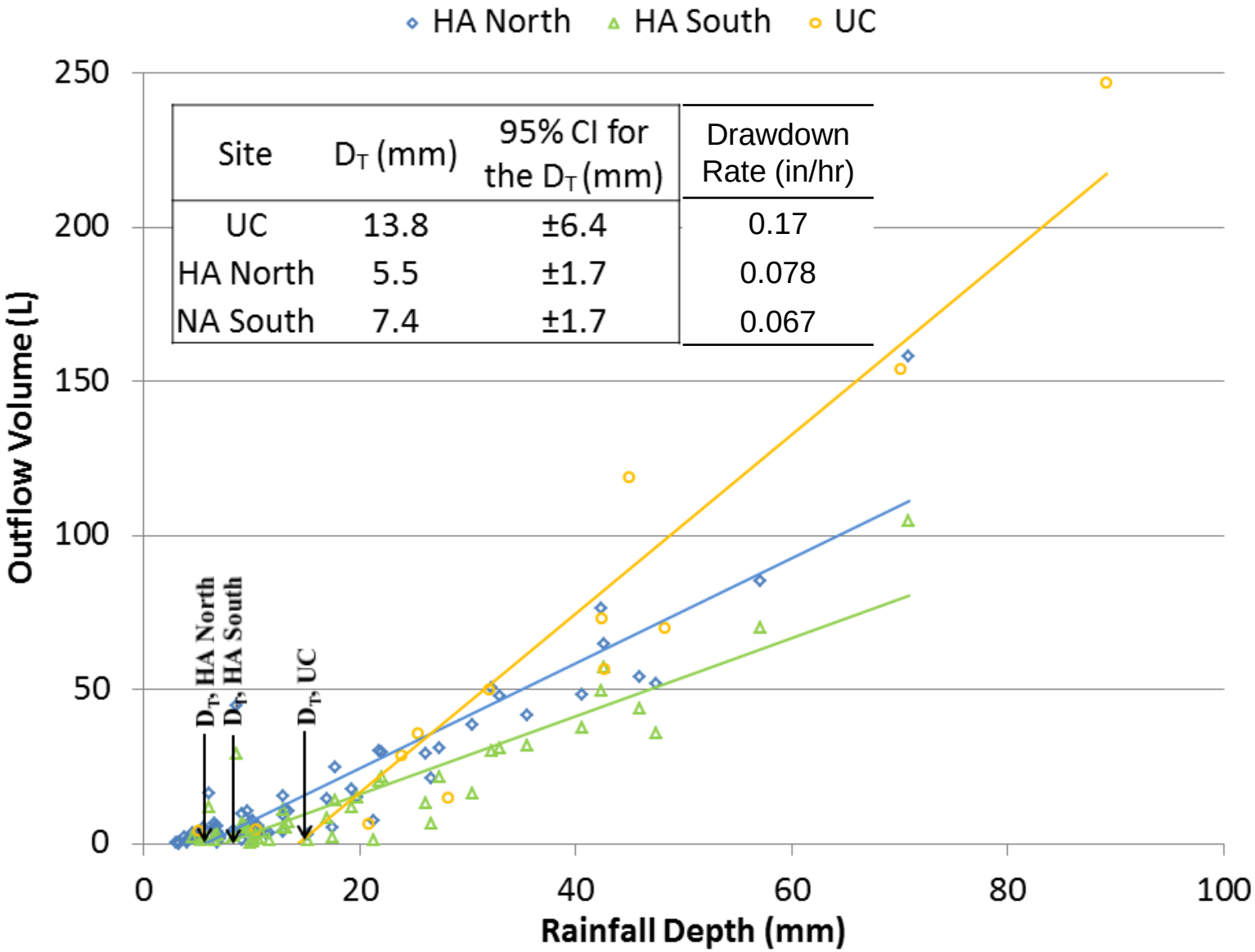
- In tight soils, IWS zone is key to bioretention performance
  - With IWS, exfiltration during 3-4 average dry period.
  - Without IWS, exfiltration during max 48 hrs
- Lateral exfiltration appears to be a dominant mechanism
  - Non-linear drawdown

Water Balance Summary

Cell	Drawdown Rate (in/hr)	Drainage (%)	Overflow (%)	Exfiltration + ET (%)
UC	0.17	33	8	59
HA South	0.078	51	7	42
HA North	0.067	57	7	36
Rocky Mount Sand*	60	0	0	100
Rocky Mount SCL*	2.1	18	7	75

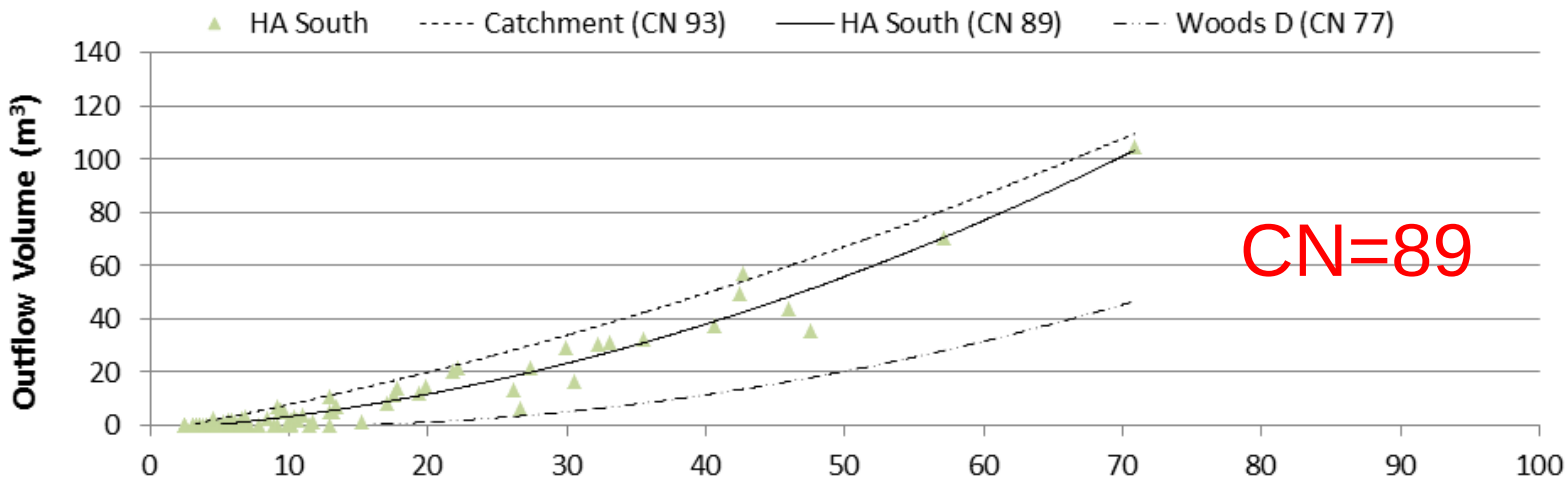
* Source: Brown 2011

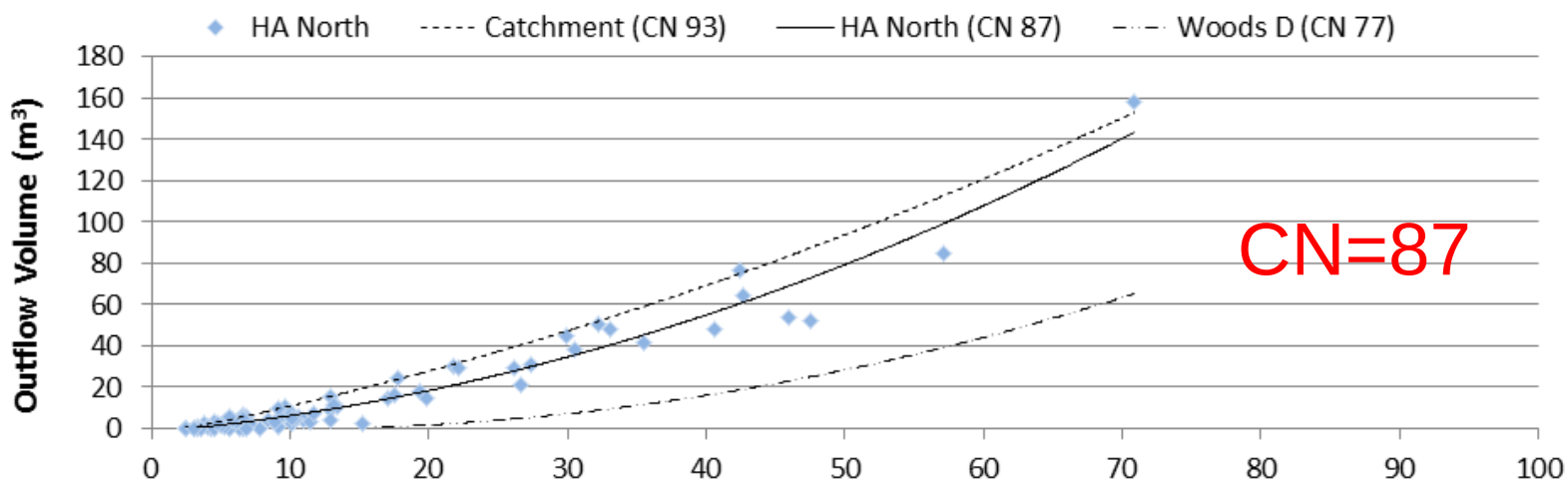
Discharge Threshold



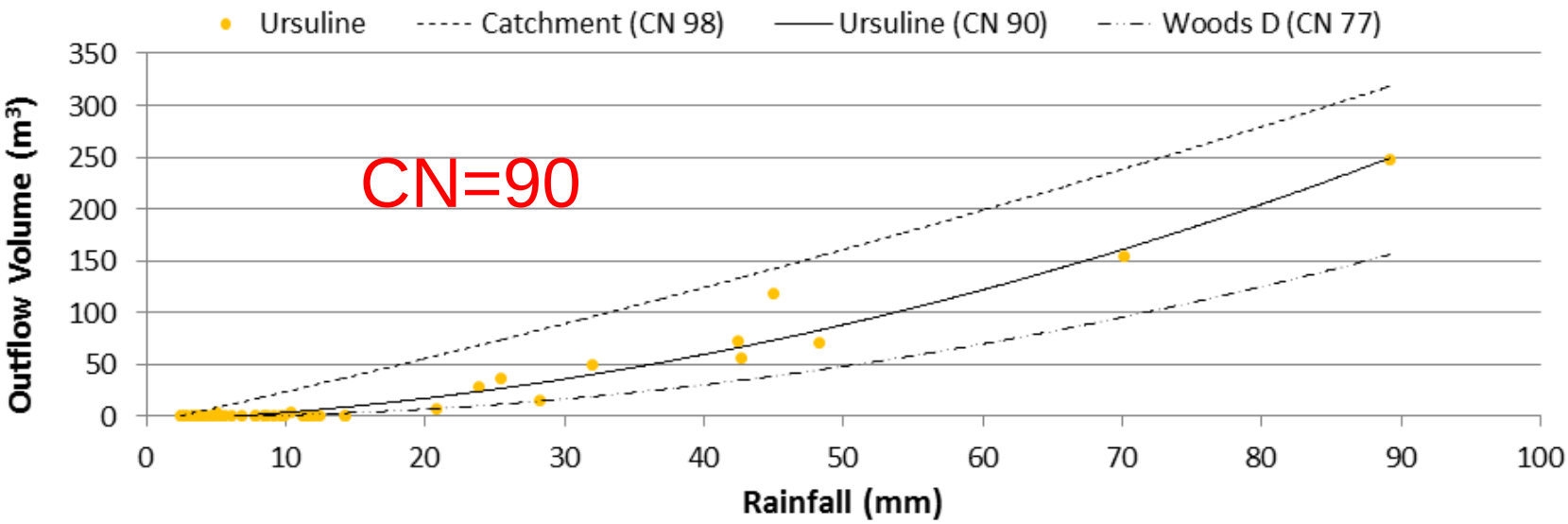
Site	D_T (mm)	95% CI for the D_T (mm)	Drawdown Rate (in/hr)
UC	13.8	±6.4	0.17
HA North	5.5	±1.7	0.078
NA South	7.4	±1.7	0.067

