Welcome to the University of Vermont Bioretention Laboratory

Amanda Cording, PhD

The UNIVERSITY of VERMONT

PhD Dissertation:
Evaluating Stormwater Pollutant Removal Mechanisms by Bioretention in the Context of Climate Change

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Committee Member: Dr. Arne Bomblies

WATERSHED CONSULTING ASSOCIATES, LLC
ECOSOLUTIONS innovative designs – living systems
CONTECH ENGINEERED SOLUTIONS
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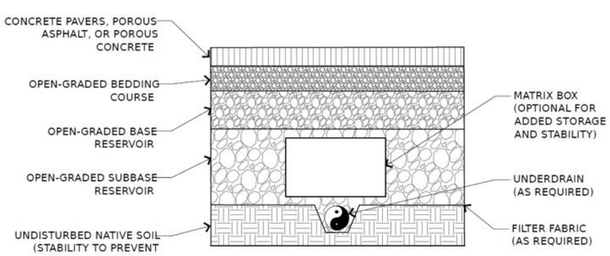
LAKE CHAMPLAIN Sea Grant
The UNIVERSITY of VERMONT
COLLEGE OF Agriculture and Life Sciences

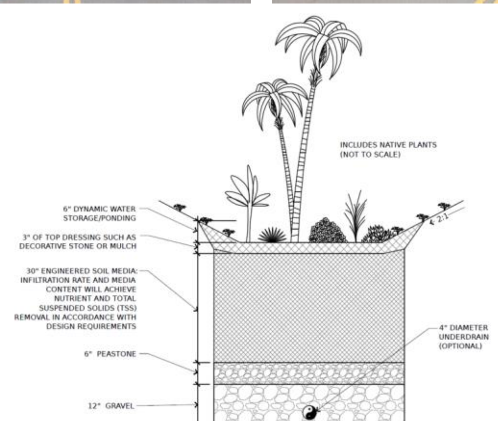
Low Impact Design & Development

LID is an approach to development that aims to mimic pre-development hydrology and uses ecological engineering to remove pollutants in stormwater, for re-use and/or replenishment of groundwater supplies.

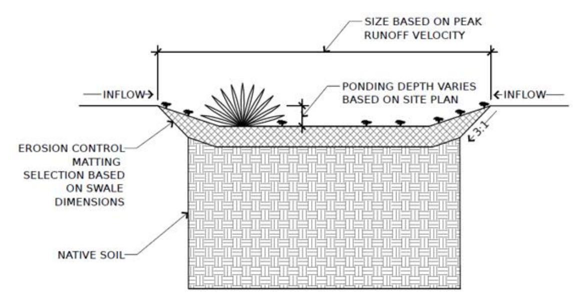
LID uses Green Stormwater Infrastructure (GSI) as a tool.



Porous Materials



Bioretention “Green Streets”



Vegetated Swales

Many National Champions of Low Impact Development

U.S. GREEN BUILDING COUNCIL
USGBC

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NOAA
U.S. DEPARTMENT OF COMMERCE

UNITED STATES
ENVIRONMENTAL PROTECTION AGENCY

U.S.
FISH & WILDLIFE
SERVICE
DEPARTMENT OF THE INTERIOR

DEPARTMENT OF STATE
UNITED STATES OF AMERICA

NATIONAL MARINE
SANCTUARIES

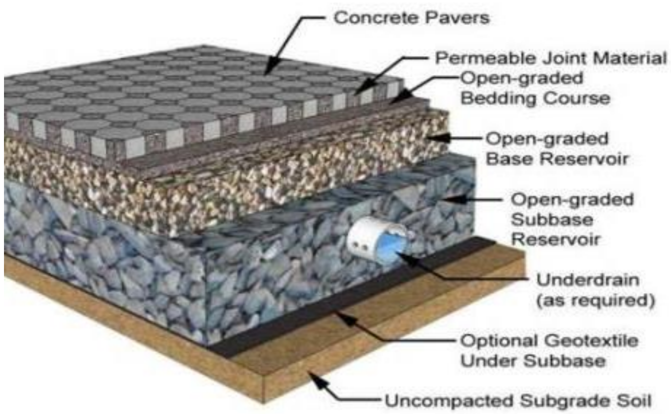
SURFRIDER
FOUNDATION

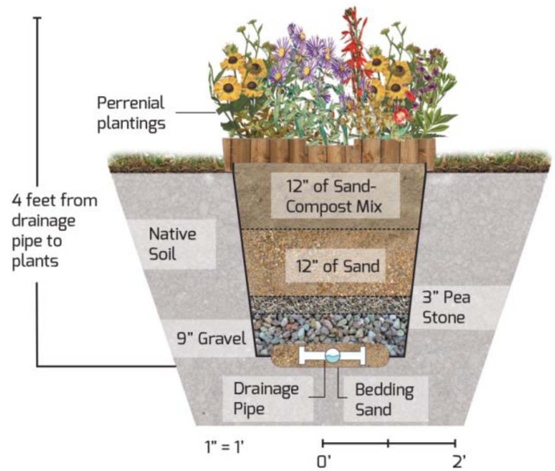
CENTER FOR
WATERSHED
PROTECTION

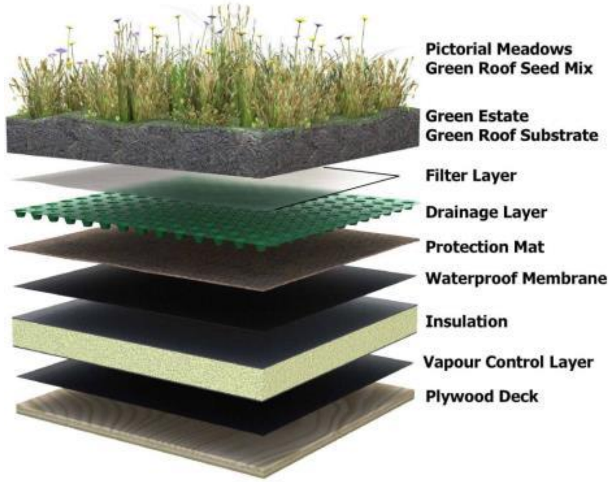
The Nature Conservancy

SIERRA
CLUB
FOUNDED 1892

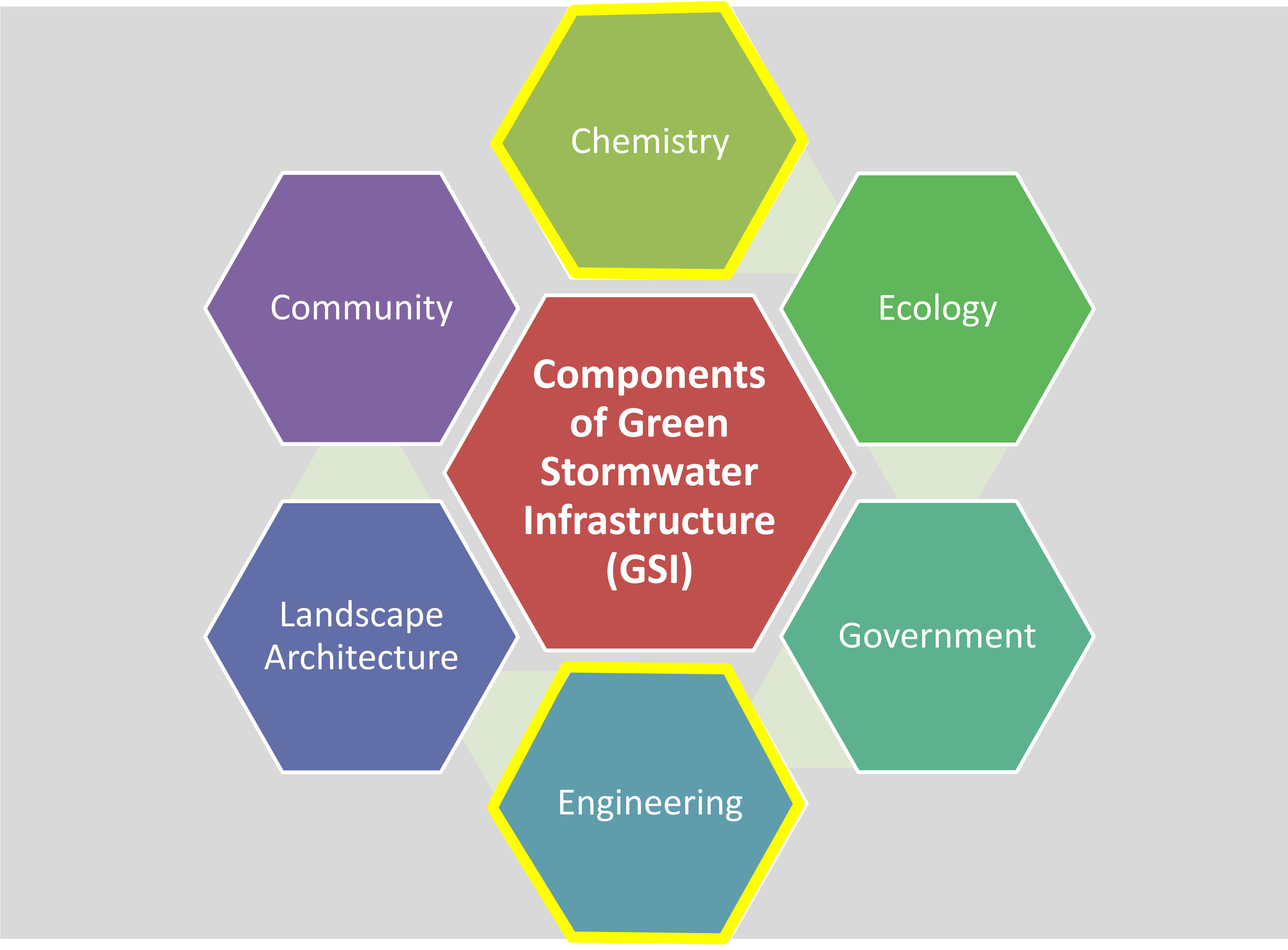
Green Stormwater Infrastructure (GSI)



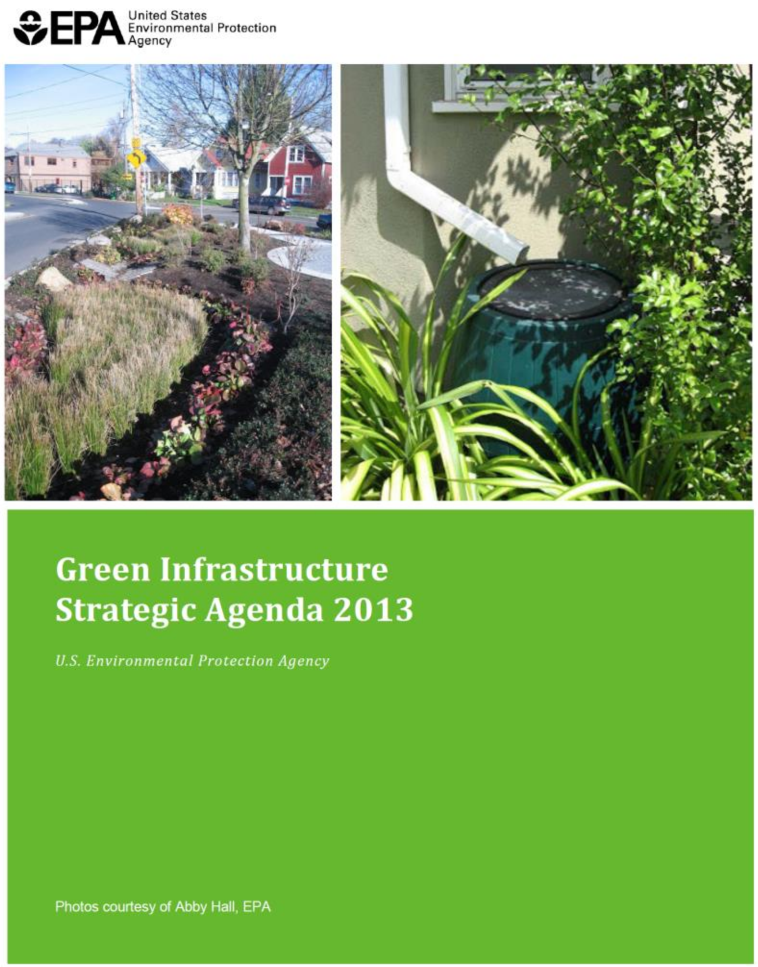




Davis 2008; Dietz and Clausen 2006; Zinger et al. 2013; Collins et al. 2010.