Curve Numbers over HSG D Soils



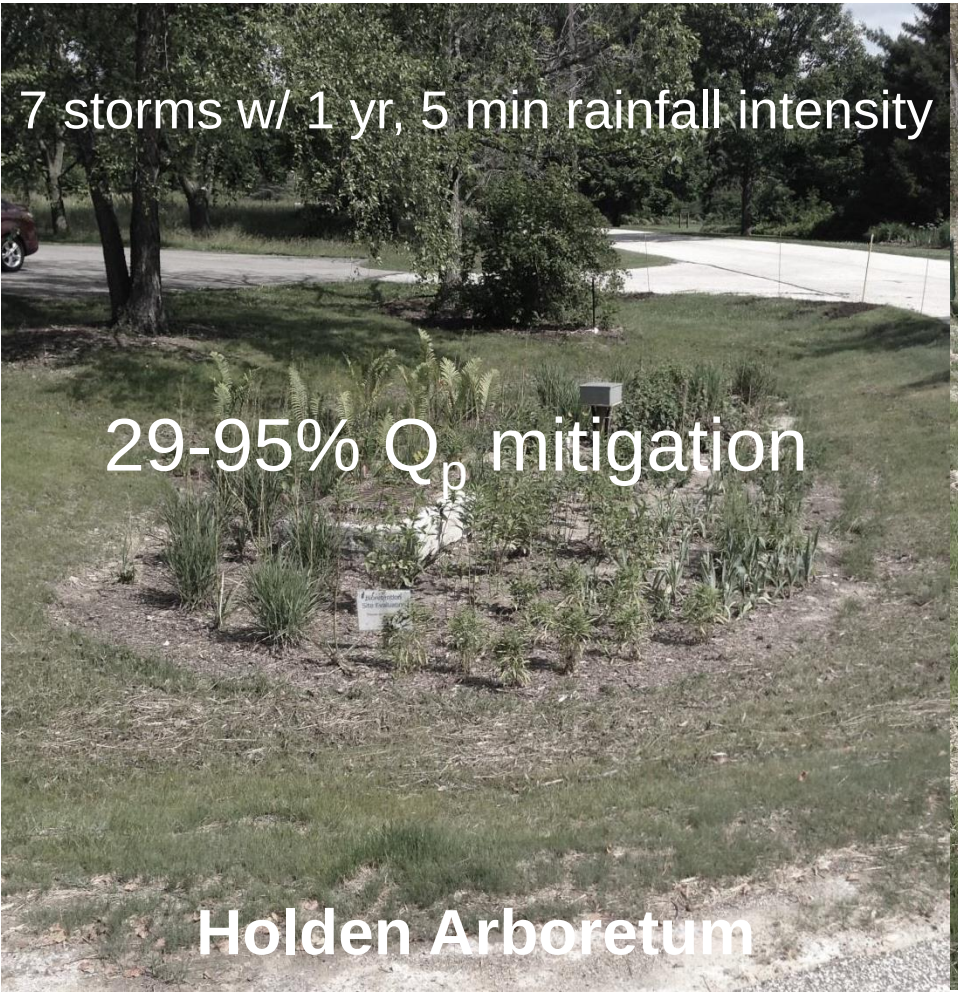


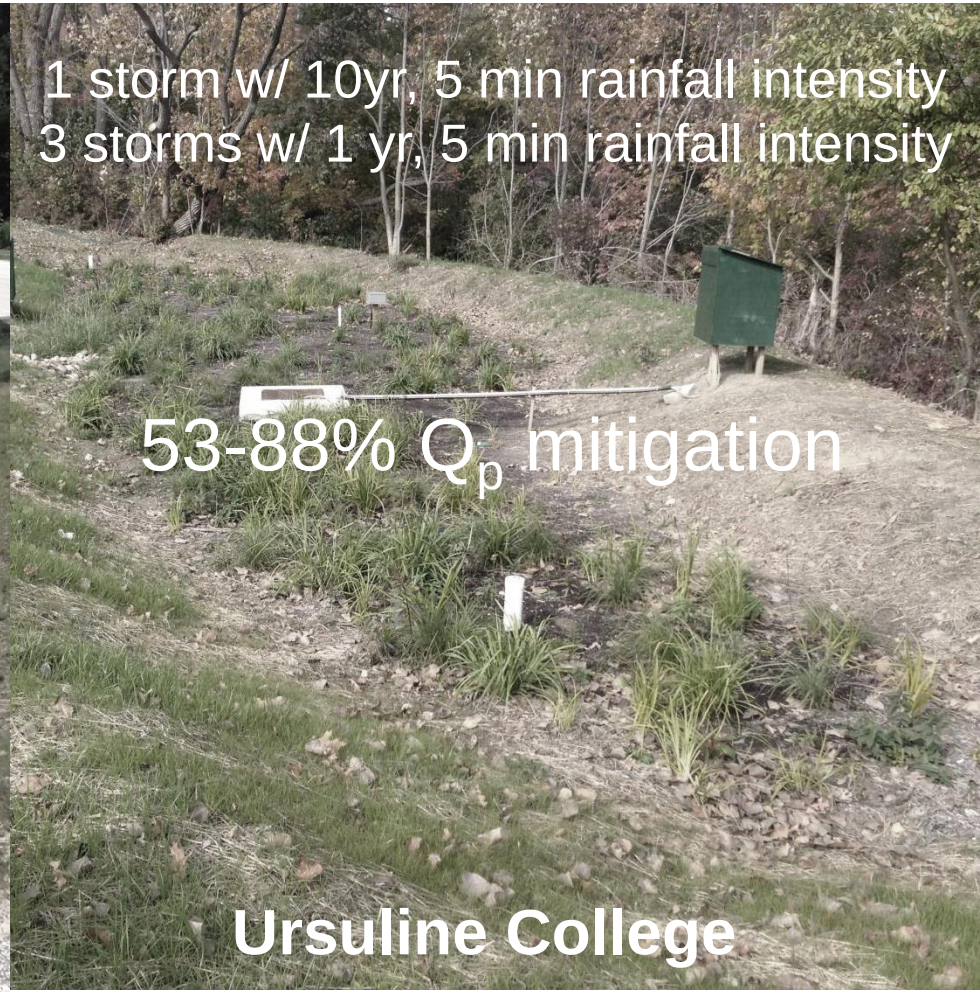
Curve Numbers over HSG D Soils



Curve Number Derived from Field Data		
Site	Watershed CN	Watershed + BRC
Holden North	93.1 → (6)	87
Holden South	93.1 → (4)	89
Ursuline	98.5 → (8)	90

Q_p Mitigation during Most Intense Rainfall Events





Bioretention Monitoring Summary

- Measured post-construction drawdown rates were 3-8 times greater than pre-construction soil K_{sat}
  - Due to lateral exfiltration, greater driving head, and minor amounts of ET
- 36-59% volume reduction
- >29% peak flow mitigation during design rainfall intensities
- Discharge thresholds between 0.22-0.54 inches

Function of drawdown rate & IWS zone

Lessons Learned

- Provide construction oversight
  - Pre-construction meeting
  - Engineering support on call
  - Approving alternatives
- During construction:
  - Avoid/break up compaction
  - Check grades
  - Look for clogging layers after rainfall

On-Site Meetings: Critical

- Pre-construction (kick-off)
- At critical junctures

- Provide construction sequencing
- Be available to answer questions

Construction: Checking Grades

Looks Pretty Good!

Post Mortem: Storage Volume

Compaction?

Construction Techniques: Avoiding Soil Compaction

- Pitt et al., 2009:
  - **In sandy soils**, compaction can decrease infiltration rate by one order of magnitude
  - **In clay soils**, compaction can decrease infiltration rate by factor of 50
- Must minimize subgrade compaction to promote exfiltration

"Ripping" the Subsoil
Tyner et al. (2009)

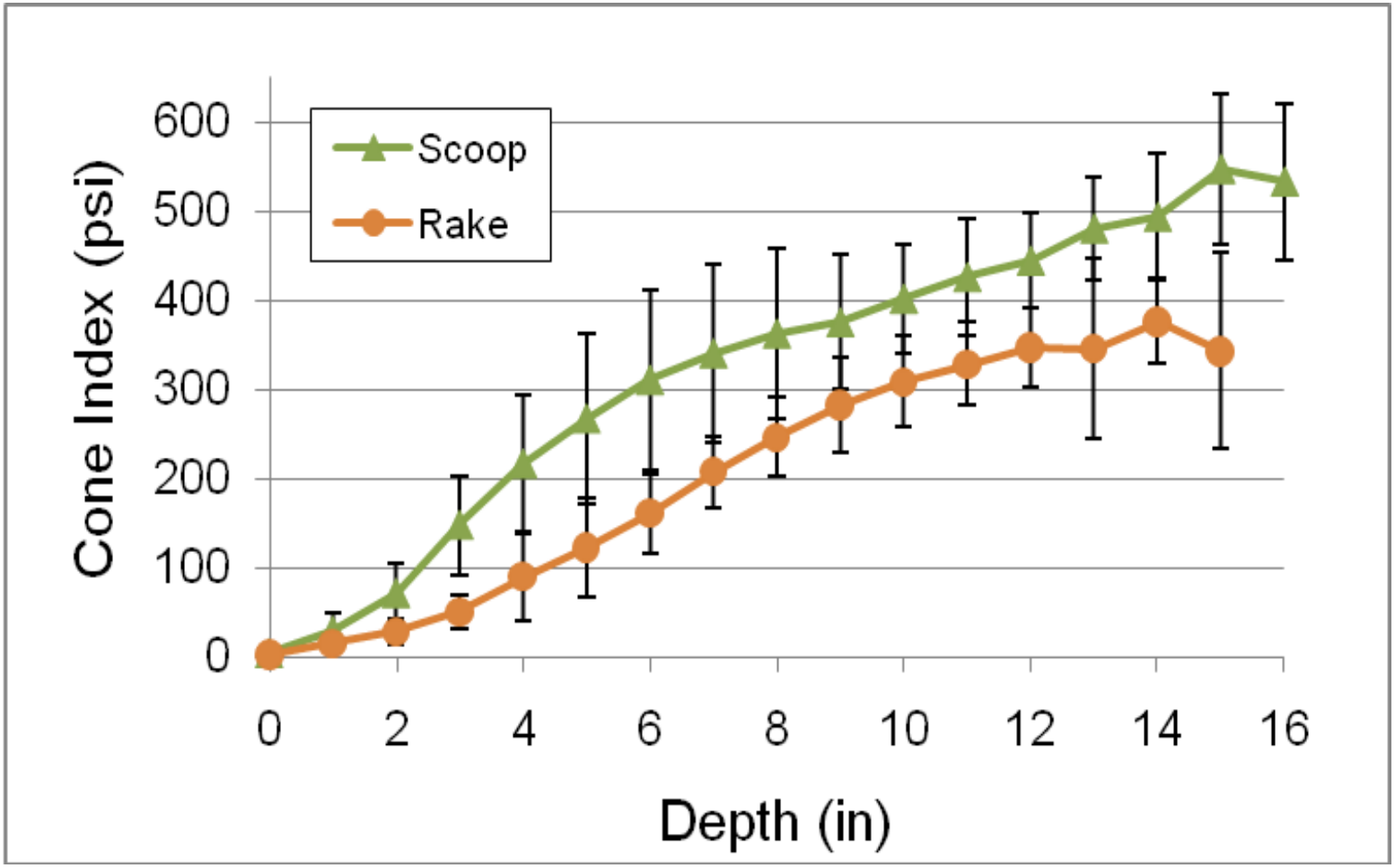
Minimizing Compaction

- Excavate in dry conditions as often as practicable
- "Back out" equipment
- Use tracked vehicles
- Excavate final 9-12" with teeth of bucket **(DO NOT SMEAR)**

Does Excavation Technique Really Matter?

- Brown & Hunt, 2010:
  - Tested infiltration and hydraulic conductivity of "scooped" vs. "raked" subgrades
  - Raking decreased bulk density, significantly improved exfiltration
- Rake when dry for best performance, especially in silt/clay soils

Compaction by Construction Method



Media Installation

- 10% higher than finished elevation for consolidation

- Rainfall will consolidate media

Importance of Vegetation on Side Slopes

Clogging Layer

‘Crush and Run’ Base

Sedimentation & Clogging Layer

Bowl Drawdown

- OH recommended bowl drawdown rate
  - 24 hours (0.5-2 in/hr)
- Actual drawdown rate
  - 48+ hours (0.1 – 0.5 in/hr)

Construction Sequencing

- Sequencing is essential
- Install bioretention as close to end of construction
- Provide bypass and stabilize watershed

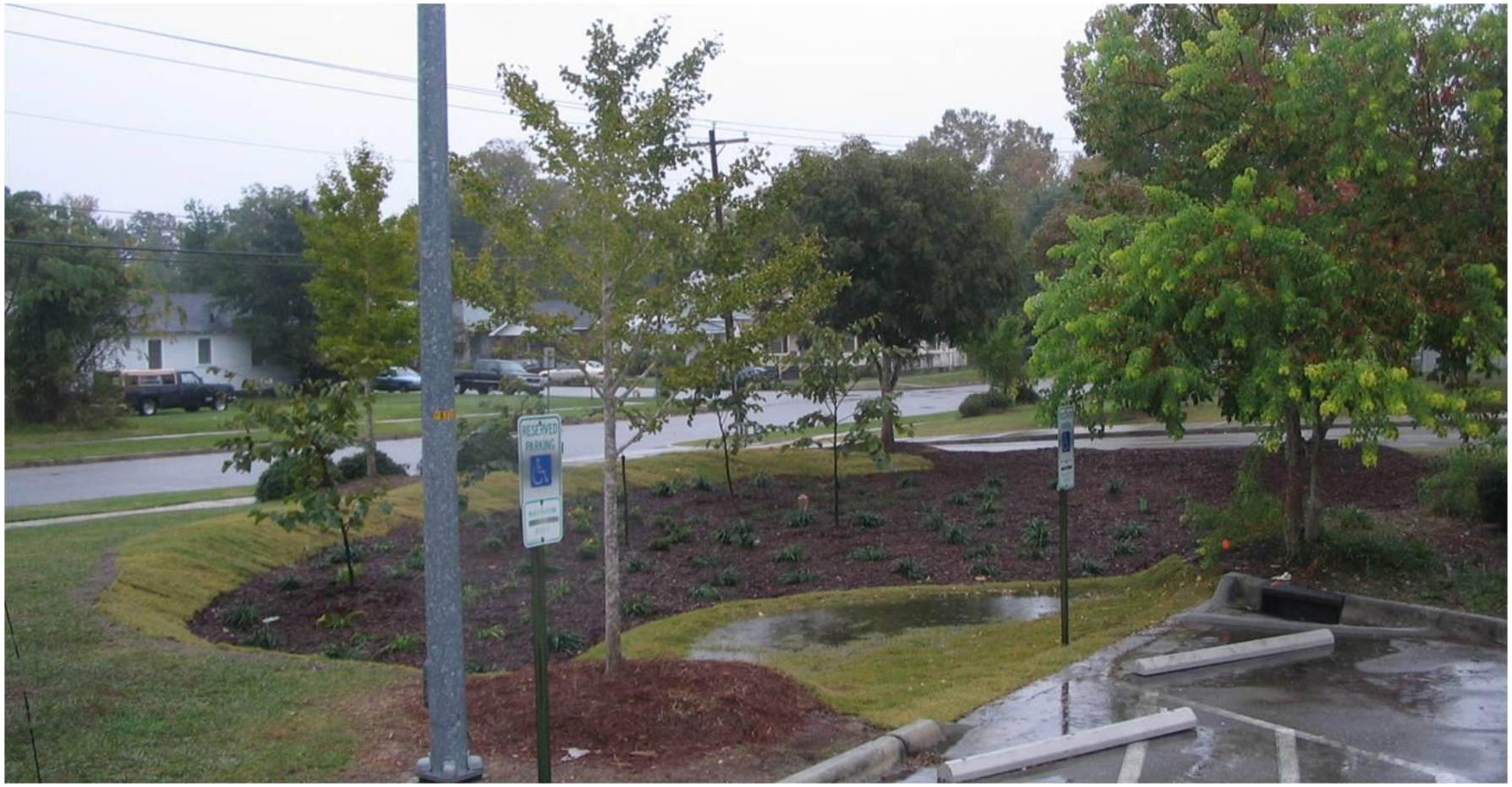
Pretreatment?

- Bioretention needs pre-treatment
  - Forebay
  - Filter strip
  - Swale
  - Deep sump
- Limit velocity of inflow to 1 ft/sec (1-yr, 24 hr storm)

Bioretention Forebays

- Rock-lined pool
- Reduce sediment before water enters BRC
- 20% of the WQv

Forebays Need Maintenance



PARKING

Pretreatment: Swales
Minimum 20 ft in length

Filter Strips

- Sod is best
- Watch for concentrated flow (parking bumpers)
- Gravel verge is a maintenance headache

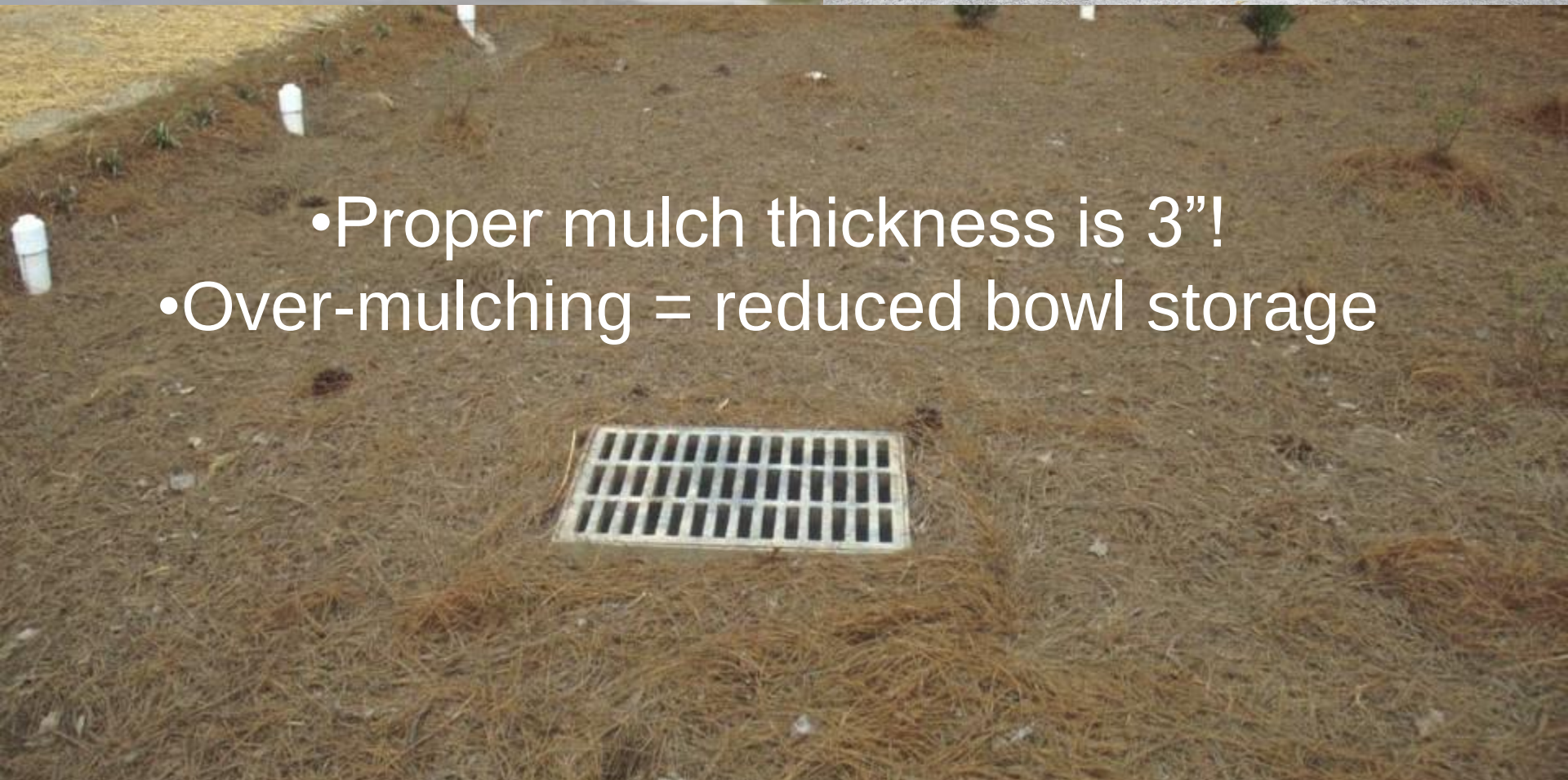
Double- or Triple-shredded Hardwood is Best

Benefits of Mulch?

- Provides Moisture for Plants
- Pollutant Removal (hydrocarbons, metals, etc)
- Food Source for Microbes
- Aesthetic Appeal (if maintained)

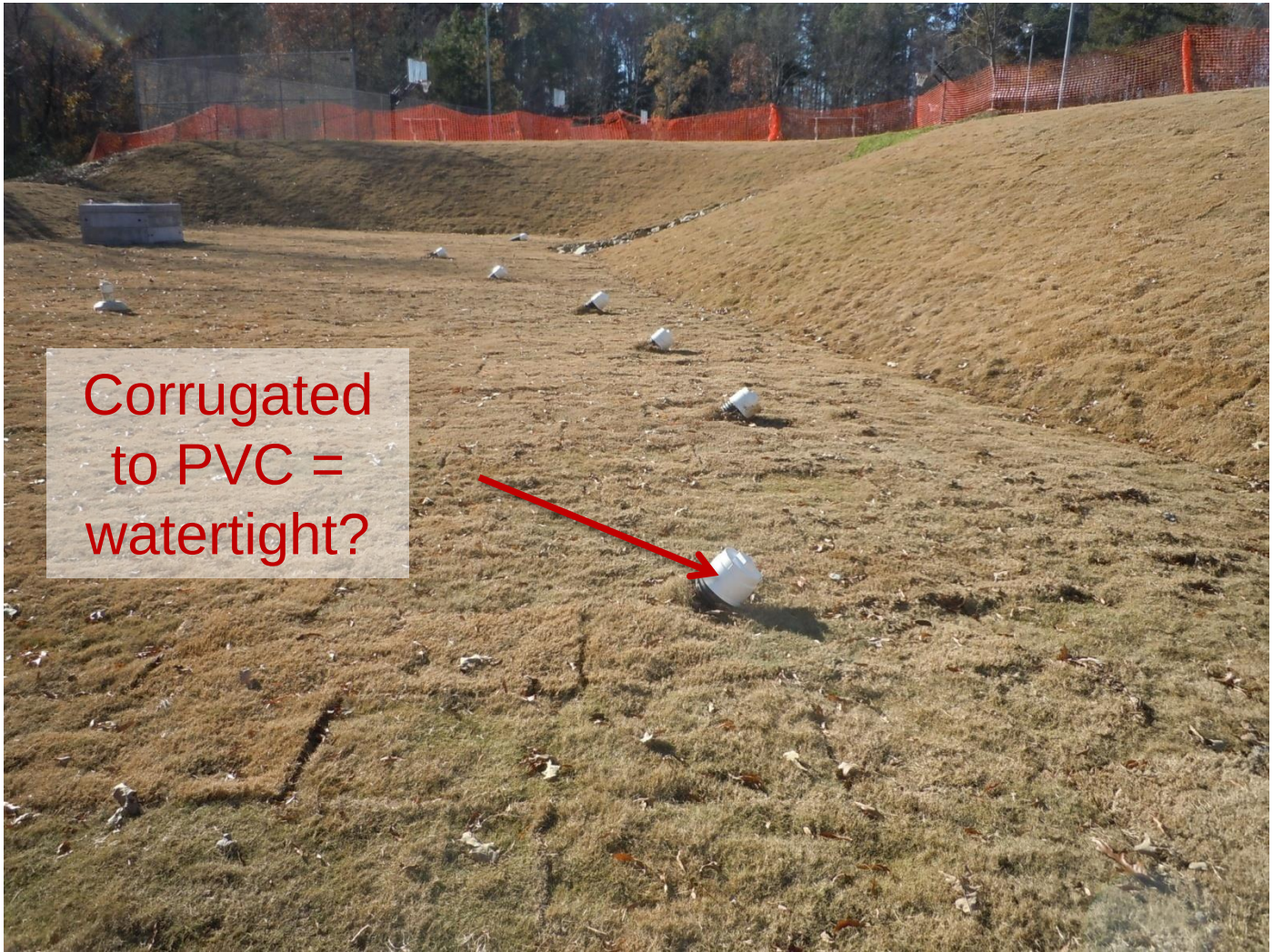
Mulch floats

Dense planting helps



- Proper mulch thickness is 3”!
- Over-mulching = reduced bowl storage

Bioretention Components: Underdrain Cleanouts



Underdrain cleanouts

Not-so-good

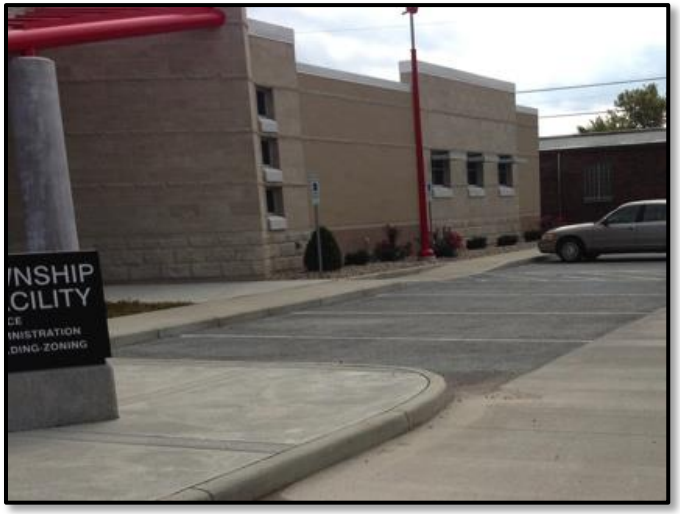
Better

Snow load compaction

Where does snow get dumped in parking lots?

QUESTIONS?

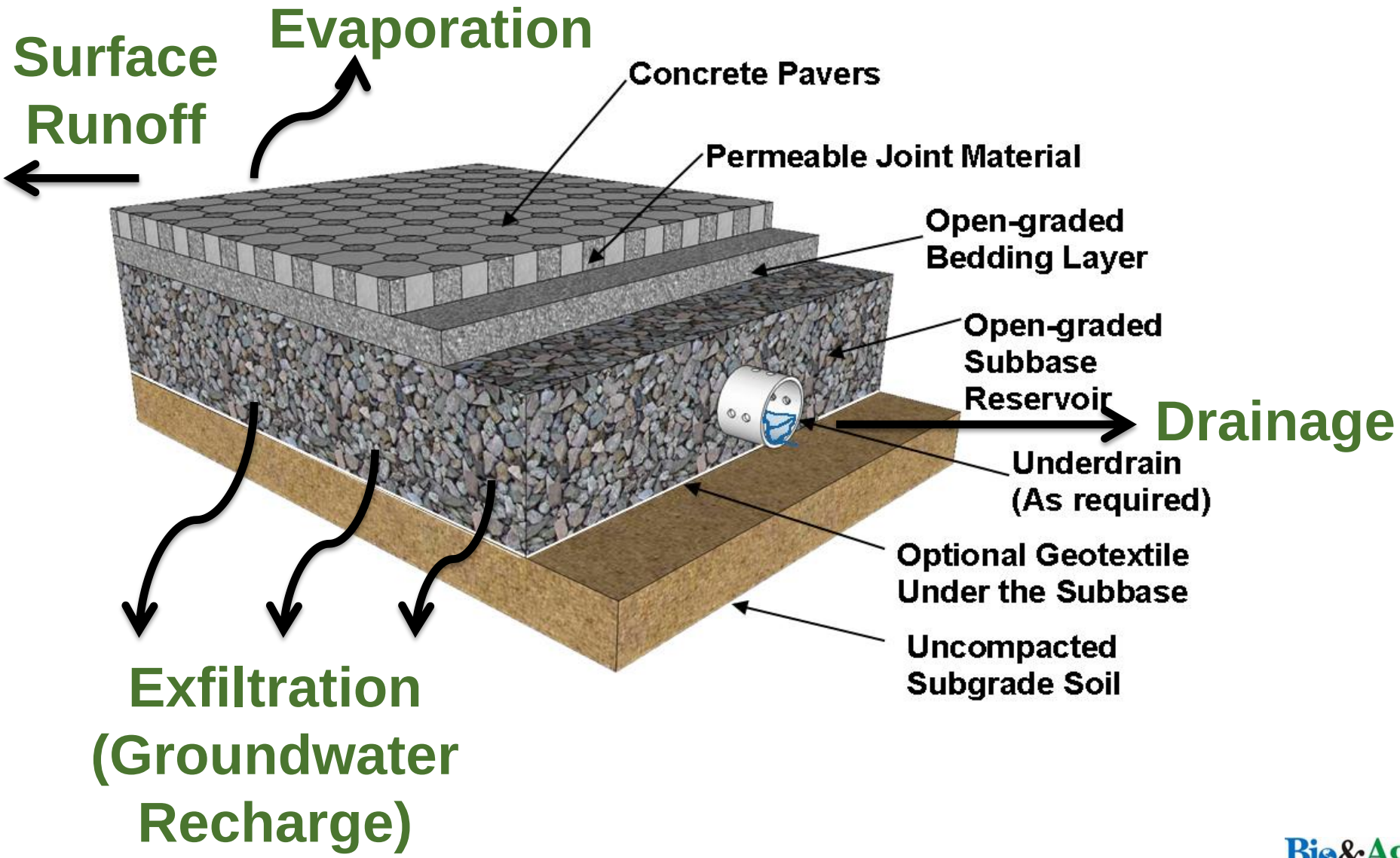
Permeable Pavements: Performance and Lessons Learned in Northeast Ohio

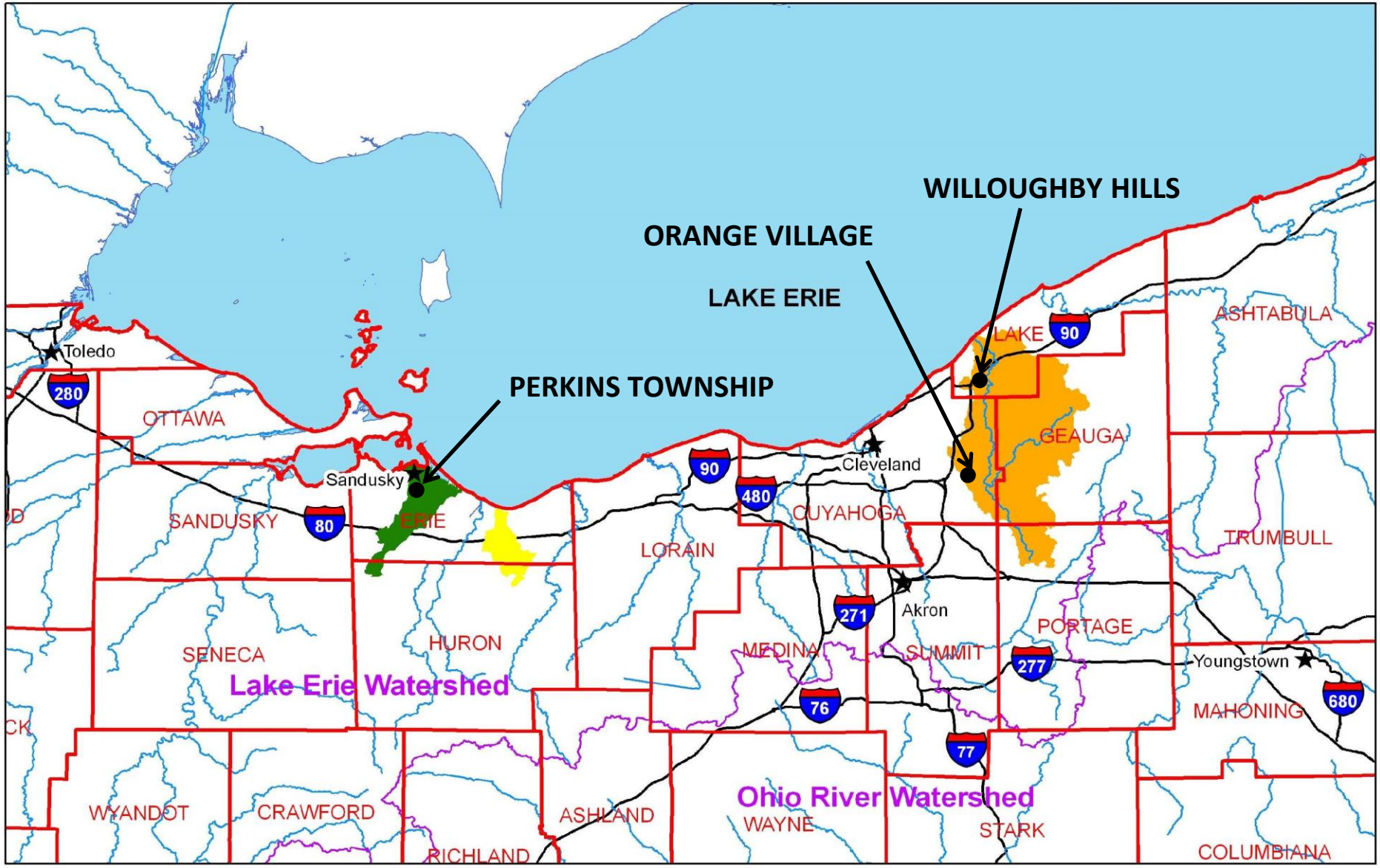


Alessandra Smolek, Ph.D., E.I.
North Carolina State University
Toledo, OH – April 14, 2016