Chemistry
Community
Ecology
Components of Green Stormwater Infrastructure (GSI)
Landscape Architecture
Government
Engineering

EPA National Green Infrastructure Strategic Agenda 2013

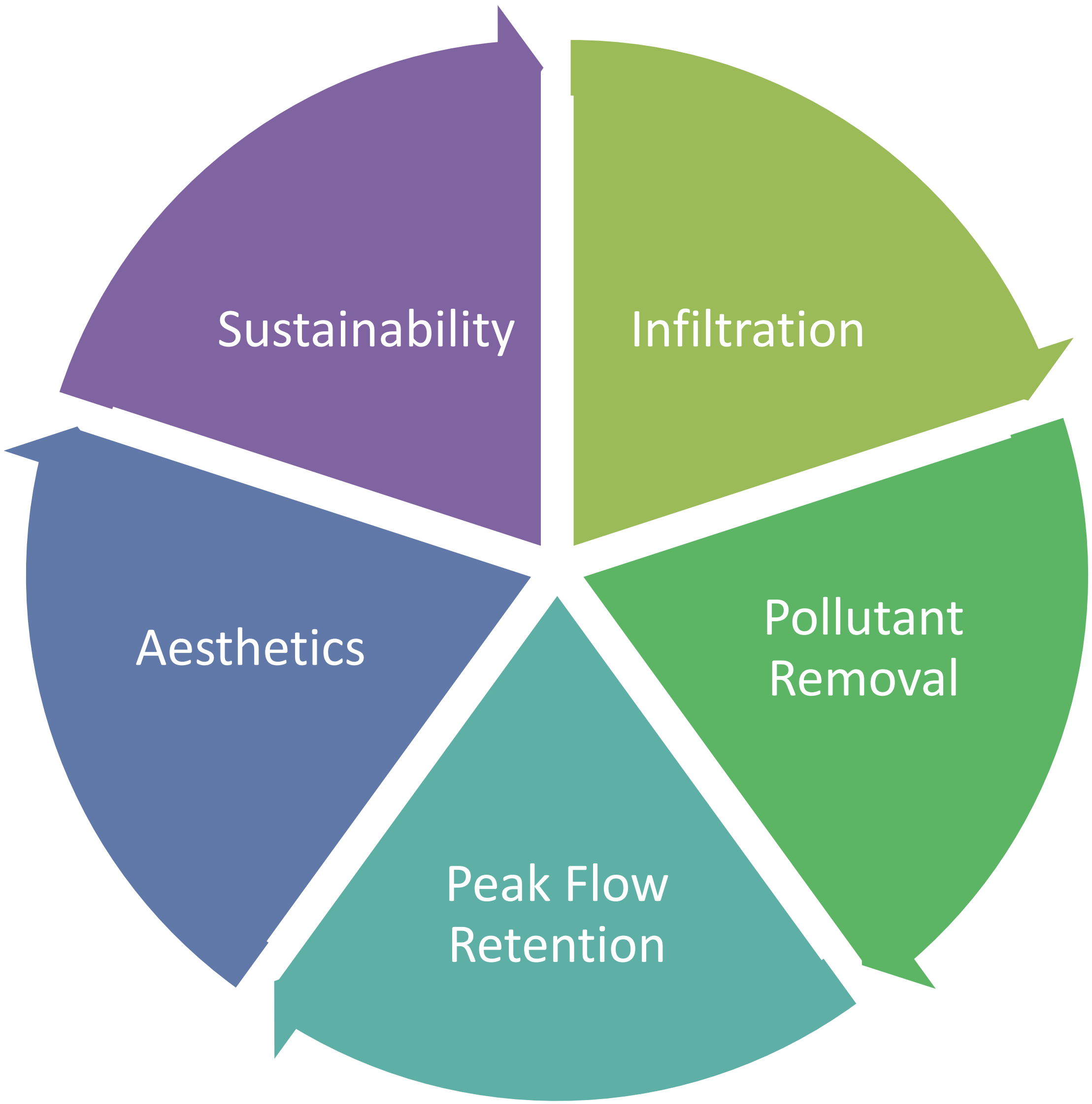


National Objectives:

1. Increase federal coordination
2. Expand Clean Water Act regulatory support
3. Strengthen research and information exchange
4. Distribute funding and financing
5. Build local capacity

U.S. Environmental Protection Agency. (2013). *Green Infrastructure Strategic Agenda 2013*.

Goals of Bioretention



What is Bioretention?

Reference	Definition
Davis, A. P., Shokouhian, M., Sharma, H., & Minami, C. (2001). Laboratory Study of Biological Retention of Urban Stormwater. *Water Environment Research*, *73*(1), 5–14.	• Layers of **soil, mulch**, and a variety of **plant** species. • Soil: **high sand content** to provide rapid infiltration but with **low** levels of **silt** and **clay** • Covered with thin layer of **wood mulch** to prevent erosion and protect the soil layer from drying.
Vermont Agency of Natural Resources. (2002). The Vermont Stormwater Management Manual Volume I - Stormwater Treatment Standards (Vol. I).	• **Shallow** depression that treats stormwater as it flows through a **soil** matrix, and is returned to the **storm drain** system
Collins, K. et al., (2010). Opportunities and challenges for managing nitrogen in urban stormwater: A review and synthesis. *Ecological Engineering*, *36*(11), 1507–1519.	• **Shallow, vegetated** depressions, back- filled with **soil** filter media that is designed to accept and infiltrate stormwater.

What is Bioretention?

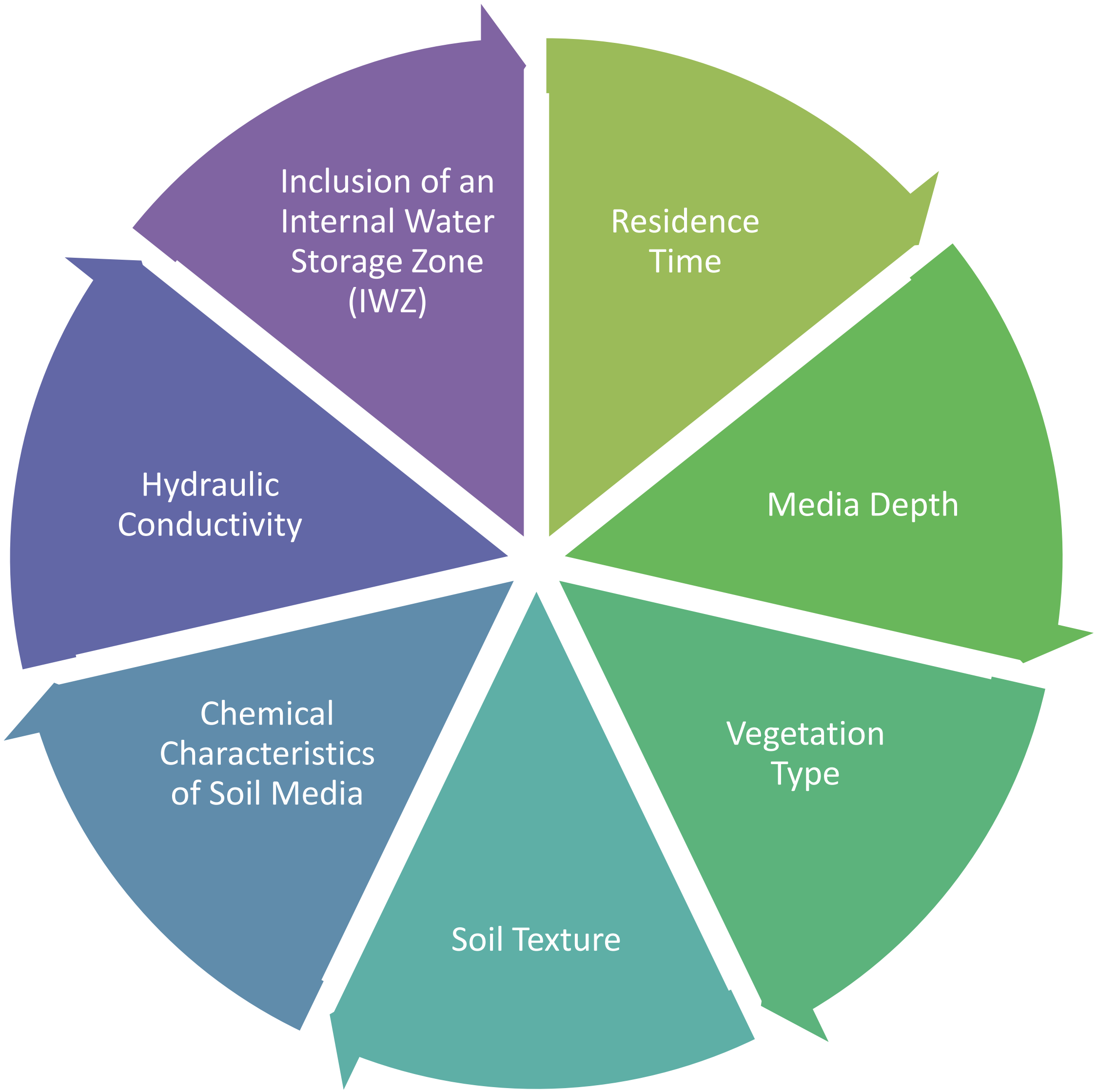
Reference	Definition
Claytor, R. A., & Schueler, T. R. (1996). *Design of Stormwater Filtering Systems* (pp. 1–220).	The term stormwater filter refers to a diverse spectrum of stormwater treatment methods utilizing various media, such as sand, peat, grass, soil or **compost** to filter out pollutants entrained in urban stormwater.
Department of Environmental Quality, Michigan. (2008). *Low Impact Development Manual for Michigan: A Design Guide for Implementers and Reviewers*.	Bioretention soils should be amended with a composted organic material. A recommended range of a soil mixture is **20-40 percent organic material (compost)**, 30-50 percent sand, and 20-30 percent topsoil, although any soil with sufficient drainage may be used for bioretention.
Washington State University Pierce County Extension. (2012). *Low Impact Development Technical Guidance Manual for Puget Sound*.	The bioretention soil media (BSM) placed in the cell or swale is typically composed of a highly permeable sandy mineral aggregate **mixed with compost**.

What is Bioretention?

Definition: bioretention systems are ecological engineered to reduce peak flow rates and volumes while also removing stormwater pollutants through physical, biological, and chemical mechanisms.

Davis 2008; Dietz and Clausen 2006; Zinger et al. 2013; Collins et al. 2010.
Image Credits: Amanda Cording (left, middle) and EcoSolutions (right).

What Design Factors Influence Bioretention Performance?

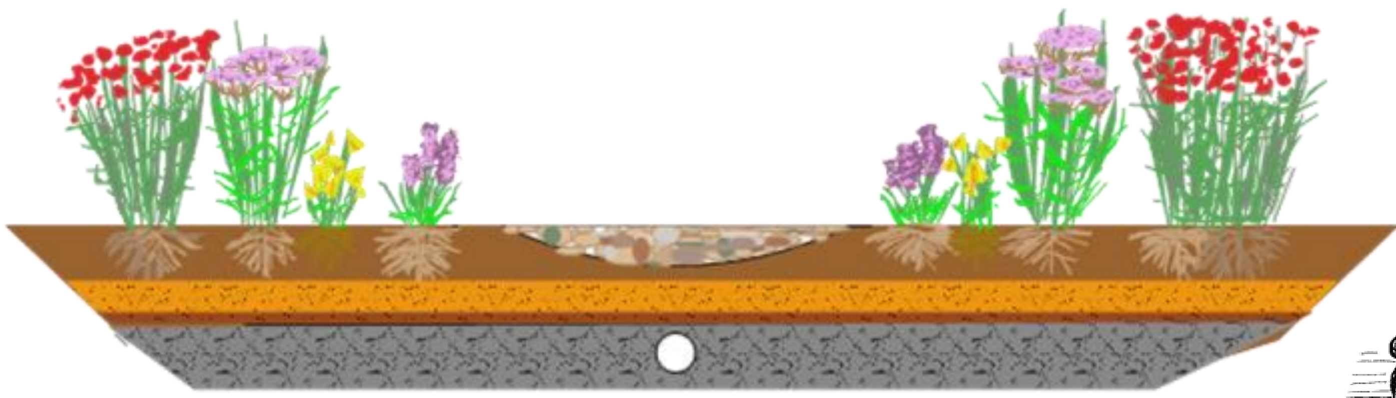


Bioretention: Nutrient Removal

Nutrient removal is extremely variable

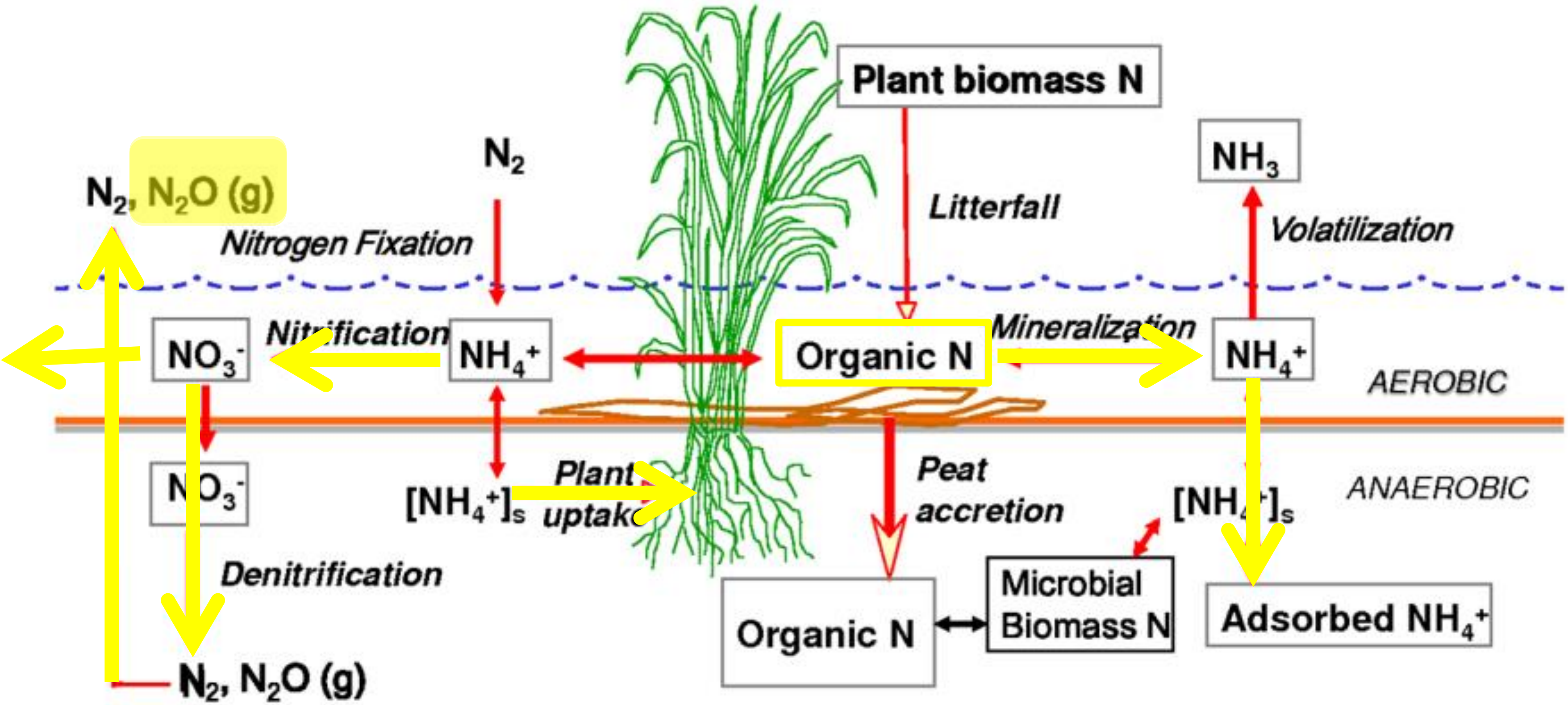
- Labile N (-630% to 98% removal)
- NO_3^- Effluent [ ] = 10 µg L^{-1} to 2,100 µg L^{-1}
- Labile P (-78% to 98% removal)
- SRP Effluent [ ] = < 10 µg L^{-1} to 2,200 µg L^{-1}