Ryan Winston, Ph.D., P.E. Jay Dorsey, Ph.D., P.E. Amy Brennan

Typical Cross-Section





Chagrin River Watershed Partners, Inc.
P.O. Box 229
Willoughby, Ohio 44096-0229
440.975.3870

Willoughby Hills
Large

Willoughby Hills
Small

Perkins
Township

Orange
Village

Willoughby Hills (WH) Site

Willoughby Hills

Small Application:

PP SA: 480 ft^2

Catchment Area: 0.08 ac

Run-on Ratio: 7.2

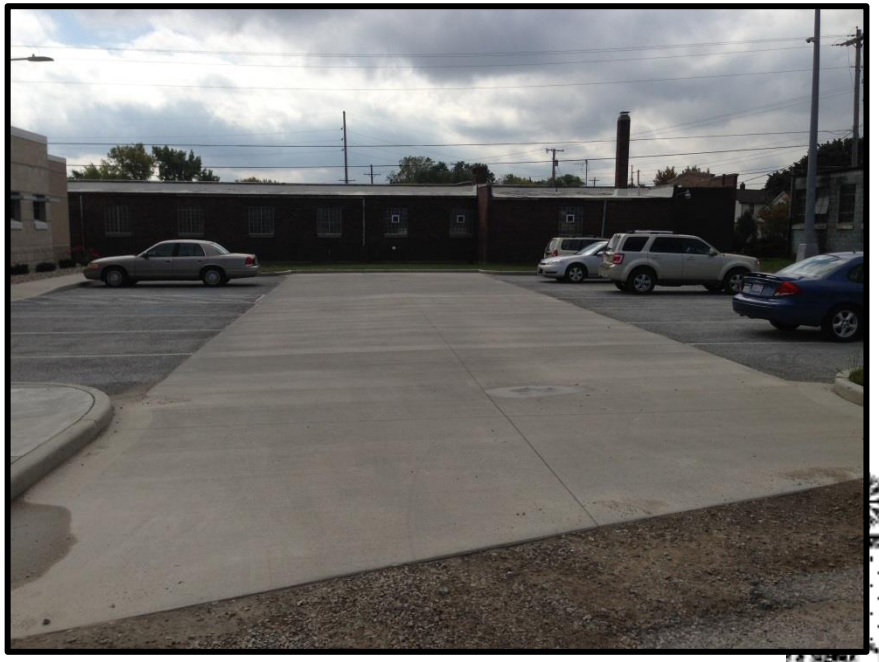
Large Application:

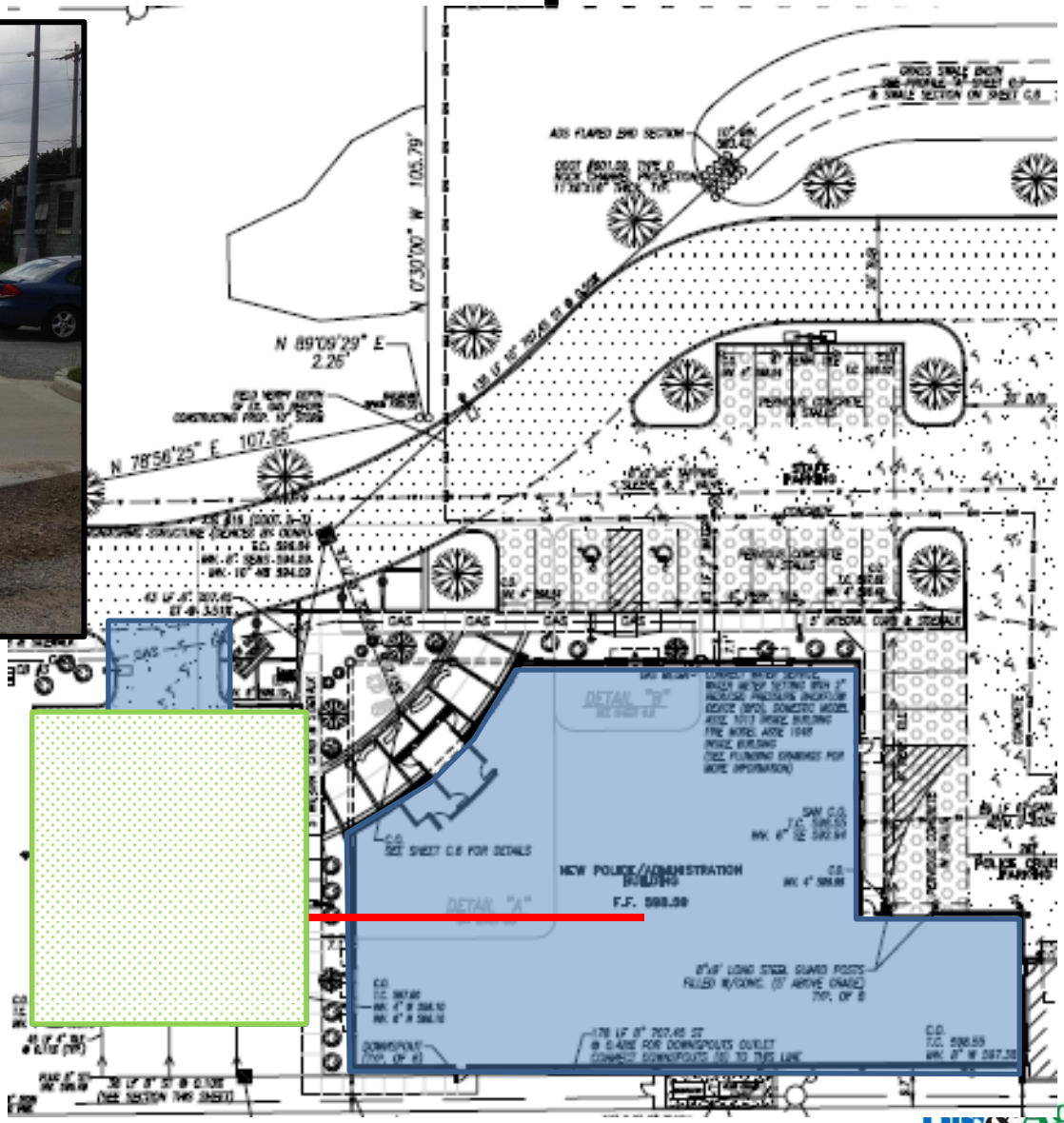
PP SA: 4420 ft^2

Catchment Area: 0.22 ac

Run-on Ratio: 2.2

Perkins Township





Site Characteristics:

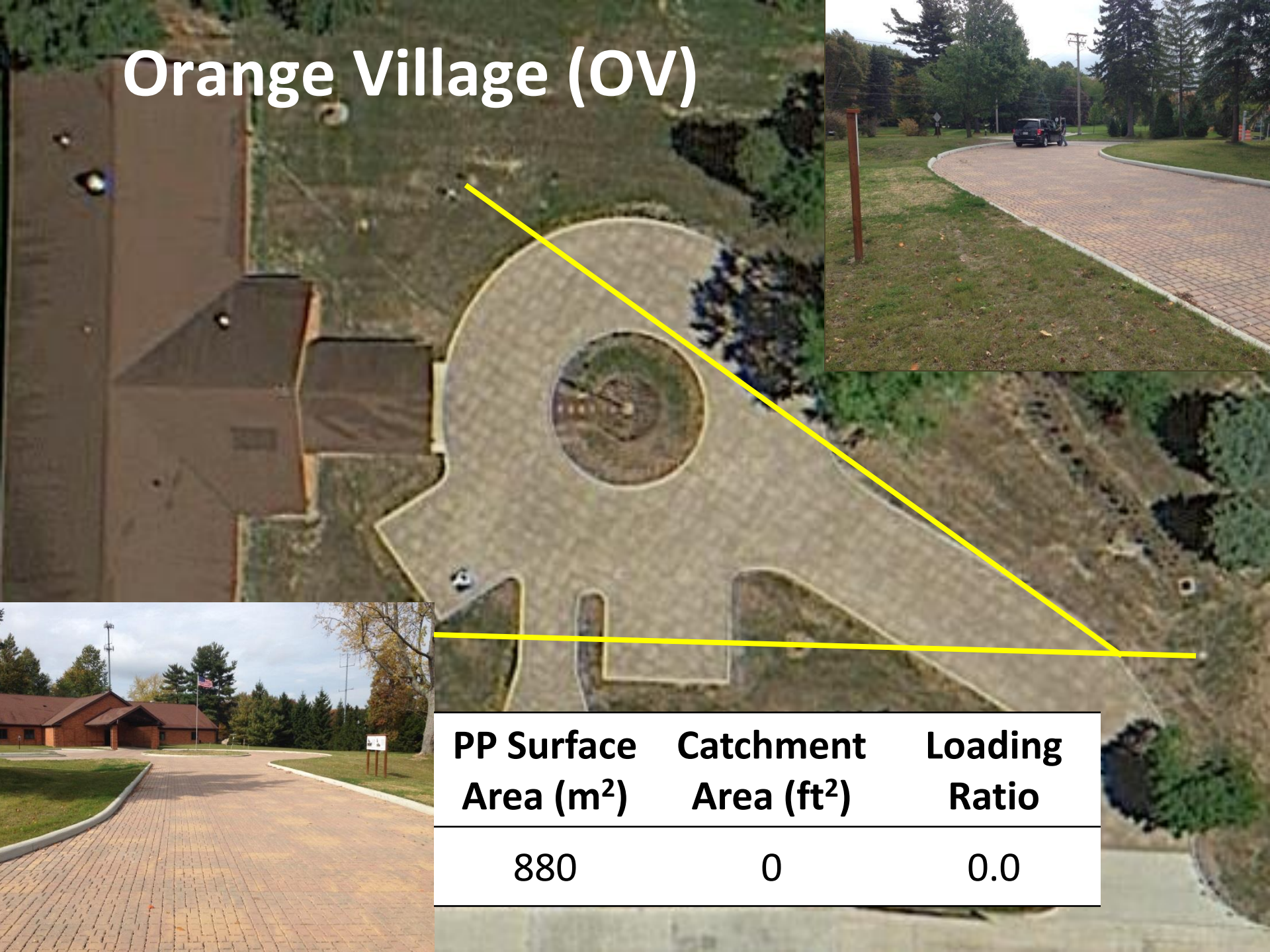
PP SA: 2590 ft^2

Inf. SA: 4820 ft^2

Catchment Area: 0.53 ac

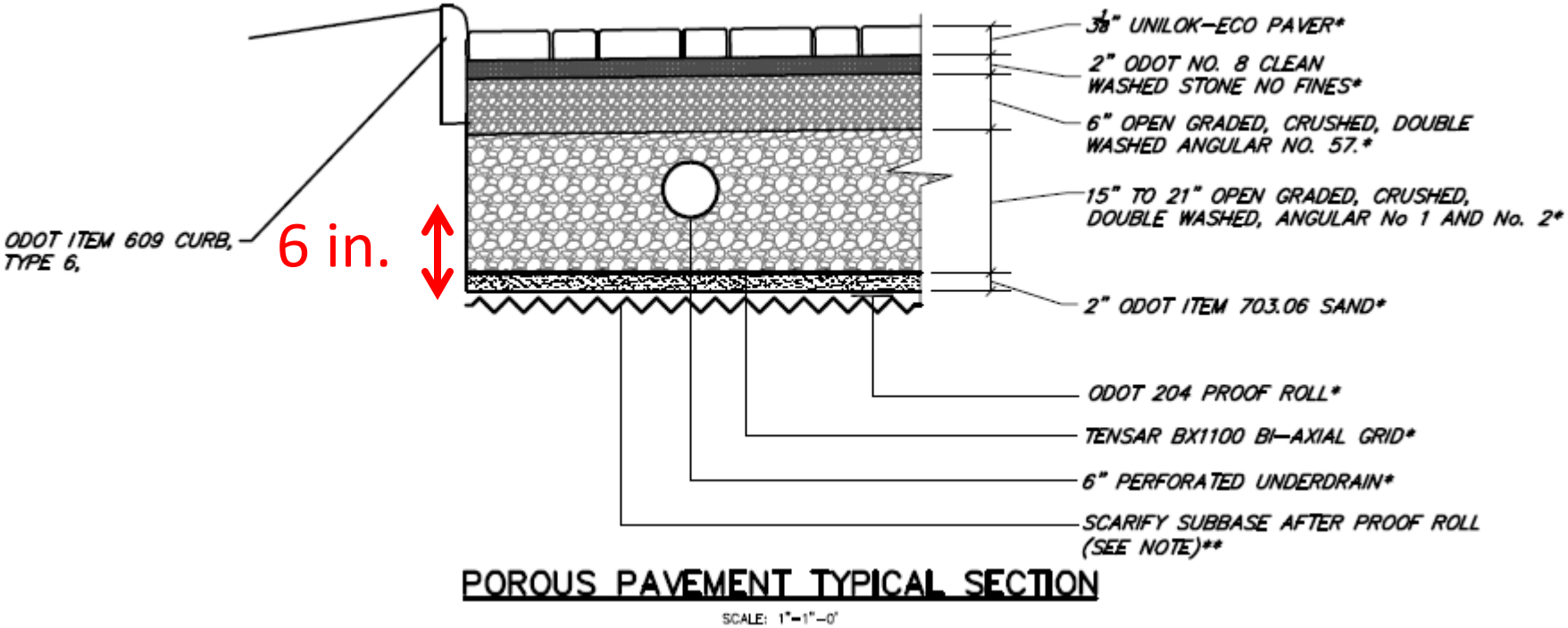
Loading Ratio: 4.8

Orange Village (OV)