*Lake Champlain P Targets: **15 – 40 µg L^{-1}**



Davis et al. (2007); Bratieres et al. (2008); Debusk et al. (2011); Dietz and Claussen (2006); Hunt et al. (2006); O'Neill and Davis (2011); Image Credit: Amanda Cording

Nitrogen Removal Mechanisms



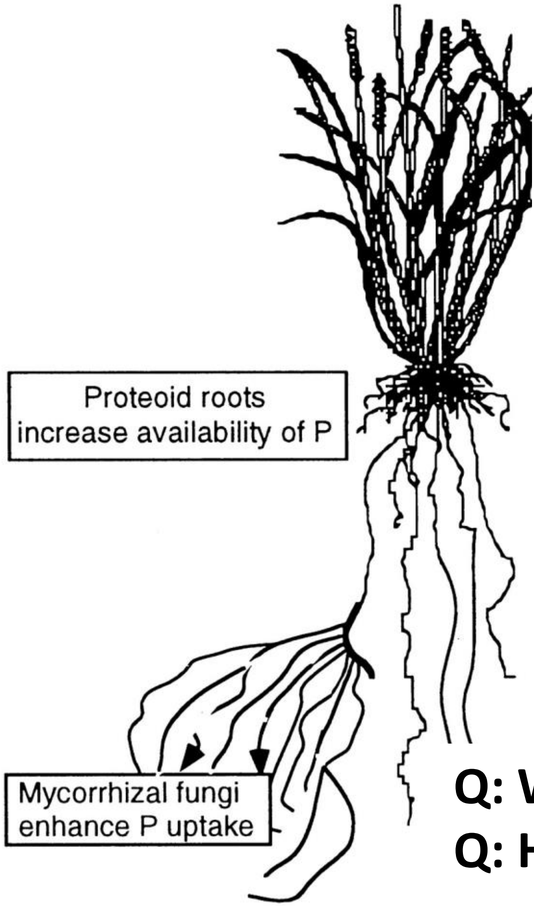
Q: Which mechanisms are dominant in bioretention?

Q: How can we maximize removal through design?

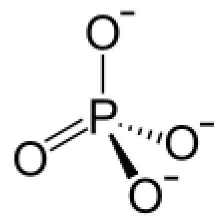
Q: Do the conditions encourage N_2O release or uptake?

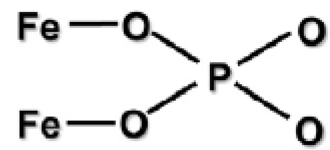
Davis et al. (2006); Bratieres et al. (2008); Kim et al. (2003); Charpuis-Lardy et al. (2007)

Phosphorus Removal Mechanisms



1. Physical Filtration: Non-labile P
2. Sorption of SRP: Fe, Ca, and Al in Soil





$$2{\equiv}FeOH^{-0.5} + PO_4^{3-} + 2H^+ = ({\equiv}FeO)_2PO_2^{2-} + 2H_2O$$

3. Plant Uptake: SRP

Q: Which mechanisms are dominant in bioretention?

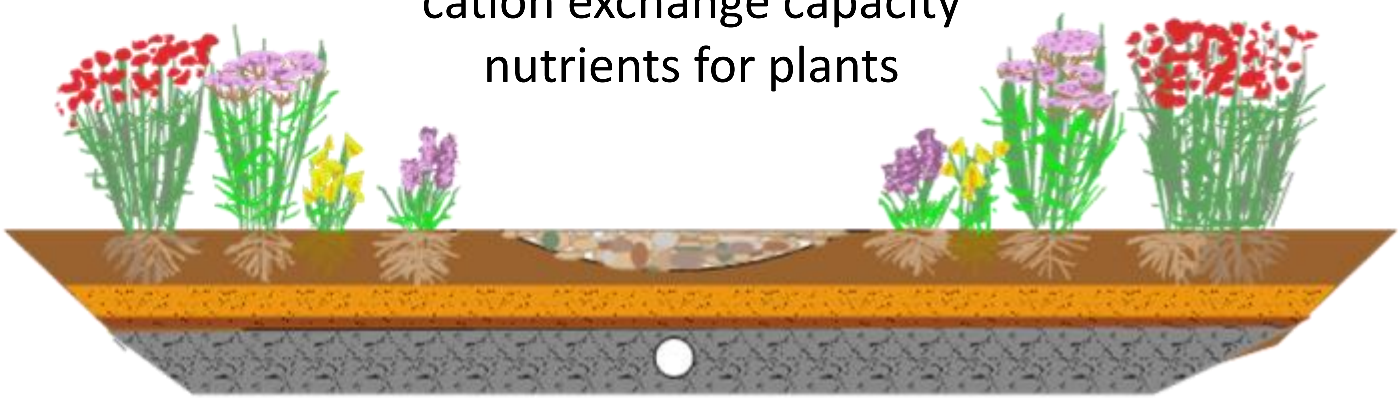
Q: How can we maximize removal mechanisms through design?

Tanner (1996); Arias et al. (2001); Lucas and Greenway (2011); Liping et al. (2012)

Inconsistent P Removal in Bioretention

- Some of the variability is thought to be attributed to the soil media selected
- Sand based bioretention soil designs are common
- Organic amendments (compost, mulch) are widely recommended to provide:

metals removal
soil moisture retention
cation exchange capacity
nutrients for plants



Bratieres et al. 2008; DeBusk and Wynn 2011; Michigan Department of Environmental Quality 2008; Thompson et al. 2008; Vermont Agency of Natural Resources 2002; Washington State University Pierce County Extension 2012.

Research Site: University of Vermont Outdoor Bioretention Laboratory

- Constructed in November of 2012
- Total area: approx. 5,000 ft^2 or 0.1 acres
- Eight small paved road sub-watersheds
- Bioretention Surface Areas: 29.73 m^2 to 120.12 m^2

Research Site

Bioretention Layout View

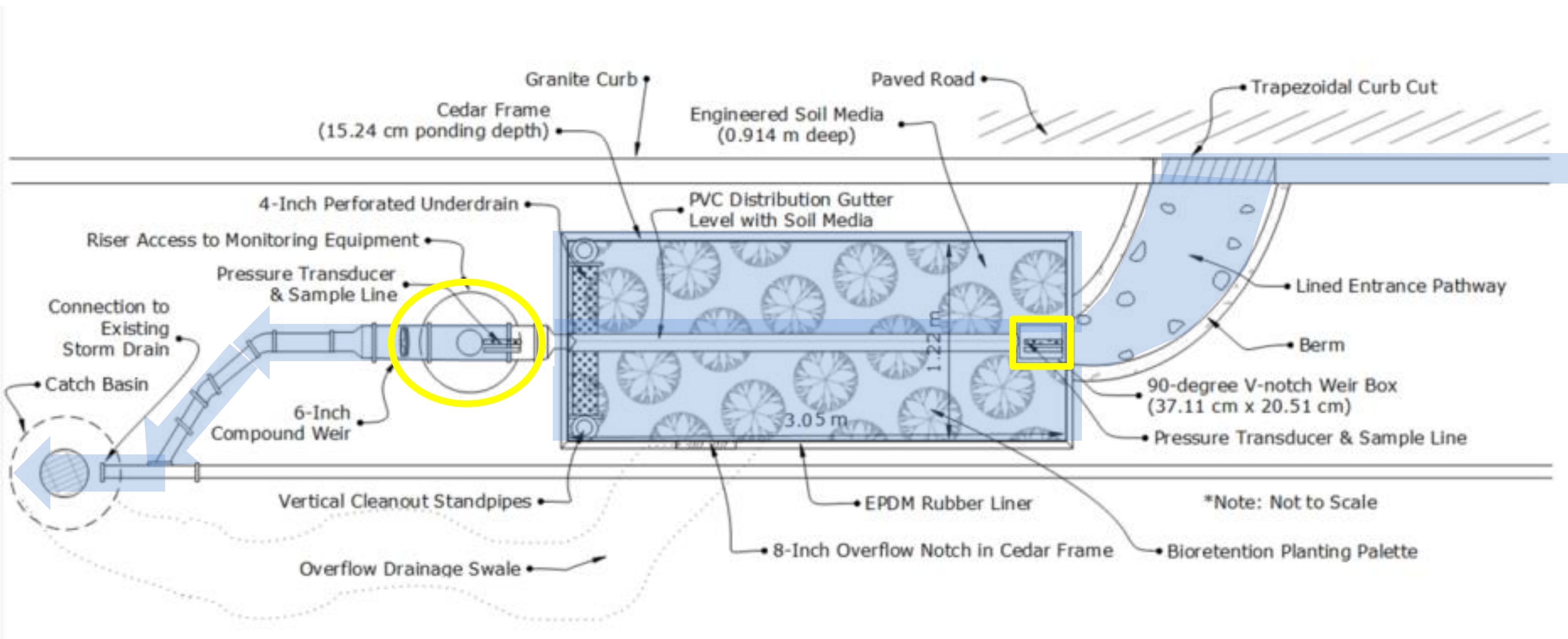
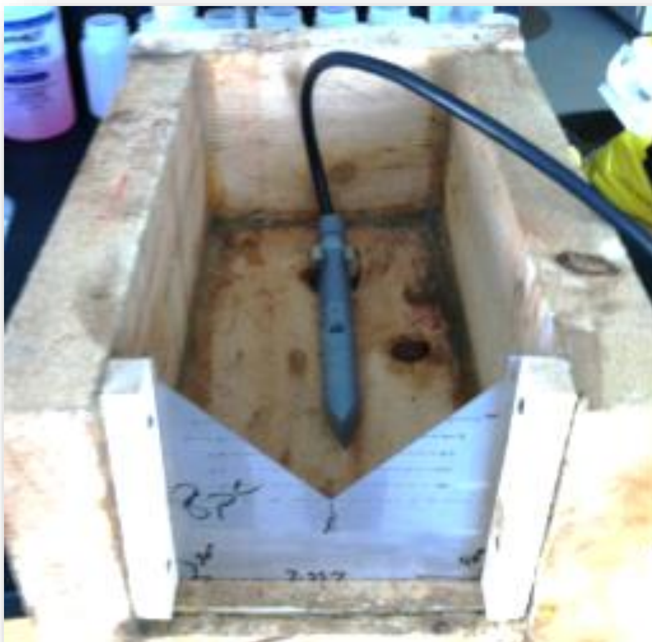


Image Reference: Cording, A., Hurley, S., Whitney, D. (**Submitted**) Monitoring methods and designs for evaluating bioretention performance. Journal of Environmental Engineering.

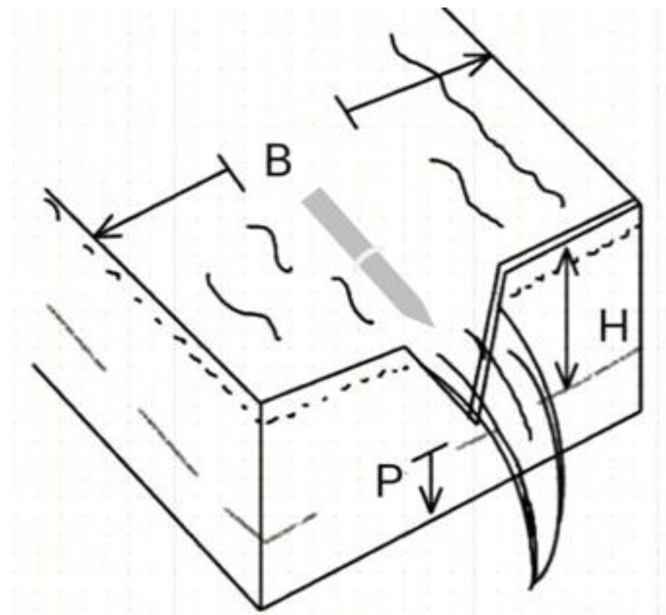
Monitoring Objectives:

Characterize stormwater mass loads from small paved road watersheds throughout the inflow and outflow hydrograph

How do you measure the runoff from the road surface?