PP Surface Area (m^2)	Catchment Area (ft^2)	Loading Ratio
880	0	0.0

Design Cross-Sections

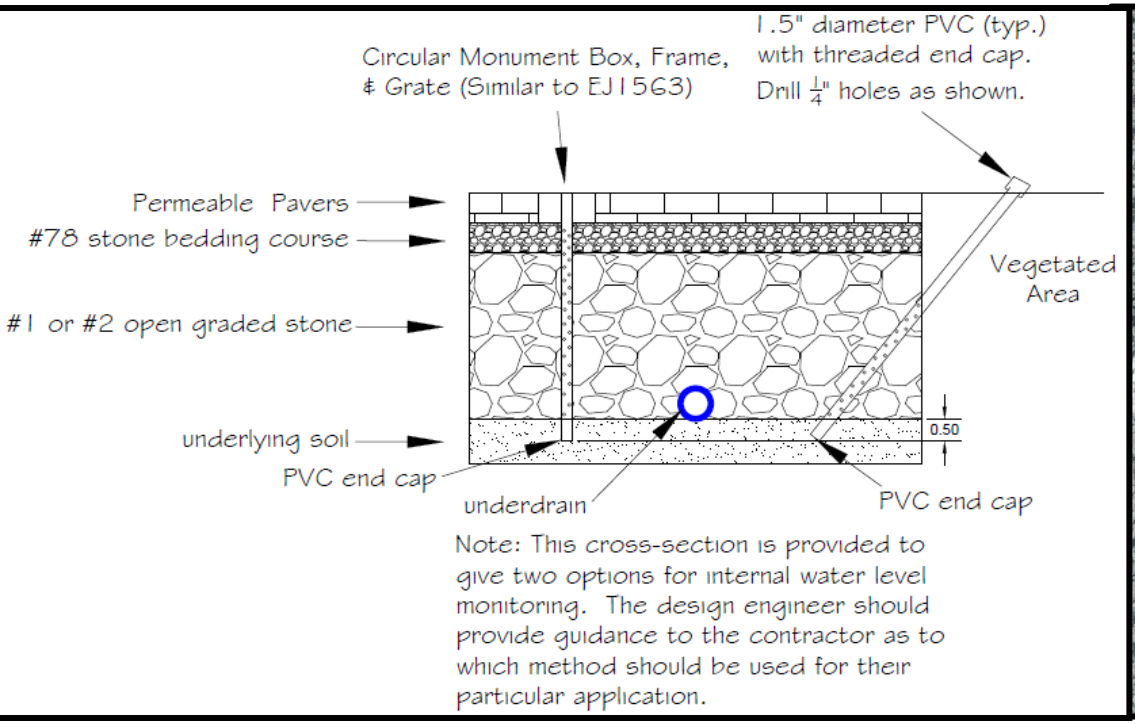


Site	WH Small	WH Large	PT	OV
Total Aggregate Depth (in)	20	20	15-18	23-29
Pavement Type	PICP	PICP	PC	PICP

Monitoring Design

Quantify the water balance for each stormwater control

Post-Construction Drawdown Rates



Courtesy: Onset Computer Corporation, 2014

Soil Testing

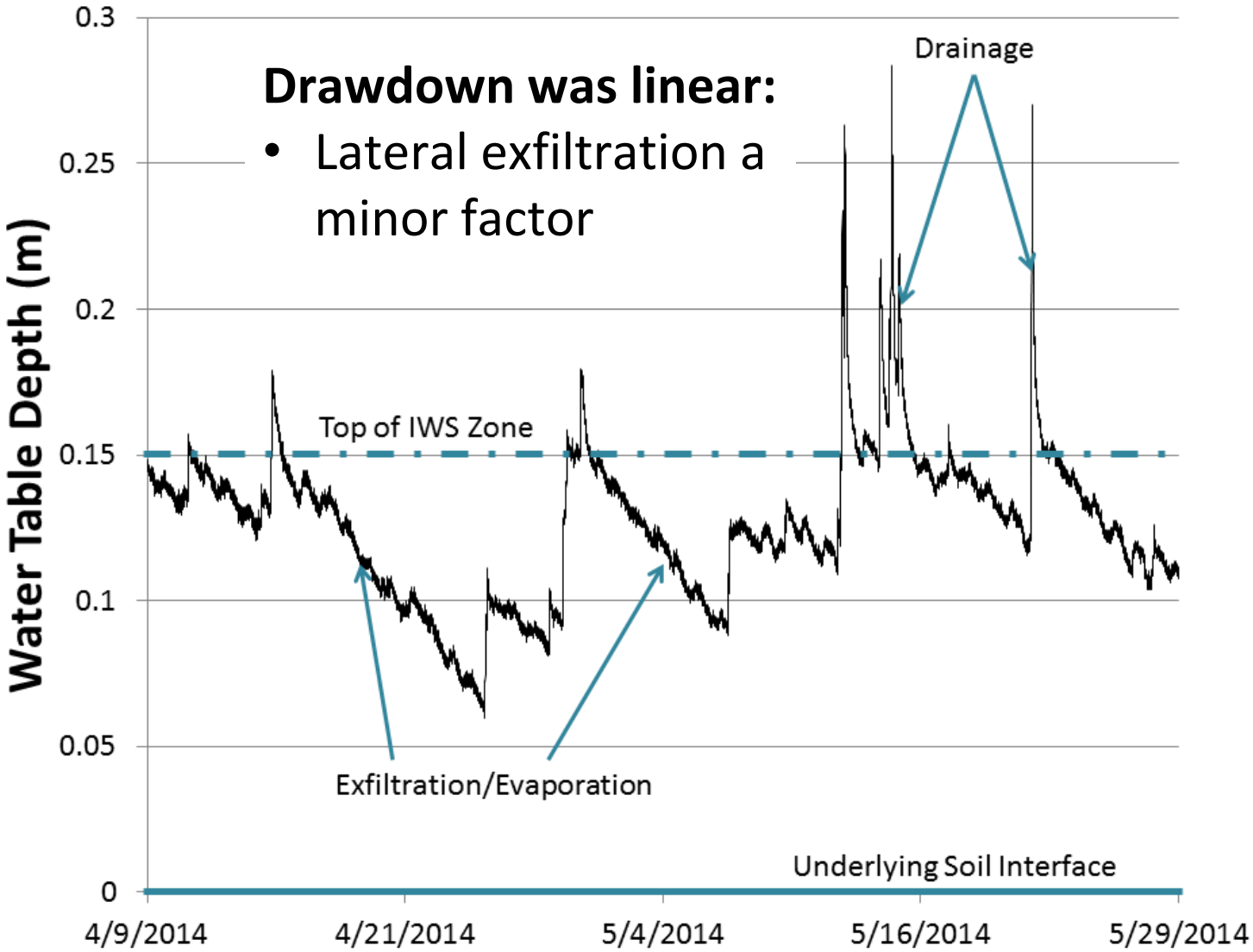
Site	Mapped Soil	Subgrade Soil Texture	Measured Kfs (in/hr)
Perkins Township	Bennington	Silty Clay Loam	0.01, 0.01, 0.04,0.05
Orange Village	Wadsworth	Fill	0.01, 0.03, 0.05, 0.06, 0.72, 1.54
Willoughby Hills	Mahoning	Fill	Small – 0.01, 0.05 Large – 0, 0.01, 0.04, 0.06

Comparison of Drawdown Rates

Site Name	Pre-Construction Kfs (in/hr)	Avg Post-Construction Drawdown Rate (in/hr)
Perkins Township	0.01-0.05 →	0.013
Willoughby Hills Small	0.01-0.05 →	0.002
Willoughby Hills Large	0-0.06 →	0.002, 0.006

Pre and post-construction rates comparable

Drawdown at Perkins Township



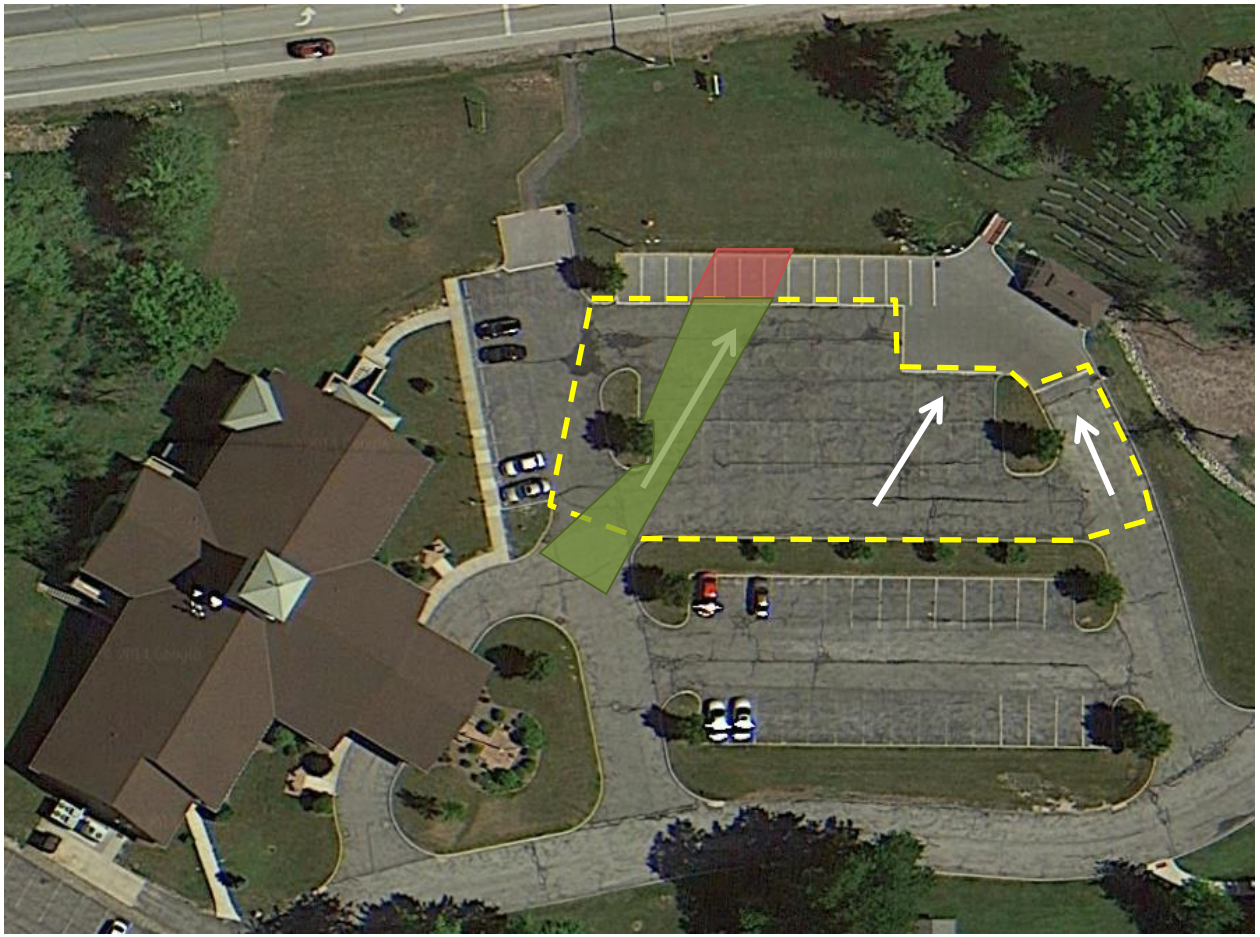
Water Balance Summary

Site	Drawdown Rate (in/hr)	Loading Ratio for Exfiltration	Drainage (%)	Surface Runoff (%)	Exfiltration & Evaporation (%)
PT	0.013	4.8	47	0	53
WH small	0.002	7.2	76	8	16
WH large	0.004	2.2	44	24	32
OV	N/A	0	1	0	99

Surface Runoff at Willoughby Hills

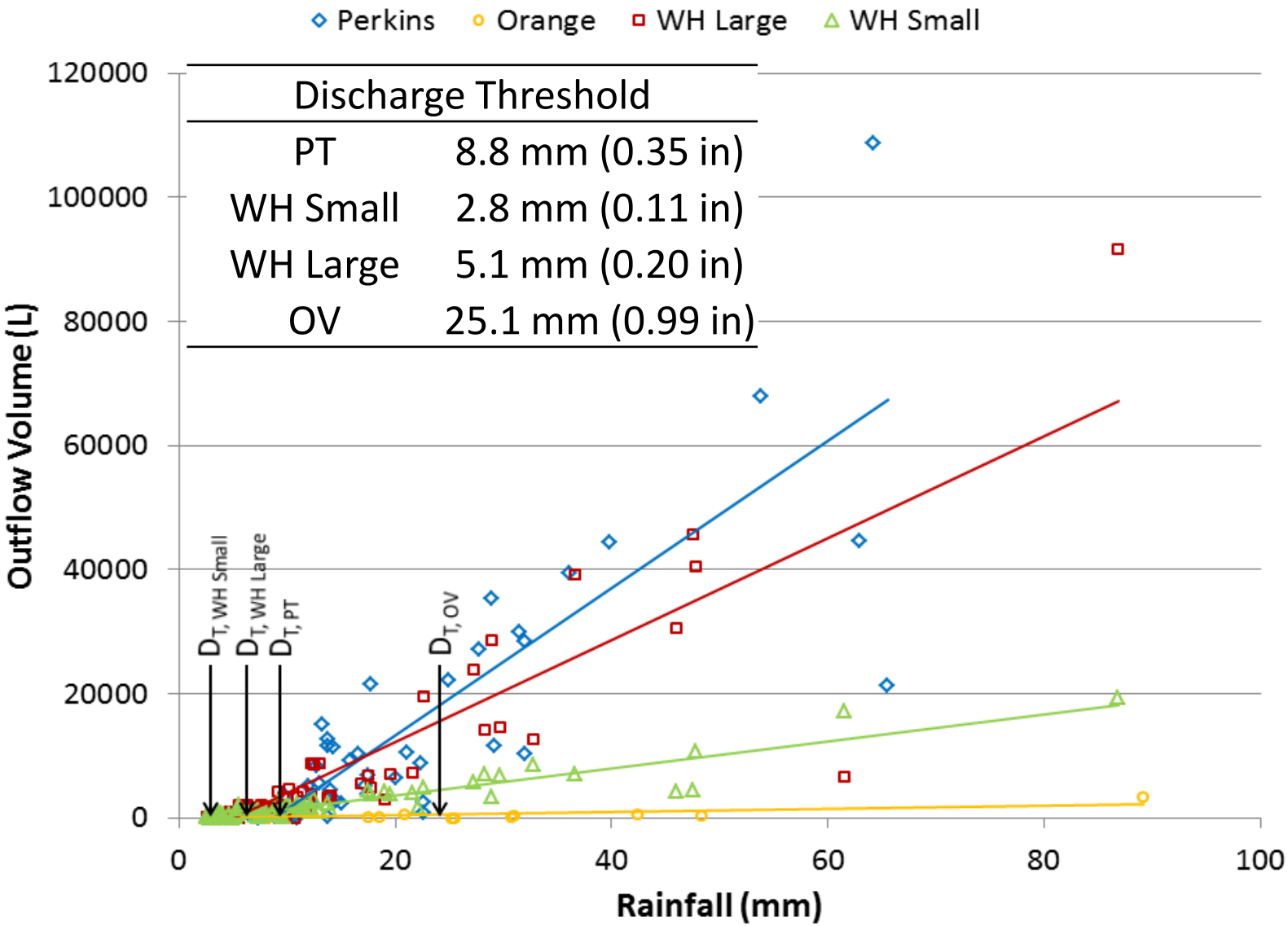
- 7/17/2014 event
- Rainfall Depth = 0.2 in
- Peak rainfall intensity = 0.35 in/hr

Why: Shallow Concentrated Flow



Lesson: consider curbing of medians in design and how that might concentrate flow