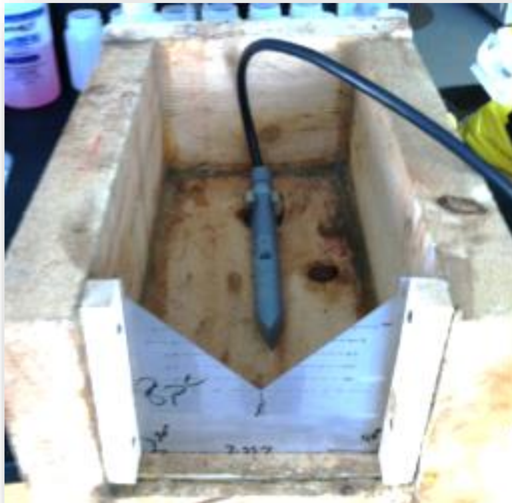
Weir thickness = 1.59 mm stainless steel
Teledyne™ ISCO Model 720 Pressure Transducer



Maximum Capacity = 10.05 L

ASTM –D5242; U.S. Bureau of Reclamation (2001)

Monitoring Bioretention Systems



Inflow 90° Weir Box

Outflow Thel-Mar™ Weir

$$Q=CH^{n}$$

Where:

Q = flow rate over the weir (cfs, L s^{-1})

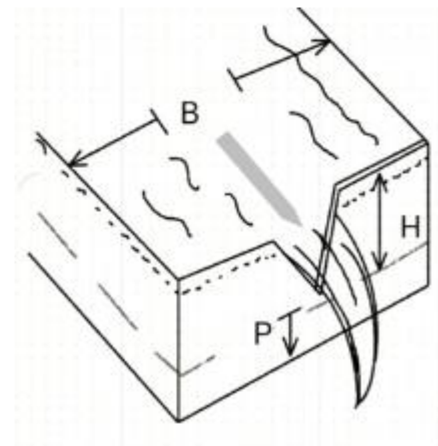
C= coefficient of discharge, or weir coefficient

H= height of water behind the weir (pressure transducer)

n = an empirical exponent (dimensionless)

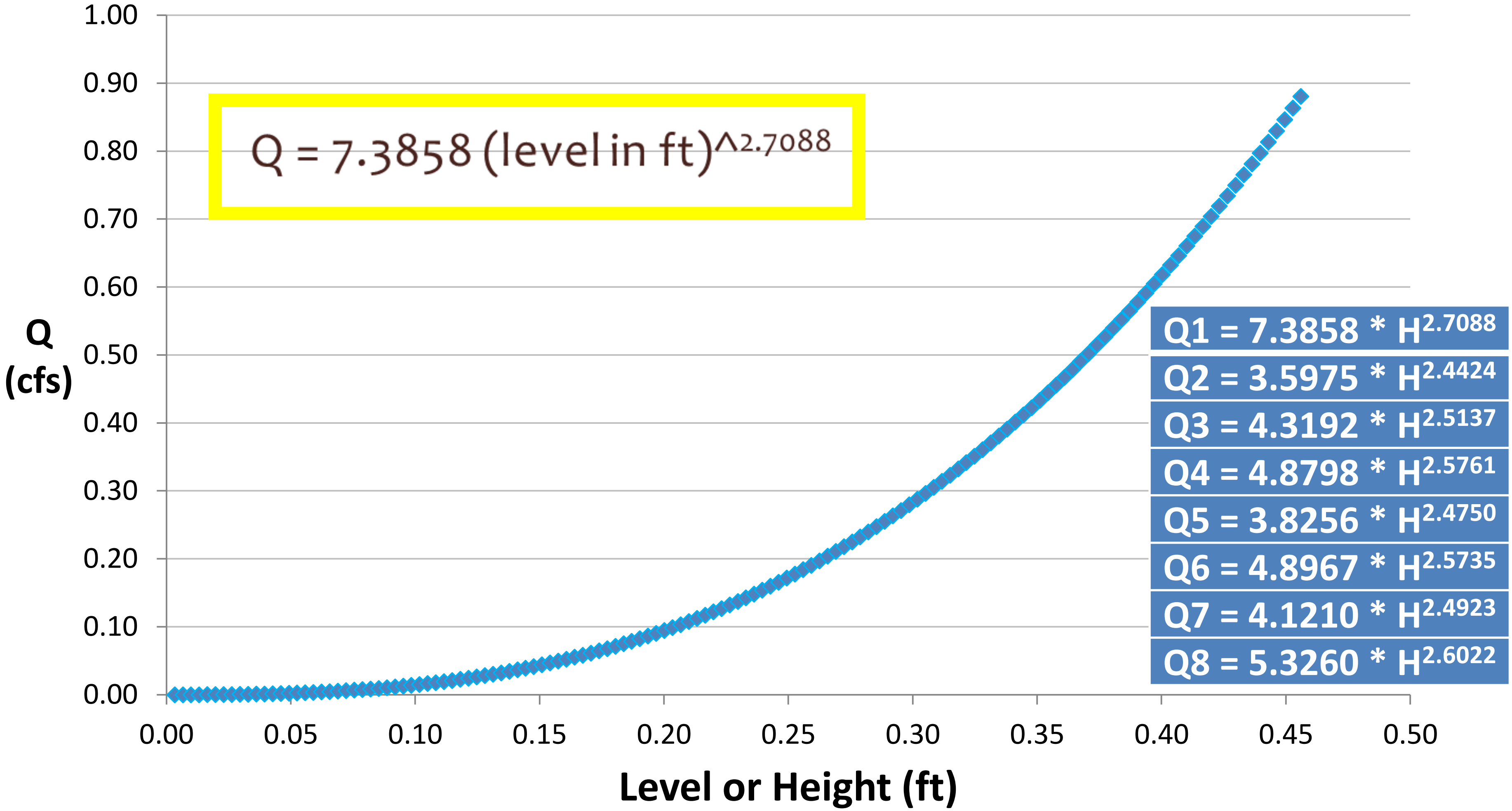
Inflow Monitoring: Weir Rating Curve

$Q=CH^n \rightarrow \log Q = \log C + n \log H \rightarrow \log Q = n \log H + \log C$

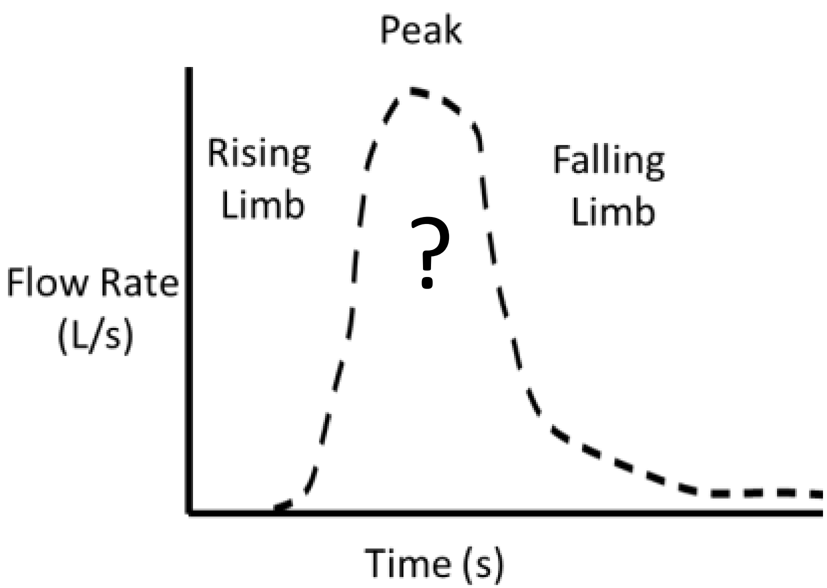


1. logQ = nlogH + logC -> y = mx + b, to get the values of C and n
2. Plot Q (Y-axis) and *H* (x-axis) on a log-log plot
3. The equation of the line contains weir coefficient and exponent

Developing a Weir Rating Curve



How to Capture the Inflow Hydrograph?



Time-Based Sampling:

- ✓ Homogeneous paved surface
- ✓ Small watersheds

1. Time of concentration (T_c) -> intensity duration frequency (IDF) curve
2. Rainfall intensity -> peak discharge with the rational method
3. Select the rainfall depth you want to sample (0.9 inches)

Harmel et al. 2003; Sansalone and Cristina 2004

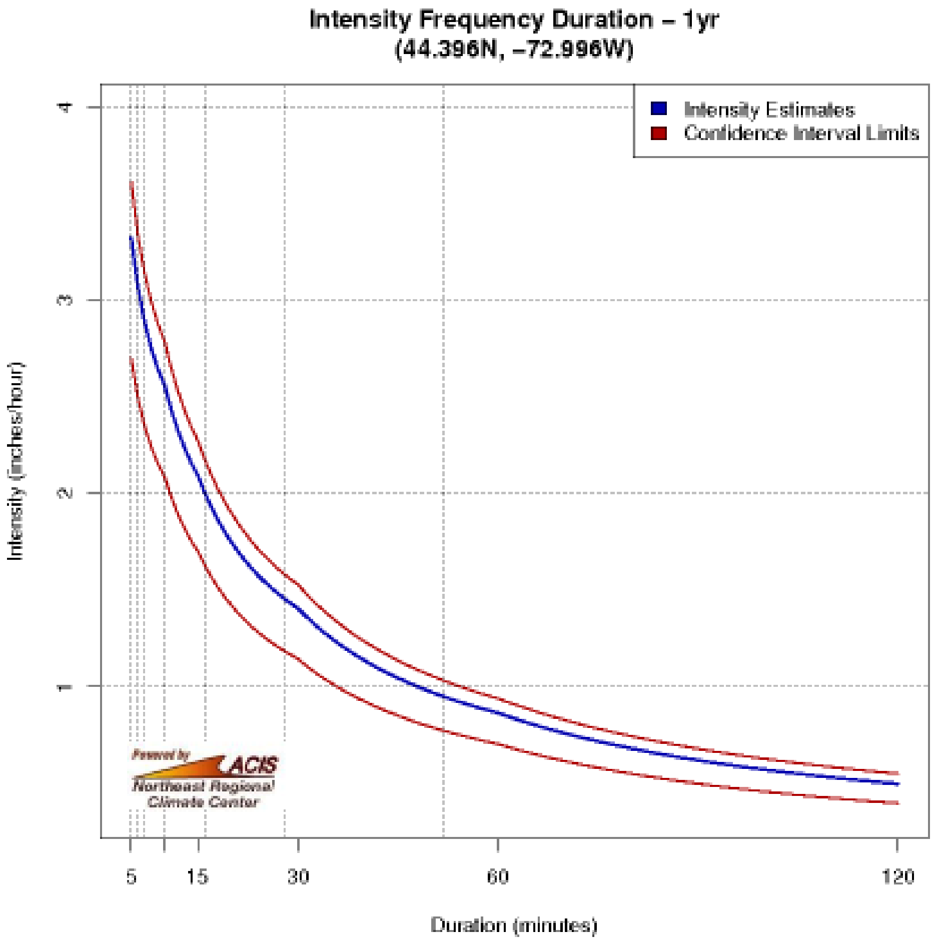
Capturing the Inflow Hydrograph: Estimating Time of Concentration

$$Tc = \frac{G\,(1.1 - C)L^{0.5}}{(100\,S)^{1/3}}$$

Where,
T_c is the time of concentration (min)
G is equal to 1.8 (FAA method, constant)
C is the runoff coefficient using the rational method (dimensionless)
L is the longest distance from the fixed location within the watershed (ft)
S is the slope of the watershed (ft ft^{-1}or m m^{-1})

T_c = 4.73 minutes to 8.27 minutes

Capturing the Inflow Hydrograph: Estimating Rainfall Intensity with the Intensity Duration Frequency Curve



Rainfall intensity:
3.32 in hr^{-1} (2.34×10^{-5} m s^{-1}) to
2.57 in hr^{-1} (1.81×10^{-5} m s^{-1})

Northeast Regional Climate Center Precipitation Data

Capturing the Inflow Hydrograph: Estimating Peak Flow Rate using the Rational Method

$$Q = C_f * C_i * A$$

Where,
Q is the peak discharge, or flow rate ($ft^3\ s^{-1}$, $m^3\ s^{-1}$, $L\ s^1$)
C_f is the runoff coefficient (dimensionless)
C_i is the rainfall intensity ($ft\ s^{-1}$ or $m\ s^{-1}$)
A is the drainage area (ft^2 or m^2)

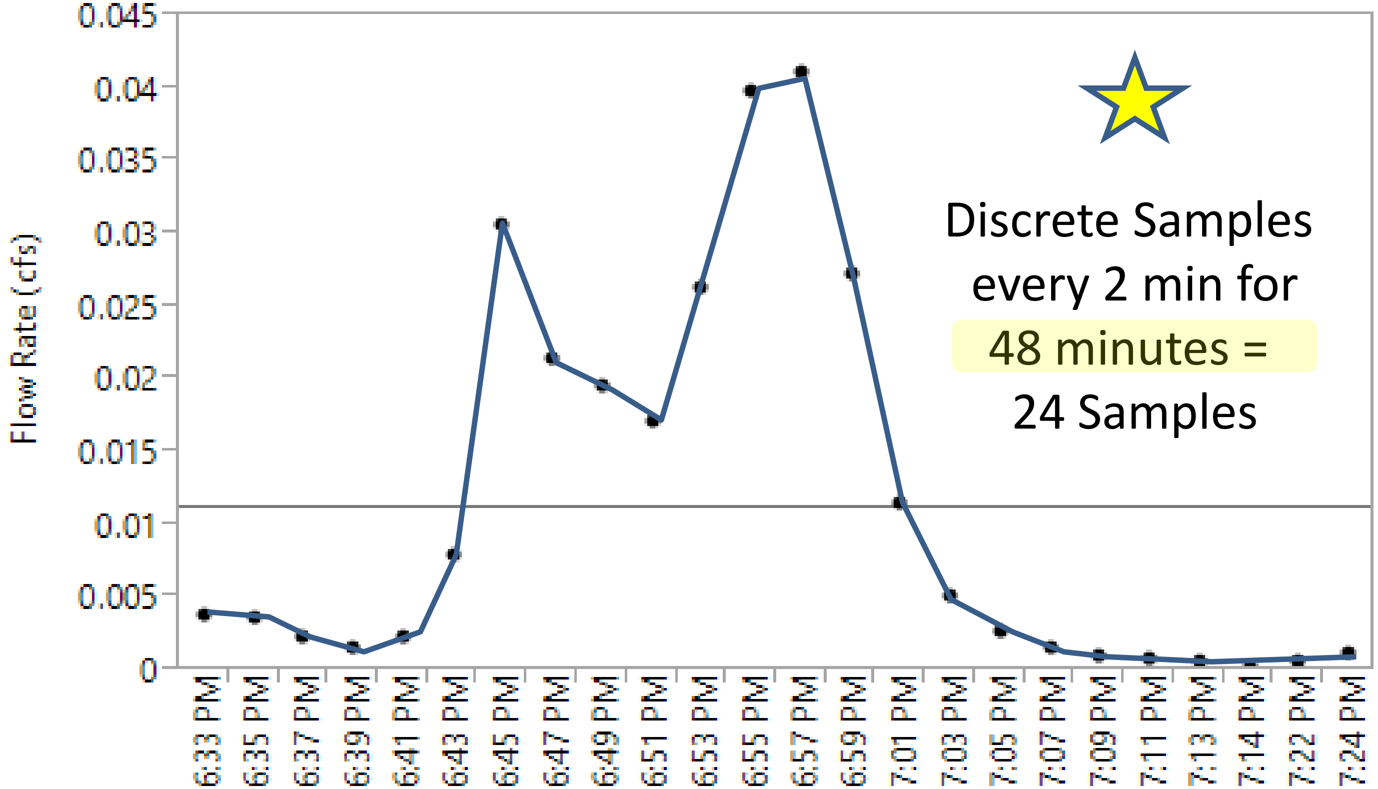
Q_{peak} = 0.02 to 0.07 $ft^3\ s^{-1}$

Natural Resources Conservation Service (1986)

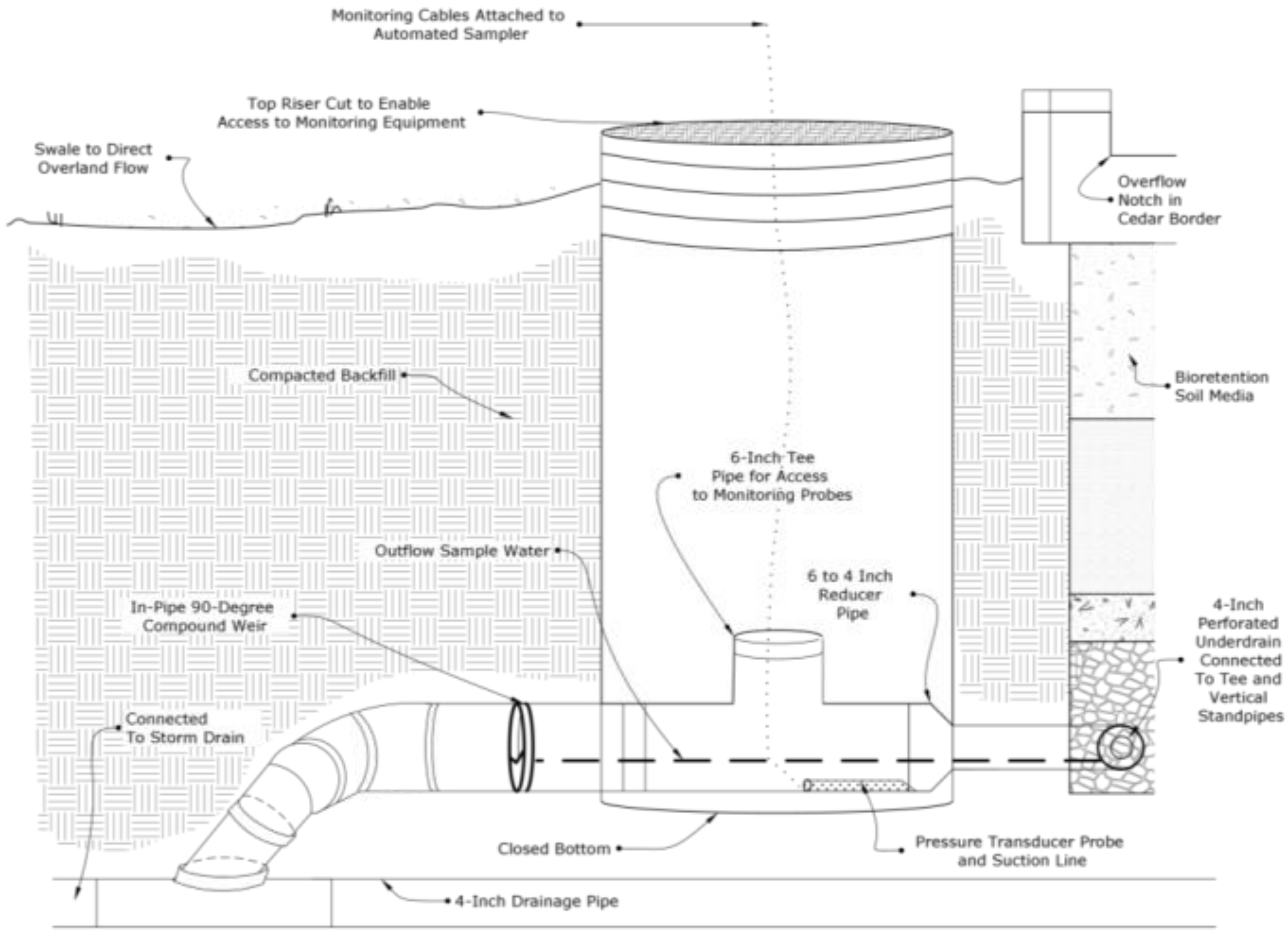
Sampling the Inflow Hydrograph

$$Time = \frac{watershed\ area\ x\ rainfall\ depth}{peak\ flow\ rate}$$

Time to Monitor Inflow Hydrograph (0.9 inch) = 34 to 48 minutes



What infrastructure do you need to measure the outflow from bioretention?



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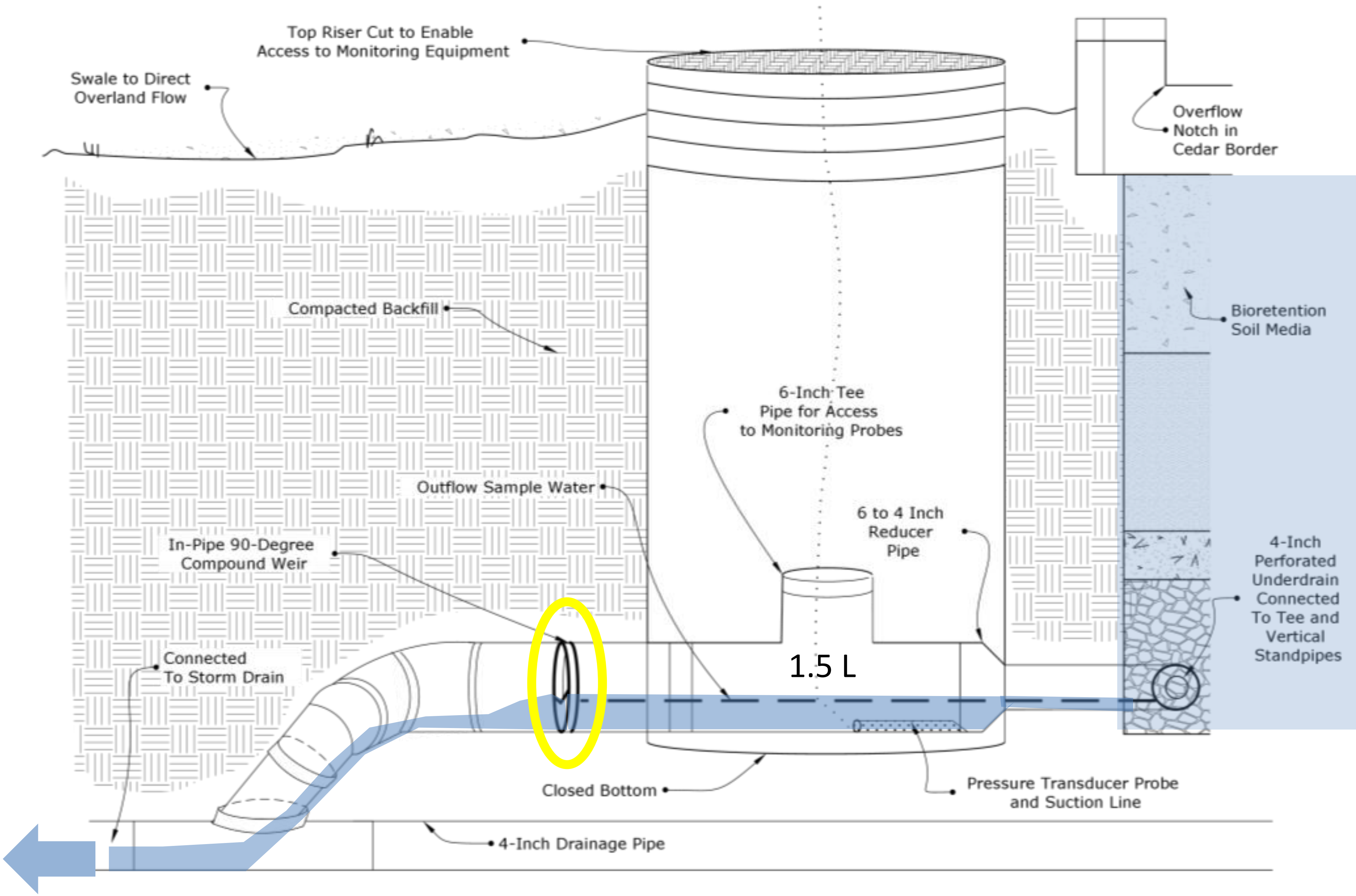
How to Capture the Outflow Hydrograph?



Capturing the Outflow Hydrograph: Estimating Hydraulic Conductivity

$$K_z = \frac{D}{\sum_{i=1}^{n} \frac{d_i}{k_i}}$$

Where,
K_z is the vertical hydraulic conductivity for the layered system (m s^{-1})
D is the total cumulative depth of the layers (m)
d_i is the depth of a given layer (m)
k_i is the hydraulic conductivity of a given layer (m s^{-1})

$$K_x = \sum_{i=1}^{n} \frac{K_i d_i}{d}$$

Where,
K_x is the horizontal hydraulic conductivity (m s^{-1})
d_i is the depth of a given layer (m)
K_i is the hydraulic conductivity of a given layer (m s^{-1})
d is the horizontal distance of the given layer (m)

Conventional Bioretention Design

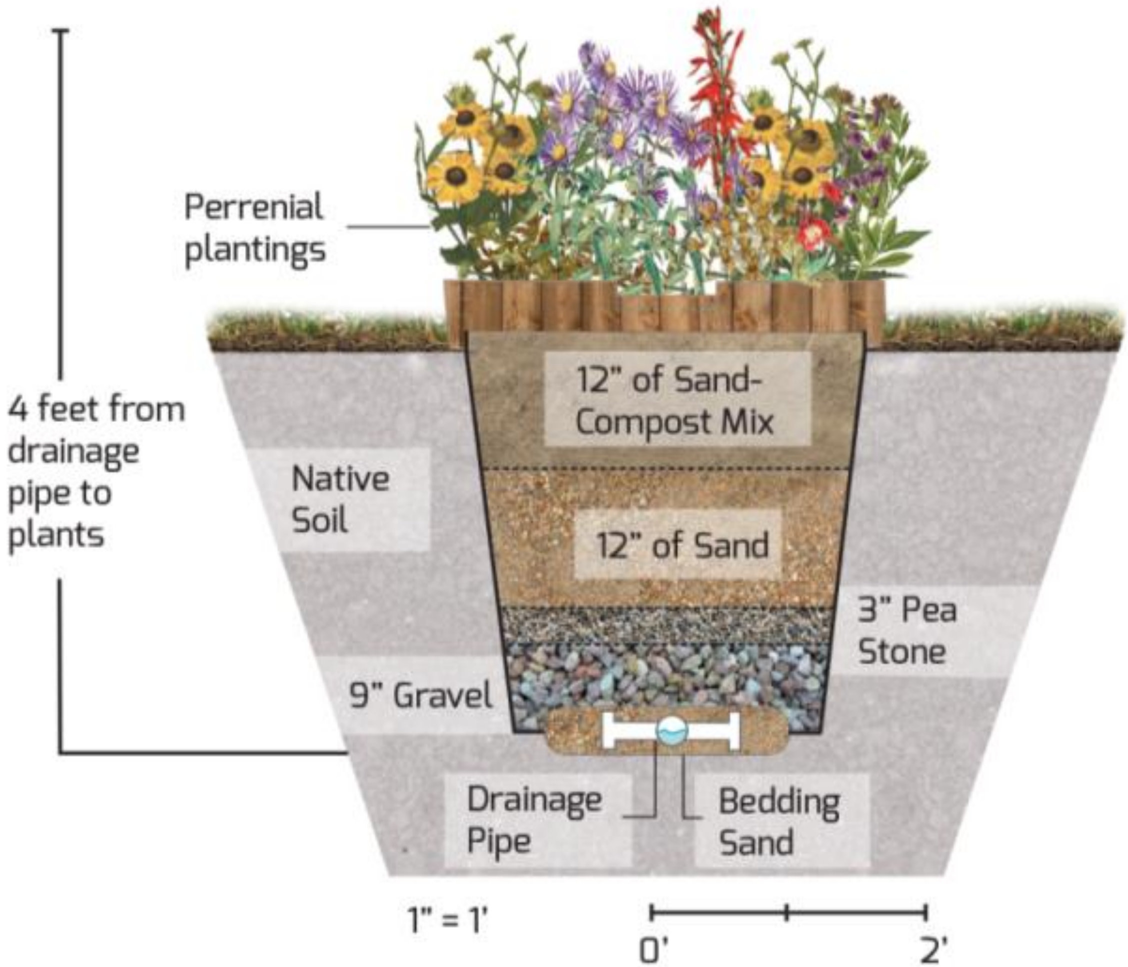


Image Reference: Cording, A., Hurley, S., Adair, E., Ross, D. (2017). *Evaluating critical bioretention designs features in the context of climate change*. Manuscript in Preparation