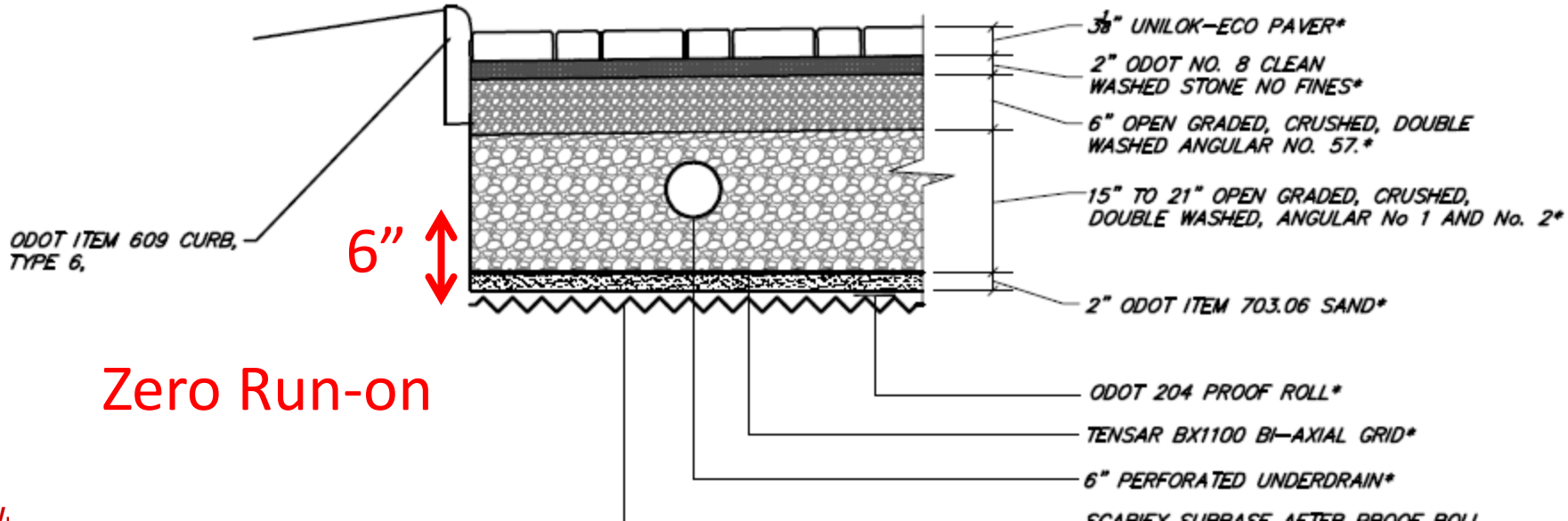
Discharge Threshold



Discharge Threshold	
PT	8.8 mm (0.35 in)
WH Small	2.8 mm (0.11 in)
WH Large	5.1 mm (0.20 in)
OV	25.1 mm (0.99 in)

Design Characteristics Critical to Performance

Site	Mapped Soil	Subgrade Soil Texture	Measured Kfs (in/hr)
PT	Bennington	Silty Clay Loam	0.01, 0.01, 0.04,0.05
OV	Wadsworth	Fill	0.01, 0.03, 0.05, 0.06, 0.72, 1.54
WH	Mahoning	Fill	Small – 0.01, 0.05 Large – 0, 0.01, 0.04, 0.06



Q_p Mitigation during Peak Rainfall Intensities

2-5 storms with peak intensities

> 1 yr, 5 min storm for Cleveland, OH

PT	WH Large	WH Small	OV
84-98	0-11	27-61	92-99

Permeable Pavement Hydrology

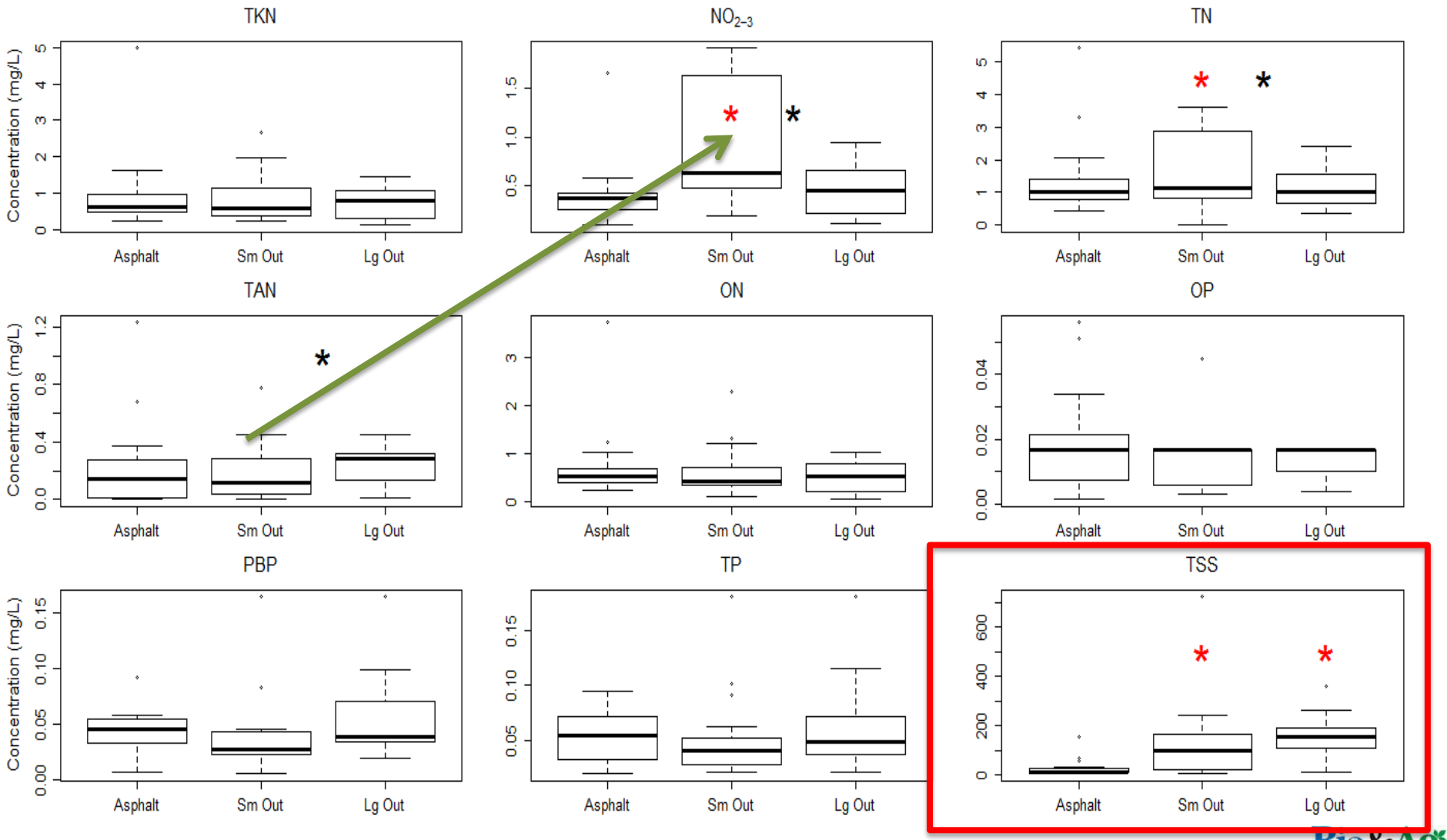
- Permeable pavement reduced runoff volume by 16-99%
  - Surface runoff 0-24% of water balance
  - Discharge threshold between 0.11 – 0.99 in.
  - Varied based on underlying soil K_{sat} and ability to de-water IWS zone
- Greater run-on:
  - More clogging
  - Reduced hydrologic benefits

Willoughby Hills Water Quality Study

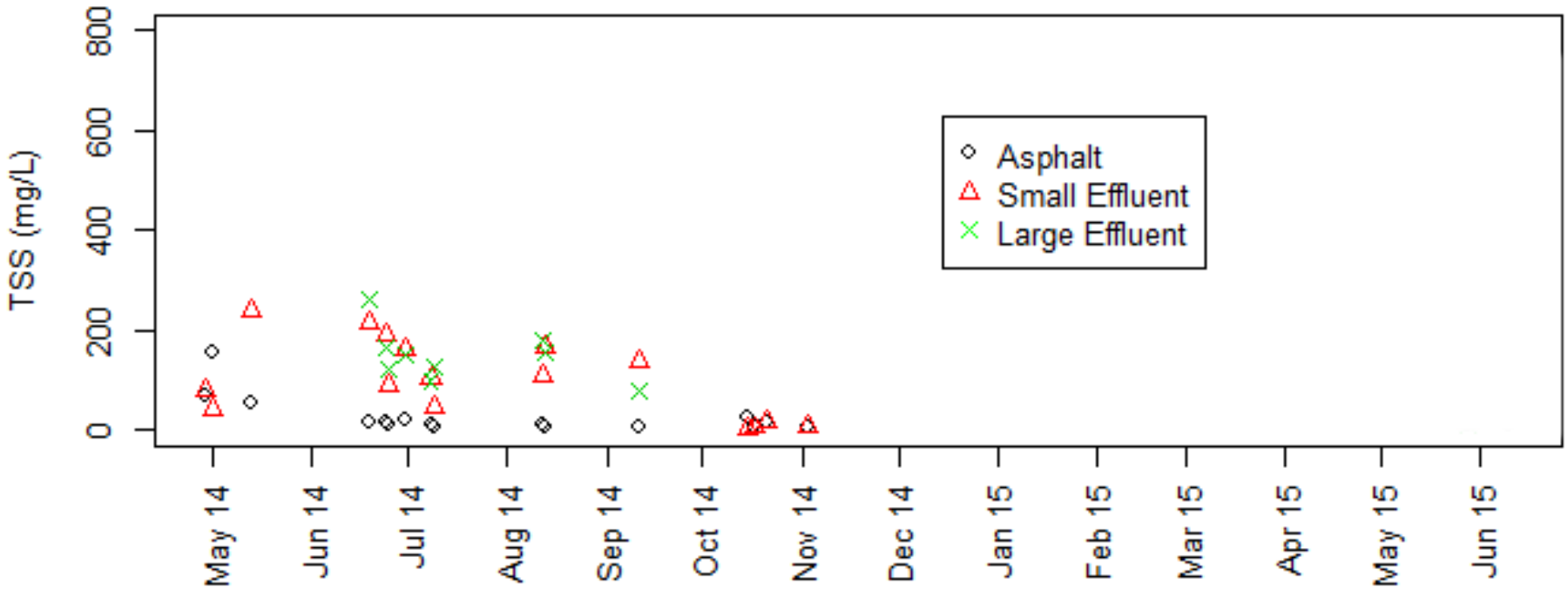
3 monitoring locations:

A) Asphalt runoff (representative of inflow to the PICP)
B) Underdrain of WH Small
C) Underdrain of WH Large