Capturing the Outflow Hydrograph: Estimating Hydraulic Conductivity

Bioretention Media	Depth (m)	Hydraulic Conductivity (m s^{-1})	d_i/k_i
Sand/Compost Mixture	0.3048	1.50E-04	2.03E+03
Medium Sand	0.3048	6.90E-04	4.42E+02
Pea Gravel	0.0762	6.40E-03	1.19E+01
Gravel	0.2286	9.14E-03	2.50E+01
Total d_i/k_i = 2.51E+03			
Total Depth = 0.9144 m			
K_z (m s^{-1}) = 3.64E-04			

K_z = 131.04 cm hr^{-1} or 51.59 in hr^{-1}

Media Infiltration Rates

Reference	Infiltration Rate
This study	Modelled Rate at Installation: 131 cm hr^{-1}
Arias et al (2001)	Actual Rate: 463 cm hr^{-1}
Brix et al. (2001)	Actual Rate: 92 cm hr^{-1}
Chen et al (2013)	Actual Rate: 1.3 cm hr^{-1}
Davis et al. (2009)	Recommends > 2.5 cm hr^{-1}
Debusk et al. (2011)	Actual Rate: 11.8 cm hr^{-1}
Dietz and Clausen (2005)	Design Rate: 10 – 13 cm hr^{-1}. Actual Rate: 3.5 cm hr^{-1}
Hatt et al. (2008)	Actual Rate: 26.028 cm hr^{-1} to 232.92 cm hr^{-1} in different treatments
Hunt et al. (2006)	Actual Rate: 7.62 cm hr^{-1} to 38.1 cm hr^{-1}
Li and Davis (2008)	Actual Rate: Reduction from 43 – 164 cm hr^{-1} to 3-11 cm hr^{-1}
Lucas and Greenway (2011)	Vegetated: 27.7 cm hr^{-1} to 59.6 cm hr^{-1}
Thompson et al. (2008)	Actual Rate: 150 to 178 cm hr^{-1} (sand/compost mix)
Washington State University Pierce County Extension (2012)	Recommends > 2.54 cm hr^{-1}

Capturing the Outflow Hydrograph: Estimating Hydraulic Conductivity

$$K_z = \frac{D}{\sum_{i=1}^{n} \frac{d_i}{k_i}}$$

Where,
K_z is the vertical hydraulic conductivity for the layered system (m s^{-1})
D is the total cumulative depth of the layers (m)
d_i is the depth of a given layer (m)
k_i is the hydraulic conductivity of a given layer (m s^{-1})

$$K_x = \sum_{i=1}^{n} \frac{K_i d_i}{d}$$

Where,
K_x is the horizontal hydraulic conductivity (m s^{-1})
d_i is the depth of a given layer (m)
K_i is the hydraulic conductivity of a given layer (m s^{-1})
d is the horizontal distance of the given layer (m)

Estimating Hydraulic Conductivity

$$T = \frac{A_w D}{K_z A_{BR(z)}} + \frac{A_w D}{K_x A_{BR(\mathbf{x})}}$$

Where,

T is the time for the outflow peak to reach monitoring equipment (s)

A_w is the watershed area (m^2)

D is the selected rainfall depth (m)

K_z is the cumulative vertical hydraulic conductivity ($m\ s^{-1}$)

K_x is the horizontal hydraulic conductivity ($m\ s^{-1}$)

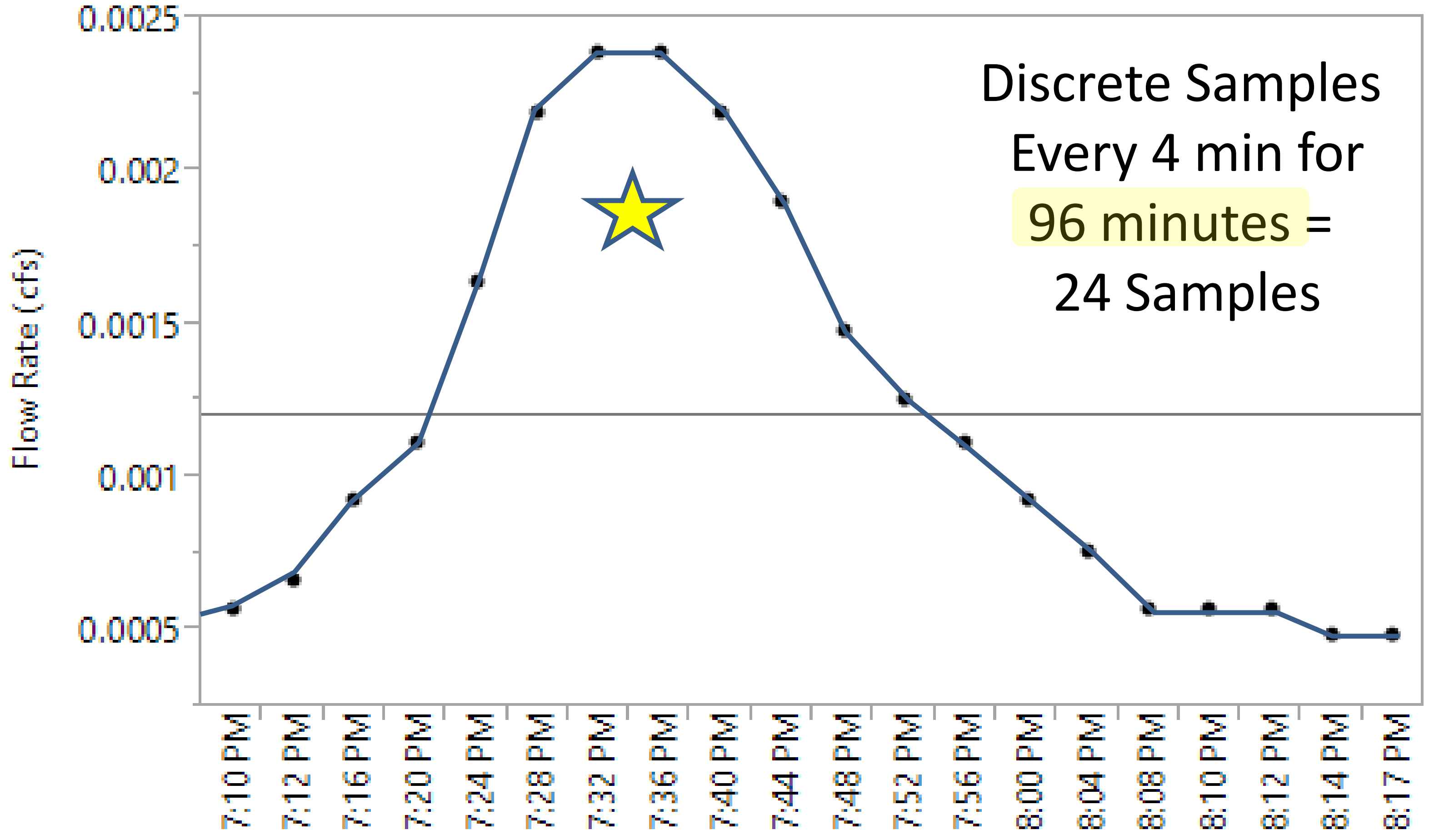
A_{BR} (z) is the vertical cross-sectional area along the Y-plane (m^2)

A_{BR} (x) is the vertical cross-sectional area of the layer directly above the flow impeding layer along the X-plane (m^2)

Time (0.9 inch storm) = 50 min + 40 min (inflow runoff travel time) = 90 min

Sampling the Outflow Hydrograph

Time Needed to Monitor Outflow Hydrograph = 90 minutes



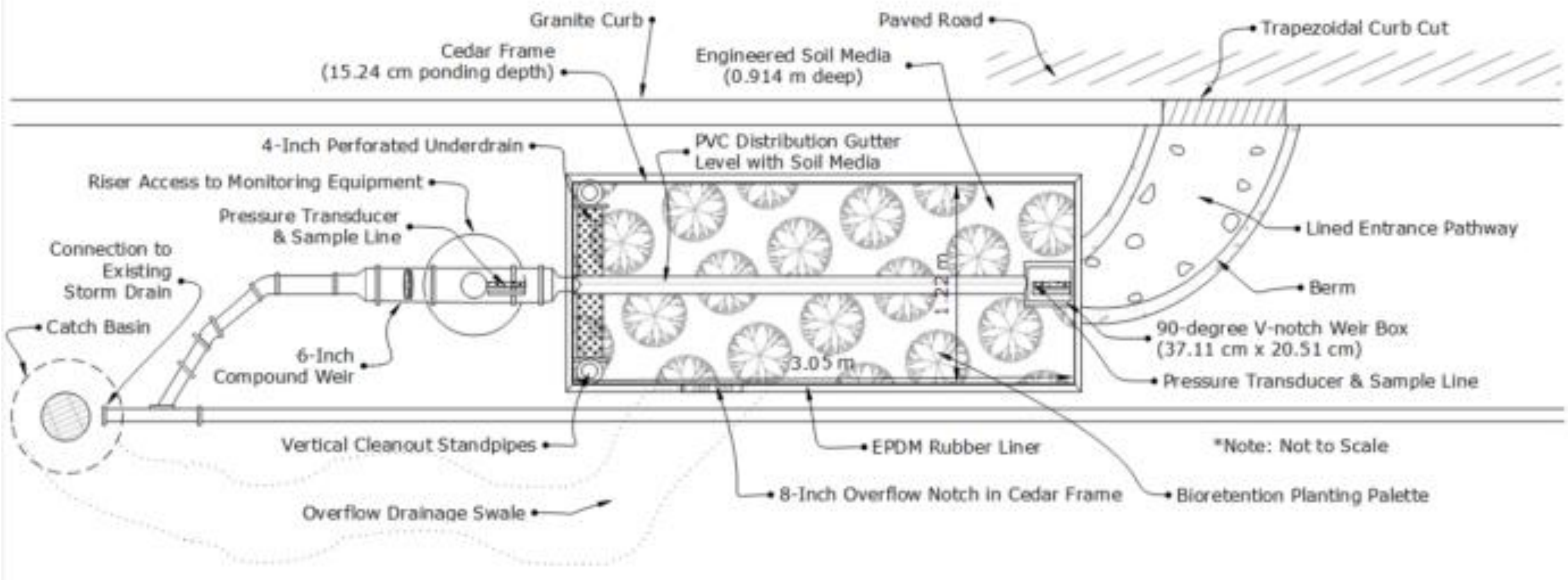
Installing Outflow Monitoring Equipment

Photo Credit: Amanda Cording (left), Paliza Shrestha (right)

Conclusions: Monitoring Methods and Designs for Evaluating Bioretention Performance

The inflow and outflow monitoring infrastructure/sampling method allowed for:

1. **multiple samples throughout the hydrograph**
2. **conversion of concentration to mass for any sample**
3. **the comparison of pollutant mass from inflow to outflow**