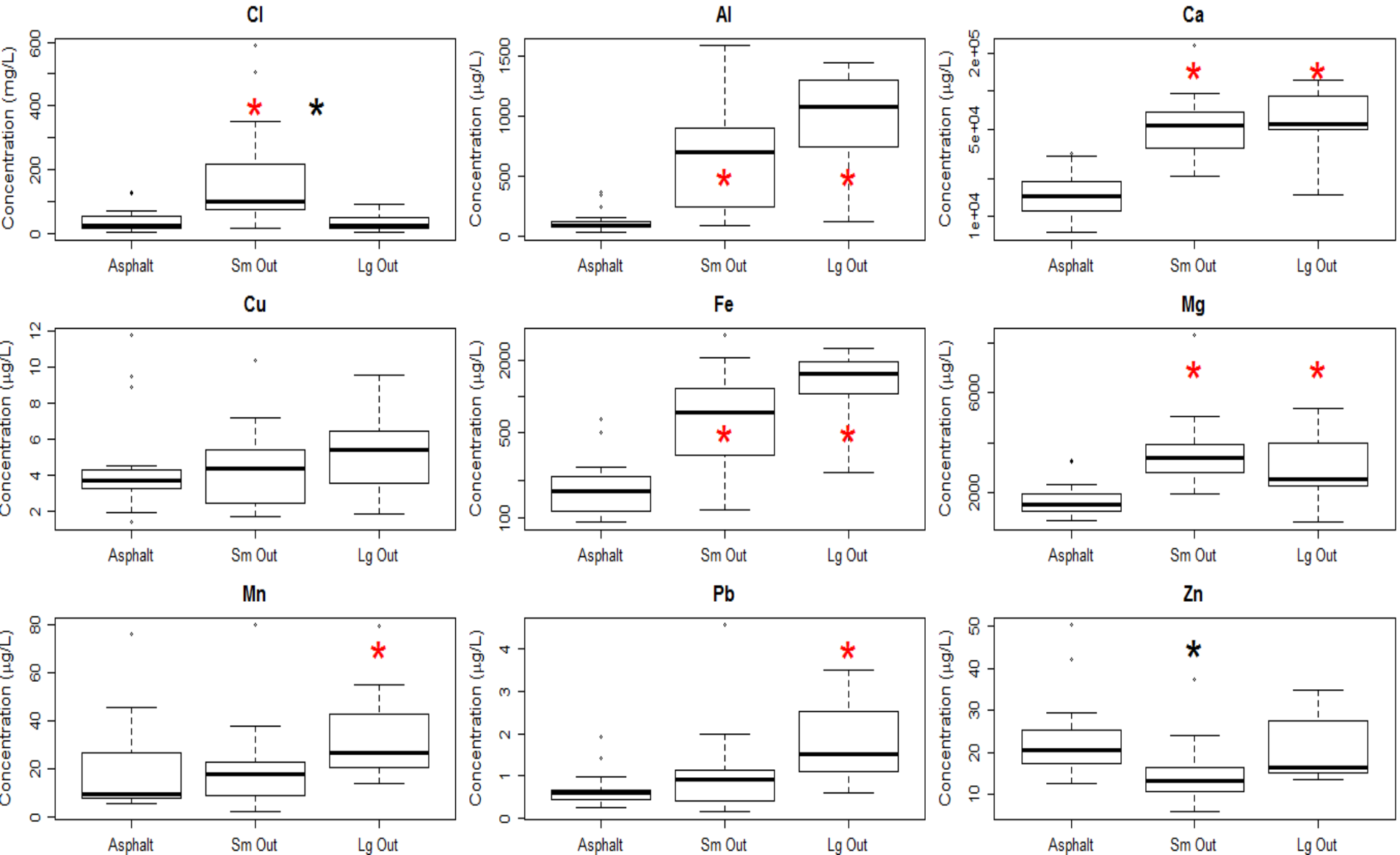
Nutrient Concentrations



Spring 2015 Monitoring…

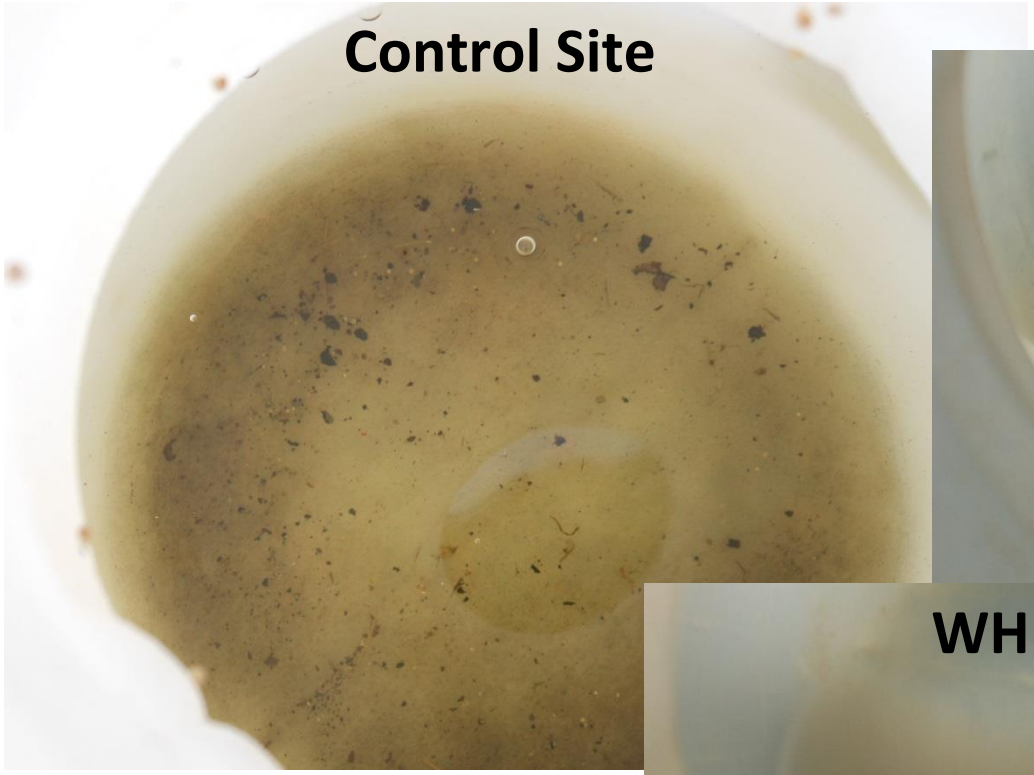


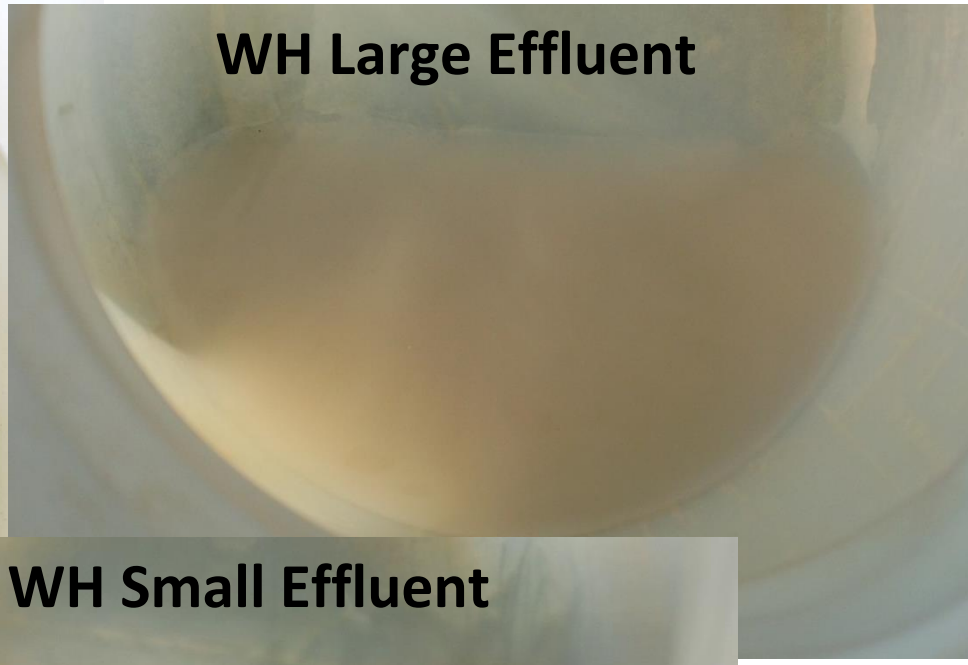
Export of sediment = Export of metals

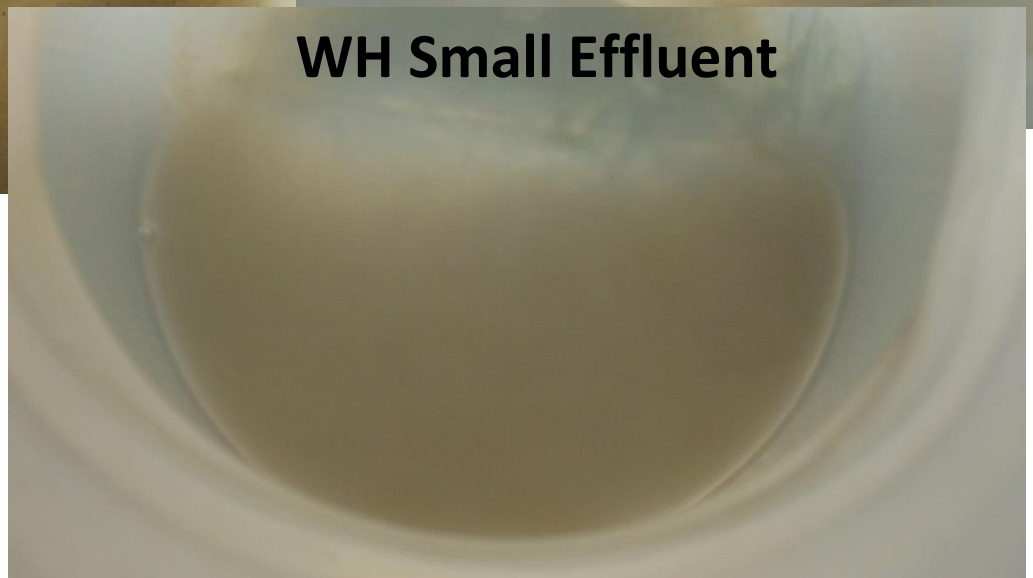


June 10, 2015

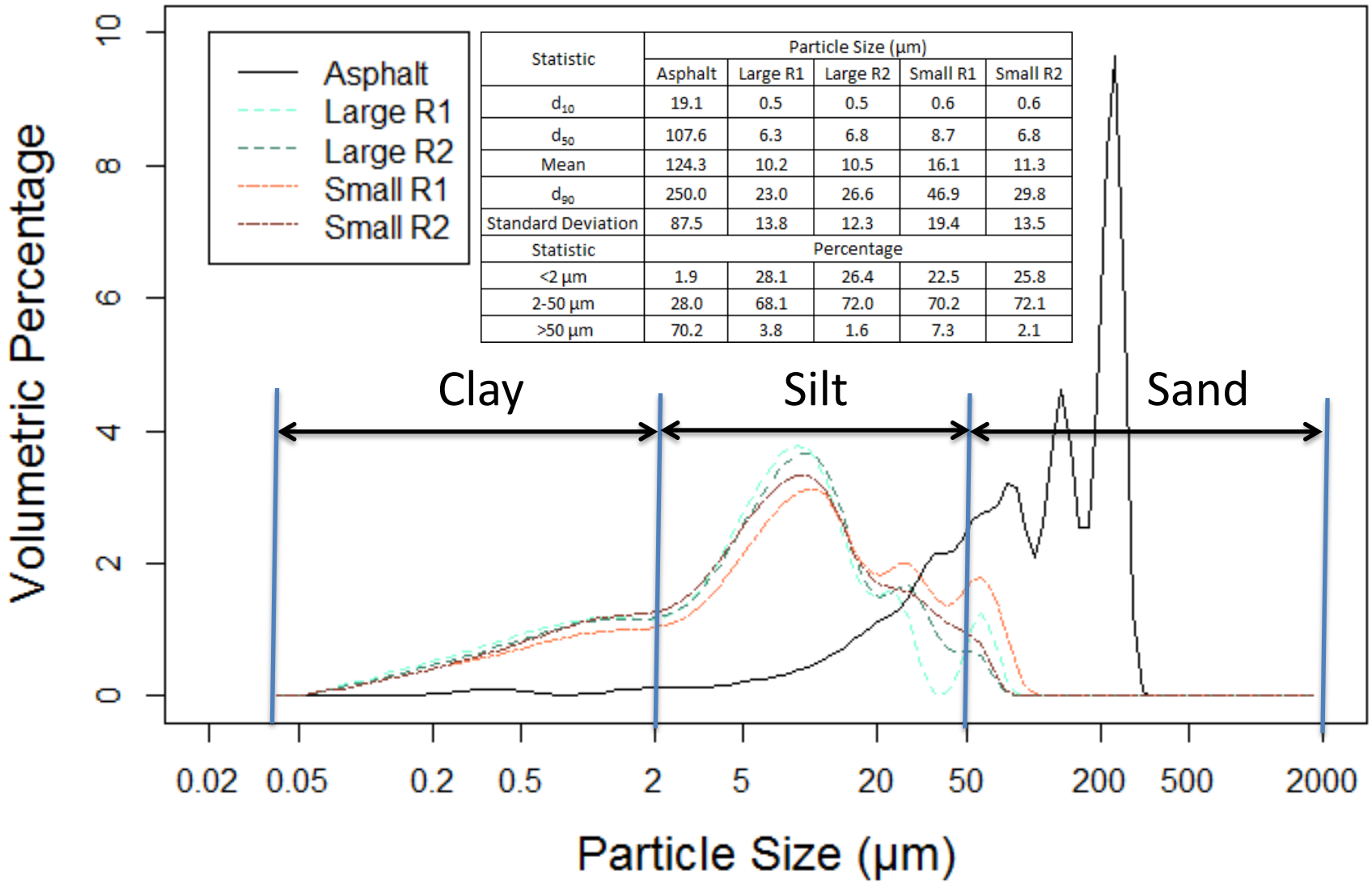
Water Quality Samples







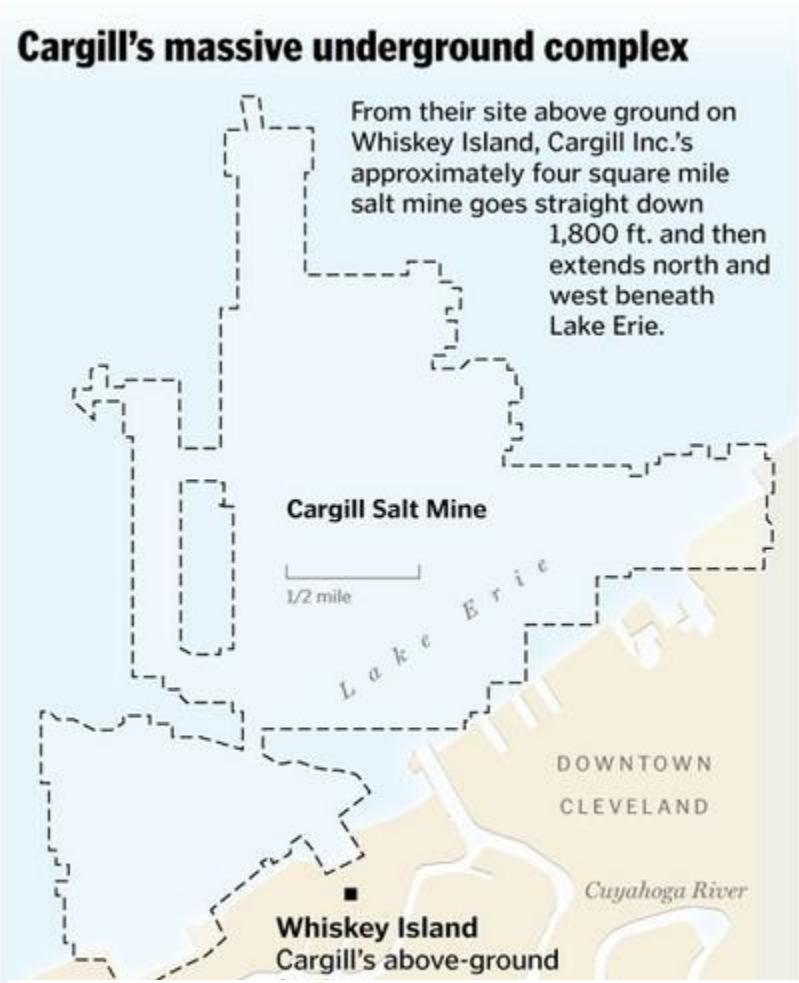
Particle Size Distributions (June 10, 2015 Event)



Statistic	Particle Size (µm)				
	Asphalt	Large R1	Large R2	Small R1	Small R2
d_{10}	19.1	0.5	0.5	0.6	0.6
d_{50}	107.6	6.3	6.8	8.7	6.8
Mean	124.3	10.2	10.5	16.1	11.3
d_{90}	250.0	23.0	26.6	46.9	29.8
Standard Deviation	87.5	13.8	12.3	19.4	13.5
Statistic	Percentage				
<2 µm	1.9	28.1	26.4	22.5	25.8
2-50 µm	28.0	68.1	72.0	70.2	72.1
>50 µm	70.2	3.8	1.6	7.3	2.1

Winter in Northeast Ohio

Lots and LOTS of salt



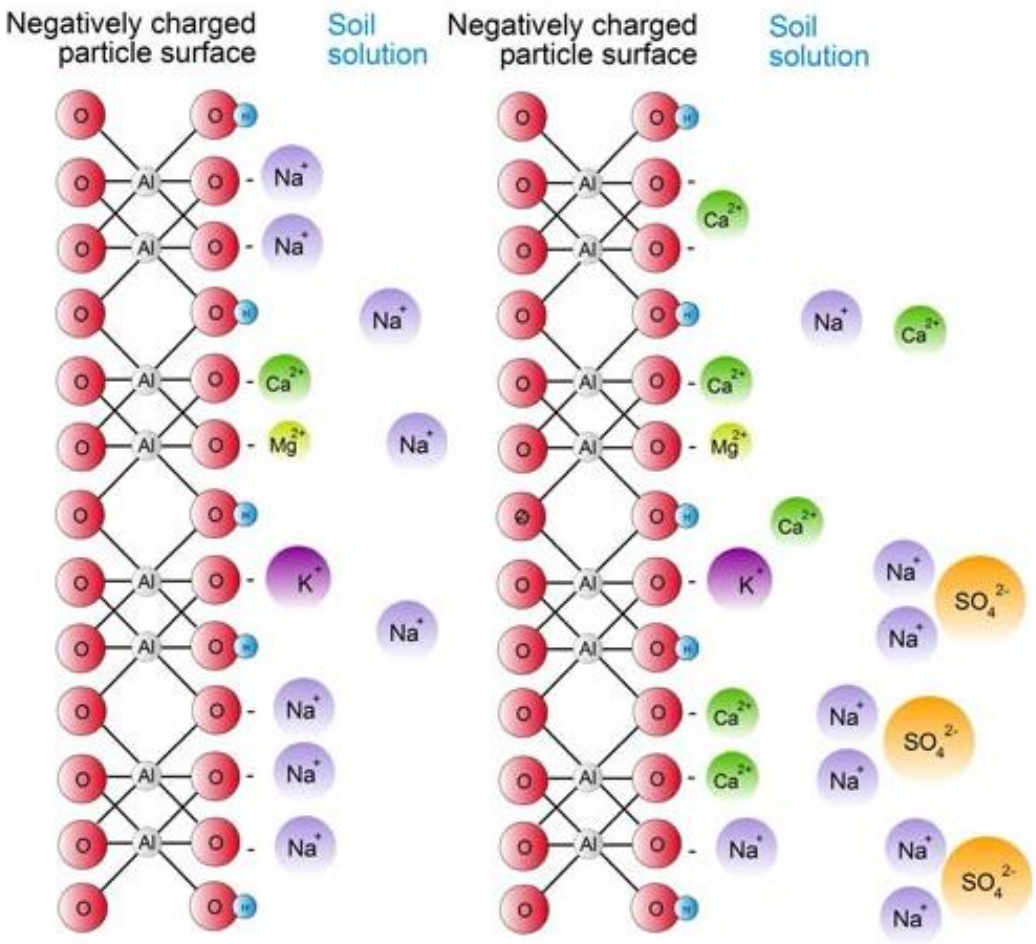
Source: Cargill and the Cleveland Plain Dealer

$$\text{S.A.R.} = \frac{Na^{+}}{\sqrt{\frac{1}{2}(Ca^{2+} + Mg^{2+})}}$$

$$ESP = \frac{(Na)_{Exc}}{(Ca + Mg + K + Na)_{Exc}}$$

How Do Elevated SAR/ESP Affect Soil?