Plan View: Water into Curb Cut

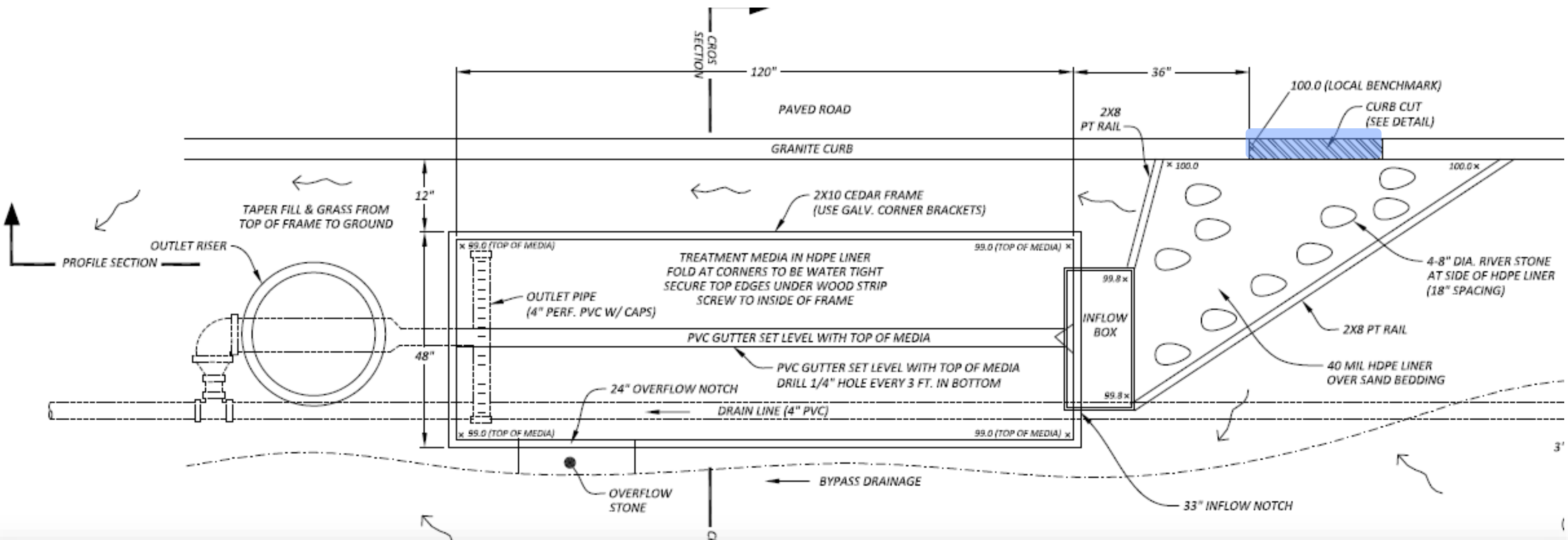
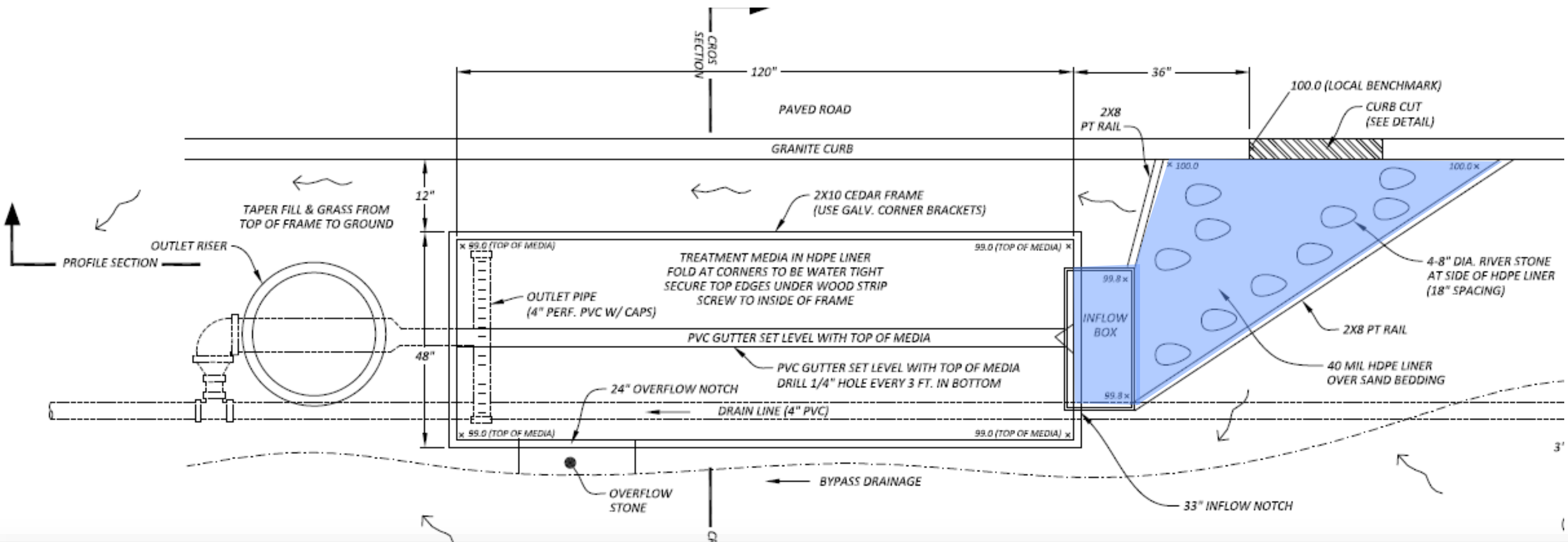
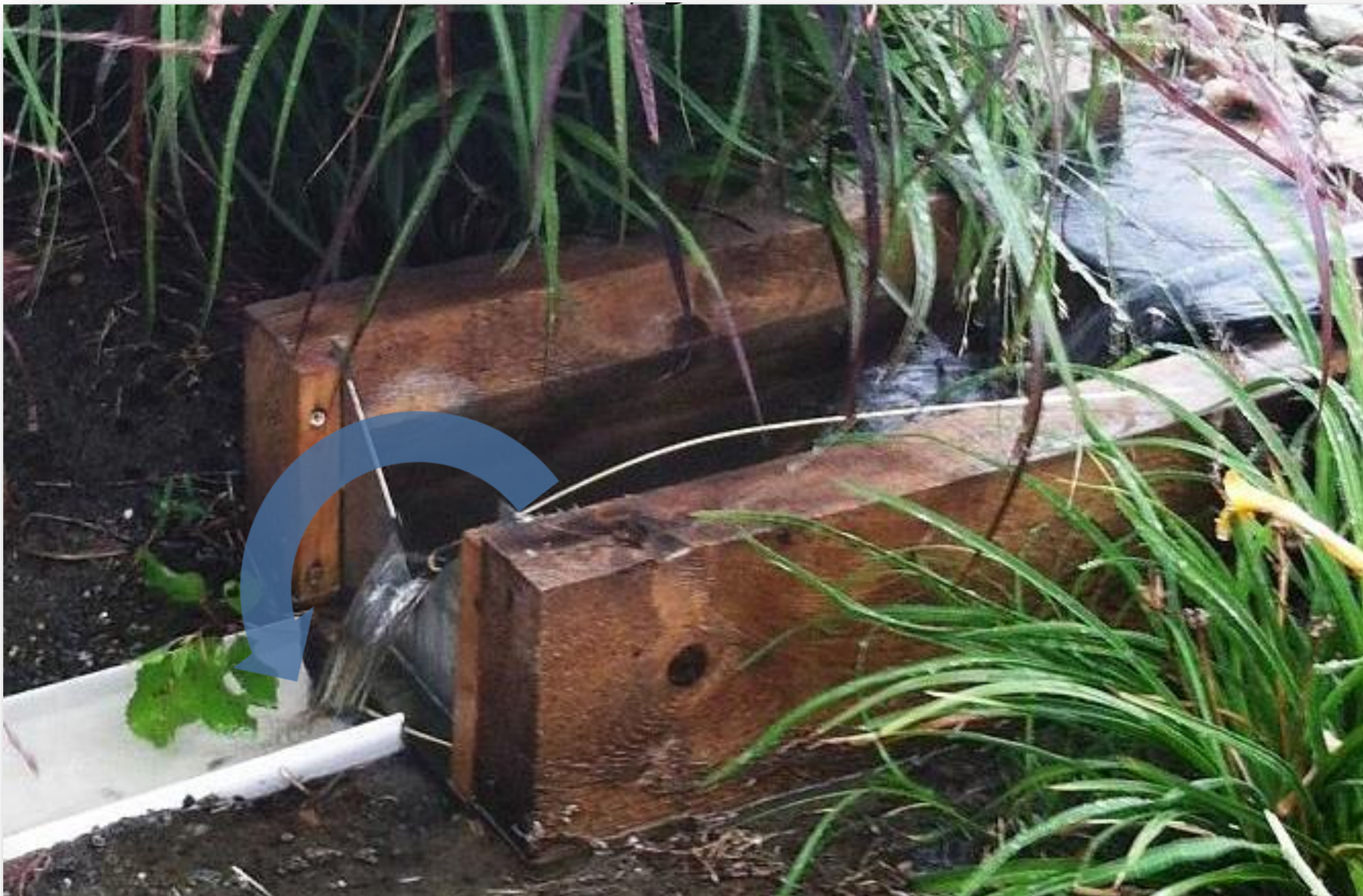