- "Caking" of fine-textured soils, reducing permeability and infiltration rate (e.g., Frenkel et al. 1978)
  - Increases soil dispersibility
  - Impact of rain drops causes greater dispersion
  - Deflocculation of clay particles (especially in 2:1 clays)



These effects are especially true when:

- No topsoil (OM) to stabilize the soil
- Nearly 60 cm cross-section at WH
- B Horizon->little OM

Courtesy: University of New South Wales

Potential Design Recommendations

- Test underlying soil for dispersion under sodic conditions prior to permeable pavement design
- Use another de-icer ($CaCl_2$, CMA, sand, gravel)
- Perhaps line systems over dispersive/high clay content soils where NaCl deicing salt use is expected
  - Treat as dry detention basin, eliminate exfiltration
- Structural concerns over time due to loss of sediment?

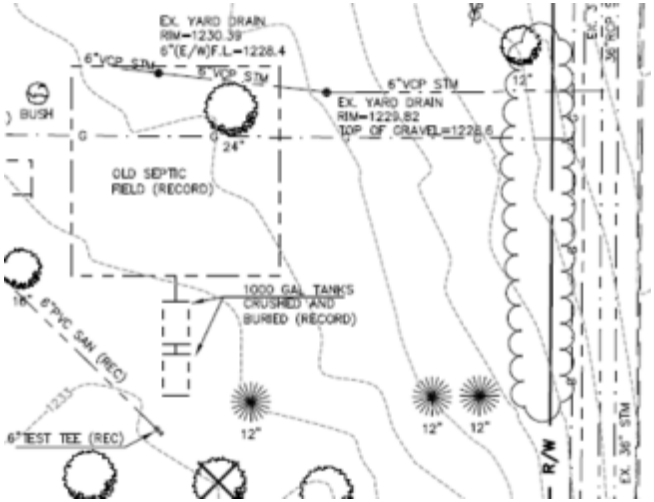
Lessons Learned: Design and Construction

Pre-Design

- Clarity of goals
- Familiarity with site (topo, soils, utilities, history and future development) is critical
- Exposure to LID practices – reality check for client/site owner
  - Appearance/aesthetics
  - Maintenance commitments
  - Cost and benefits
  - Outside funding (e.g., SWIF, 319) nice incentive

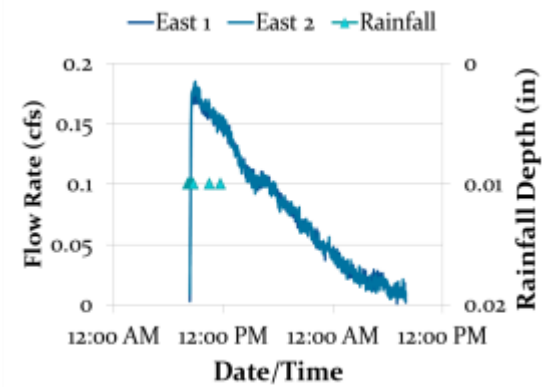
Pre-Design

- Inventory/locate existing infrastructure
- Evaluate available outlets
- Identify drainage from offsite
- Visit the site
  - Site survey/site map reality check
  - Conduct a preliminary soils investigation
    - Assume infiltration tests will be necessary in built areas



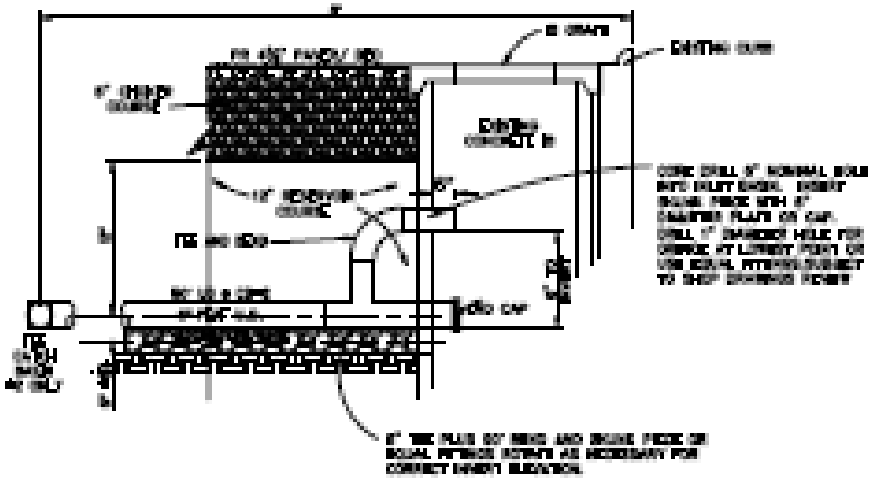
Design - General

- Engineer(s) familiarity with LID practices, their function, design procedures
  - Many functional components at odds with traditional stormwater
  - Openness to unfamiliar ideas/concepts
- Clear guidance for sourcing and verifying materials – pavement and aggregate
  - Be as specific as possible
  - Require testing/inspection for acceptance



Permeable Pavement Design

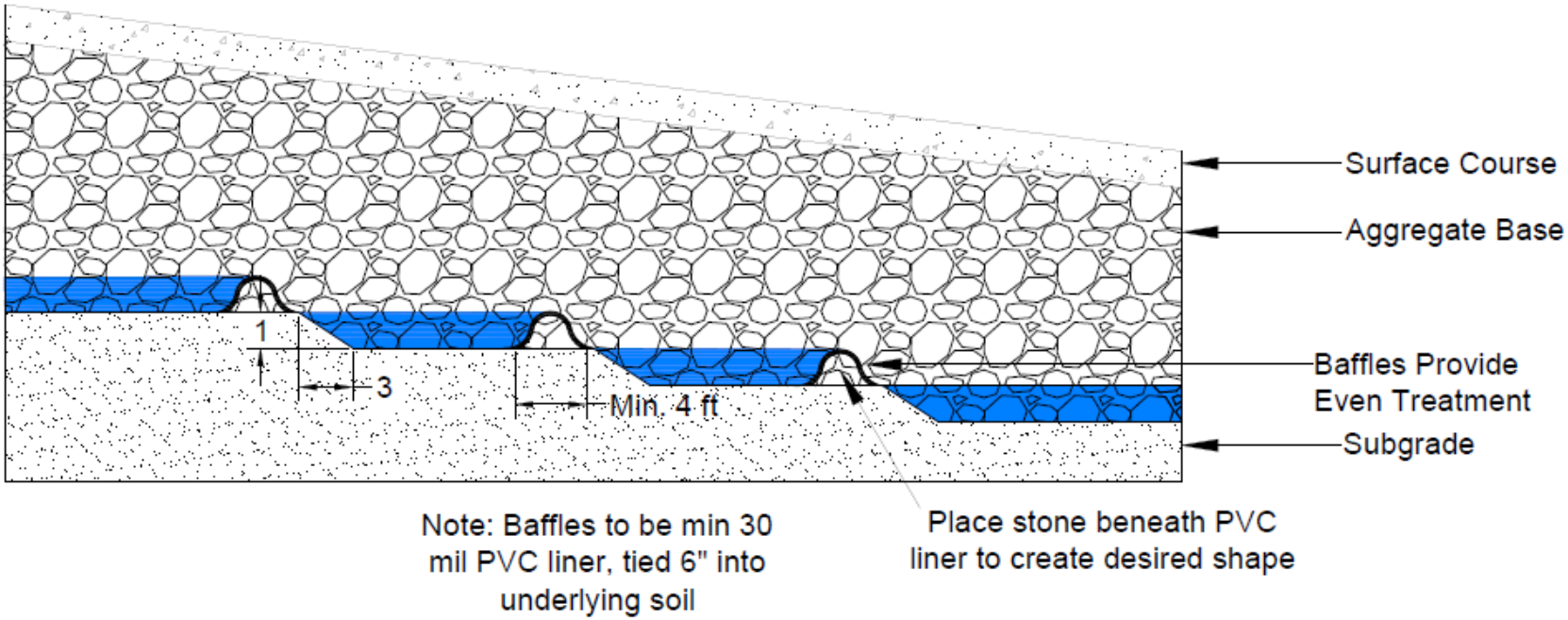
- Internal water storage (storage below the underdrain) is strongly encouraged to promote exfiltration and runoff volume reduction
  - Upturned elbow vs. raised underdrain



ORIFICE CONNECTION AT INLET BASINS

Permeable Pavement Design

- Level subgrade maximizes exfiltration through even ponding
  - For sloped areas, use terraced design
  - Add check dams and raise underdrain to provide sump



Permeable Pavement Design

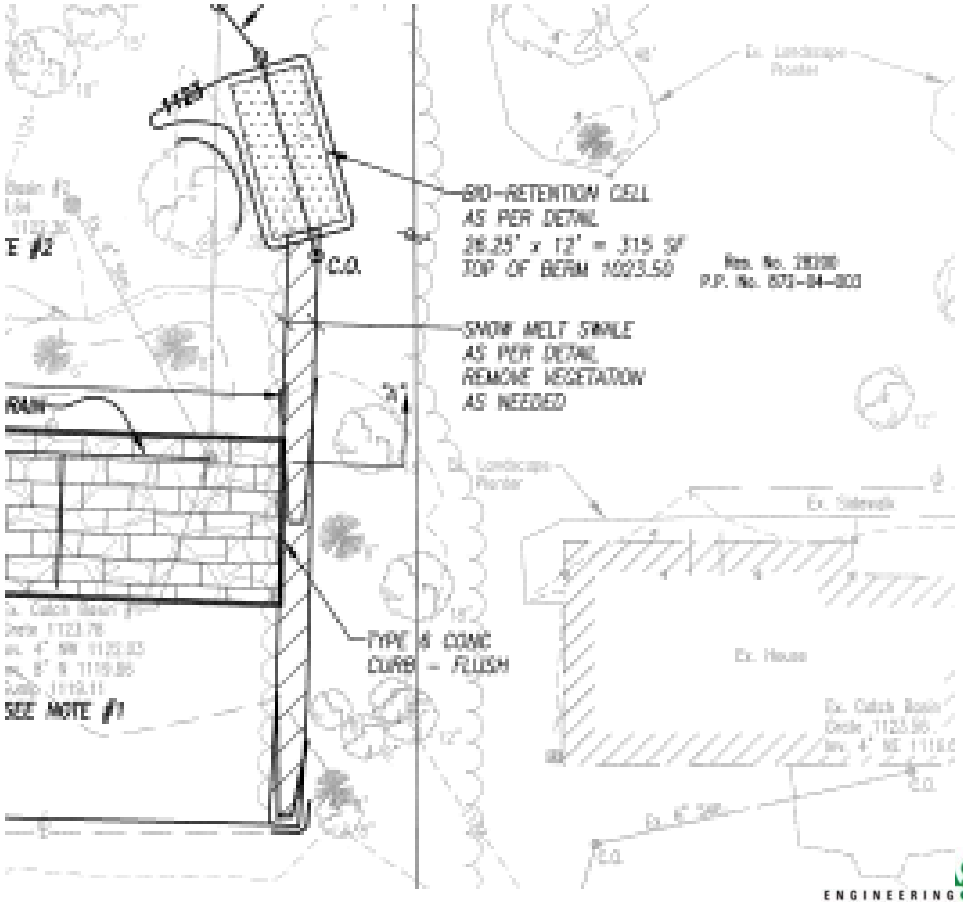
- Clear guidance for sourcing and verifying materials
  - Locally available materials
  - Clearly define criteria/expectations and specify right to reject/return any materials that don't meet specs
    - Specify washed, angular limestone for base
    - Define what "washed" means – hand wash or double wash

Permeable Pavement Design

- **Design for constructability**
  - Curved permeable paver designs more expensive to install
  - Mechanical installation reduces costs
  - Account for settling of pervious pavers adjacent to asphalt and concrete

Permeable Pavement Design

- **Design for maintainability**
  - Create separate snow storage area so snow isn't stored on permeable pavement



Permeable Pavement Construction

- **Pervious concrete**
  - Protect with plastic sheeting during curing – plan for worst case scenario (2 days of 30 mph winds)
  - Wetting subgrade may improve appearance and reduce raveling

Permeable Pavement Construction

- Materials - Orange Village permeable pavers
  - Permeable paver subbase stone was rounded & unwashed despite specification on plans for washed, angular limestone
  - Experienced paver contractor placed pavers but not subbase

Permeable Pavement Construction

Execution of design:

- Pepper Pike City Hall – installation errors can make a big difference!

Construction oversight with knowledgeable staff is critical

Proactive communication needed through plan set development, contractor selection, pre-construction, and construction

Pre-Construction Meeting

- Review plans with designers, owners, contractors and inspectors
  - Construction sequencing and practices
    - Erosion/sediment control and site stabilization to prevent clogging
    - Avoid subgrade compaction/scarify underlying soils
    - Clarify which work will be performed by specific equipment, and which work must be performed by hand
  - Material specifications and expectations
  - Monitoring equipment installation (if applies)
  - Design engineer verification at critical installation points

Lessons Learned: Summary

Pre-design

- Clarification of Goals
- LID reality check
- Thorough site evaluation – infrastructure, outlets, soils

Lessons Learned: Summary

Design

- Be as explicit as possible – materials, equipment, sequencing
- Design for constructability
- Design for maintainability

Lessons Learned: Summary

Construction

- Contractor experienced in LID construction and interested in getting it right
- Oversight by someone who understands the project
- Thorough, ongoing communication
- Willingness to reject/return materials

Questions?