Photo Credit: Amanda Cording

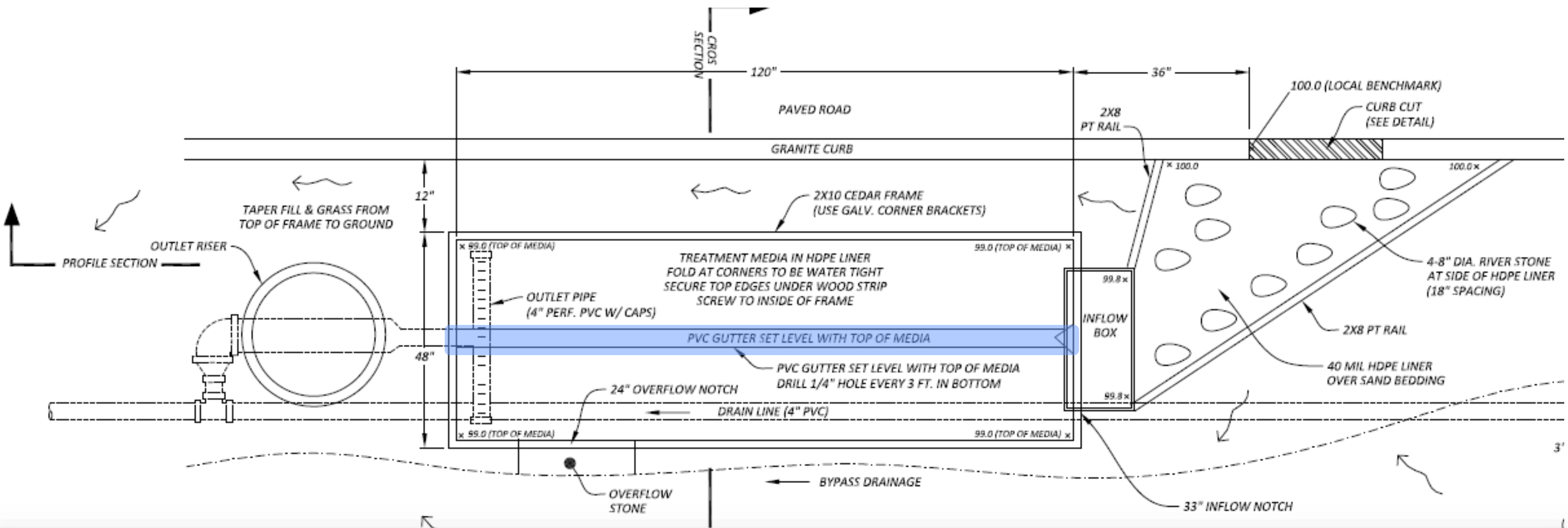
Plan View: Filter Strip



Inflow Monitoring Using 90º V-notch Weir Box

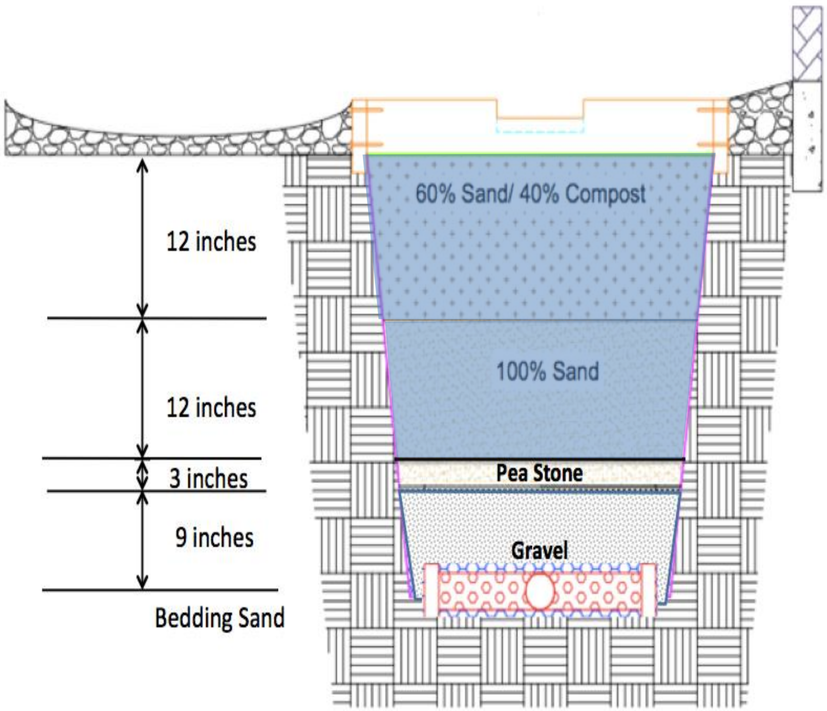


Plan View: Distribution Channel



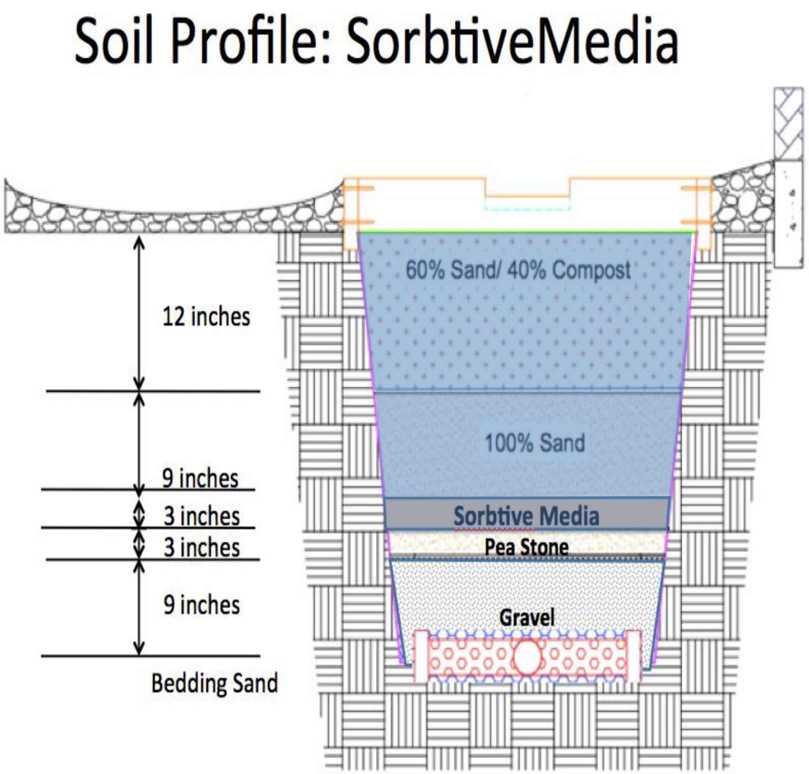
Bioretention Cell Construction

Soil Profile



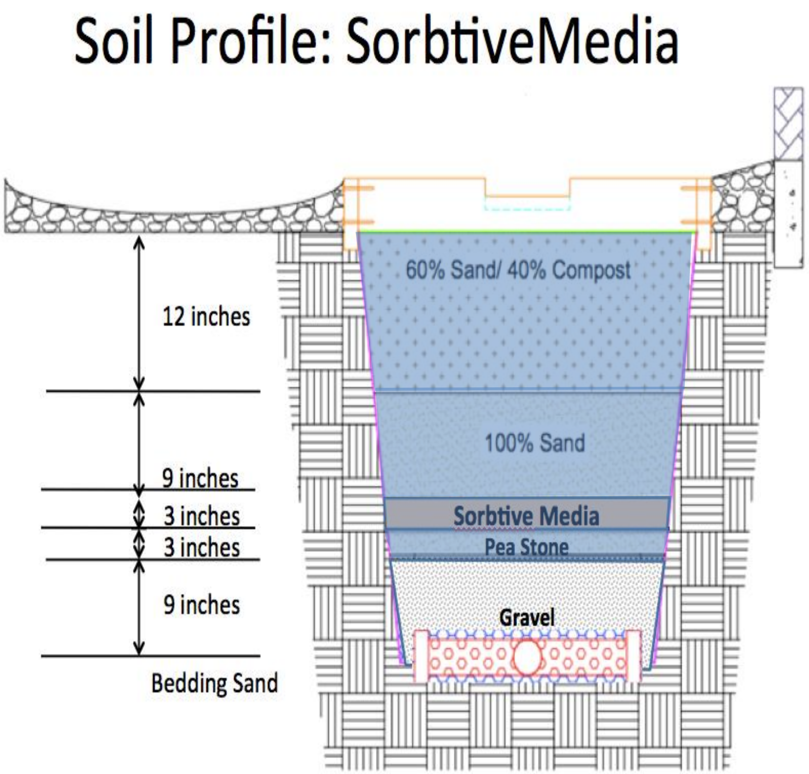
12” 60:40 sand/compost layer

Bioretention Cell Construction



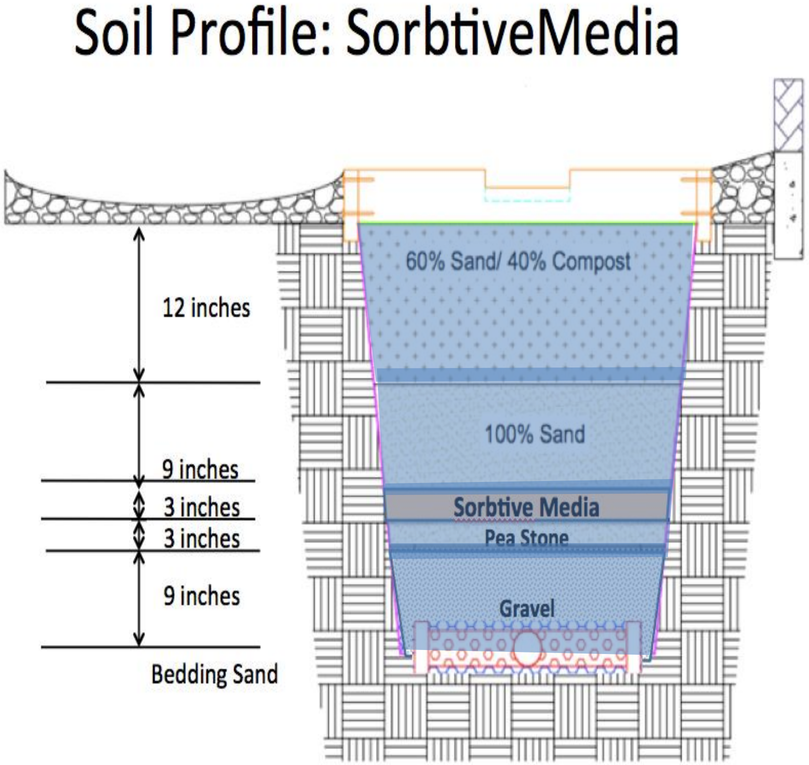
3” Imbrium Sorbtive Media™

Bioretention Cell Construction



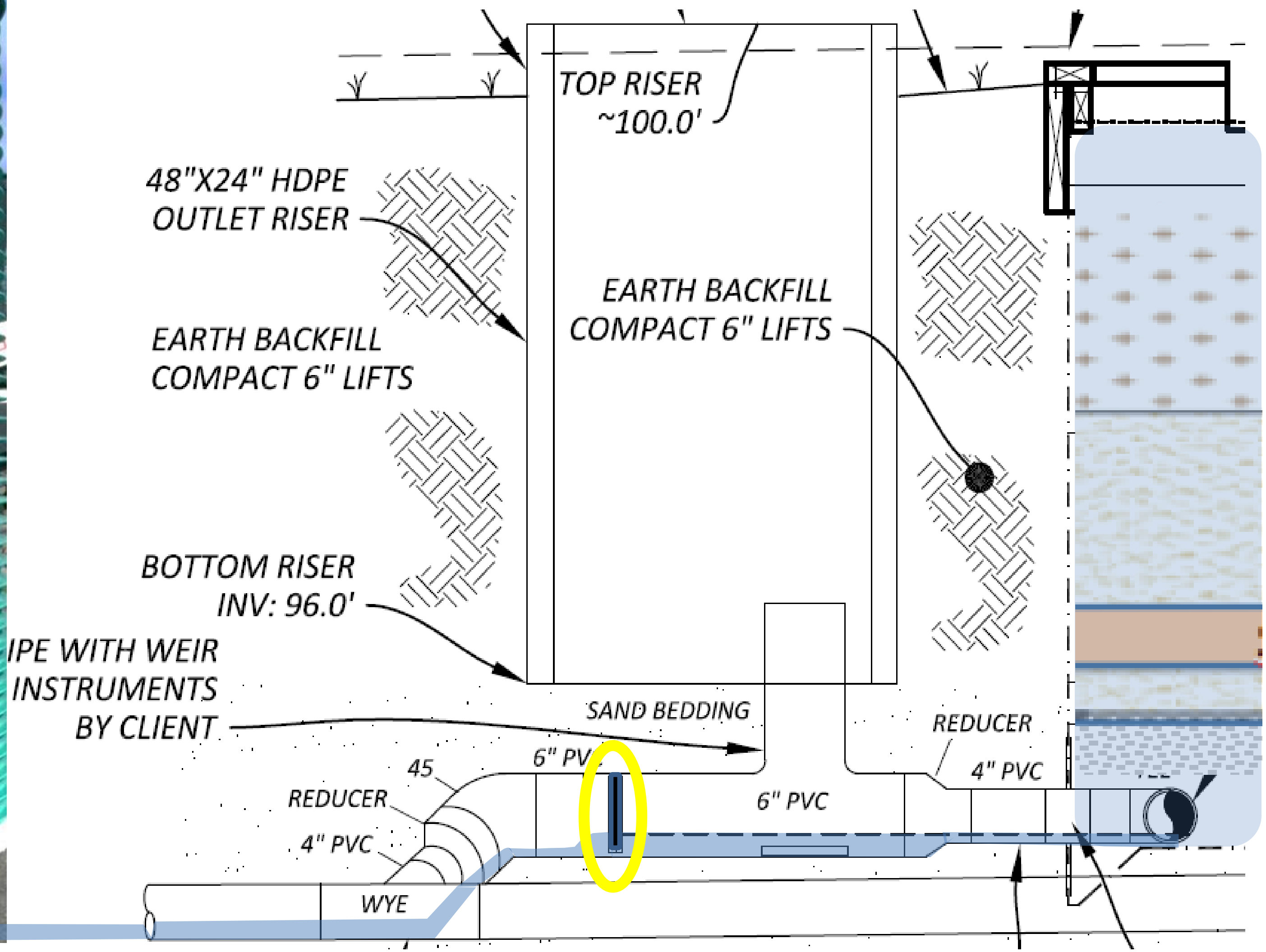
3” pea stone layer

Bioretention Cell Construction



9" gravel layer

Outflow Monitoring Using 6” In-Pipe Thel-Mar ™ Weir



Construction Complete: November 2012

Big thanks to Dave Whitney, EcoSolutions,
Andres Torizzo, Watershed Consulting , Imbrium Staff,
Arcana, Gardner's Supply, and Tri-Angle Metal Supply

Research Questions

1. How do you assess bioretention performance with monitoring?
   - What infrastructure do you need?
   - What sampling regime will capture the hydrograph?

2. What pollutant loads are coming off a medium traffic paved road?
   - Do nutrients and sediment mass exhibit a first flush effect?
   - Can we predict the total mass load from a precipitation event?

3. How do soil and vegetation influence bioretention performance?
   - Will increased precipitation due to climate change decrease bioretention performance?
   - Are bioretention cells a source or a sink for soil gas emissions?

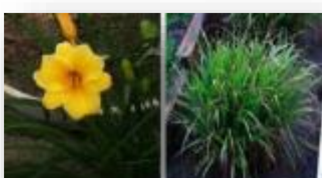
Testing Bioretention Performance Under Different Conditions

1. Soil Media: Conventional vs. Sorbtive Media™


2. Precipitation: Ambient vs. Increased due to Climate Change

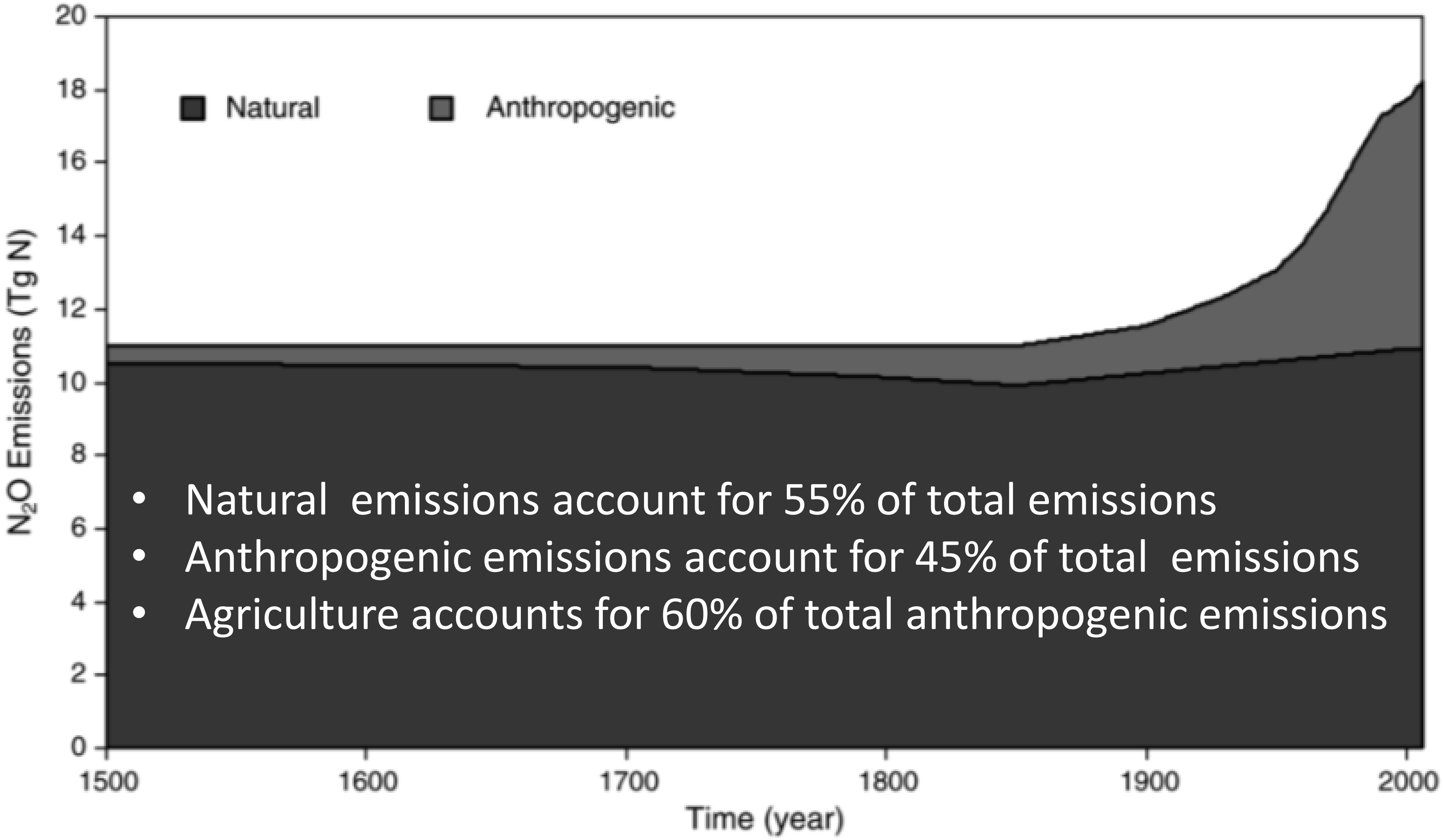
(20% increase in CM, 60% increase in SM)


3. Vegetation: Plant Palette 1 vs. Plant Palette 2




Bioretention: Source or Sink for N_2O and CH_4?

Nitrous Oxide (N_2O) Emissions

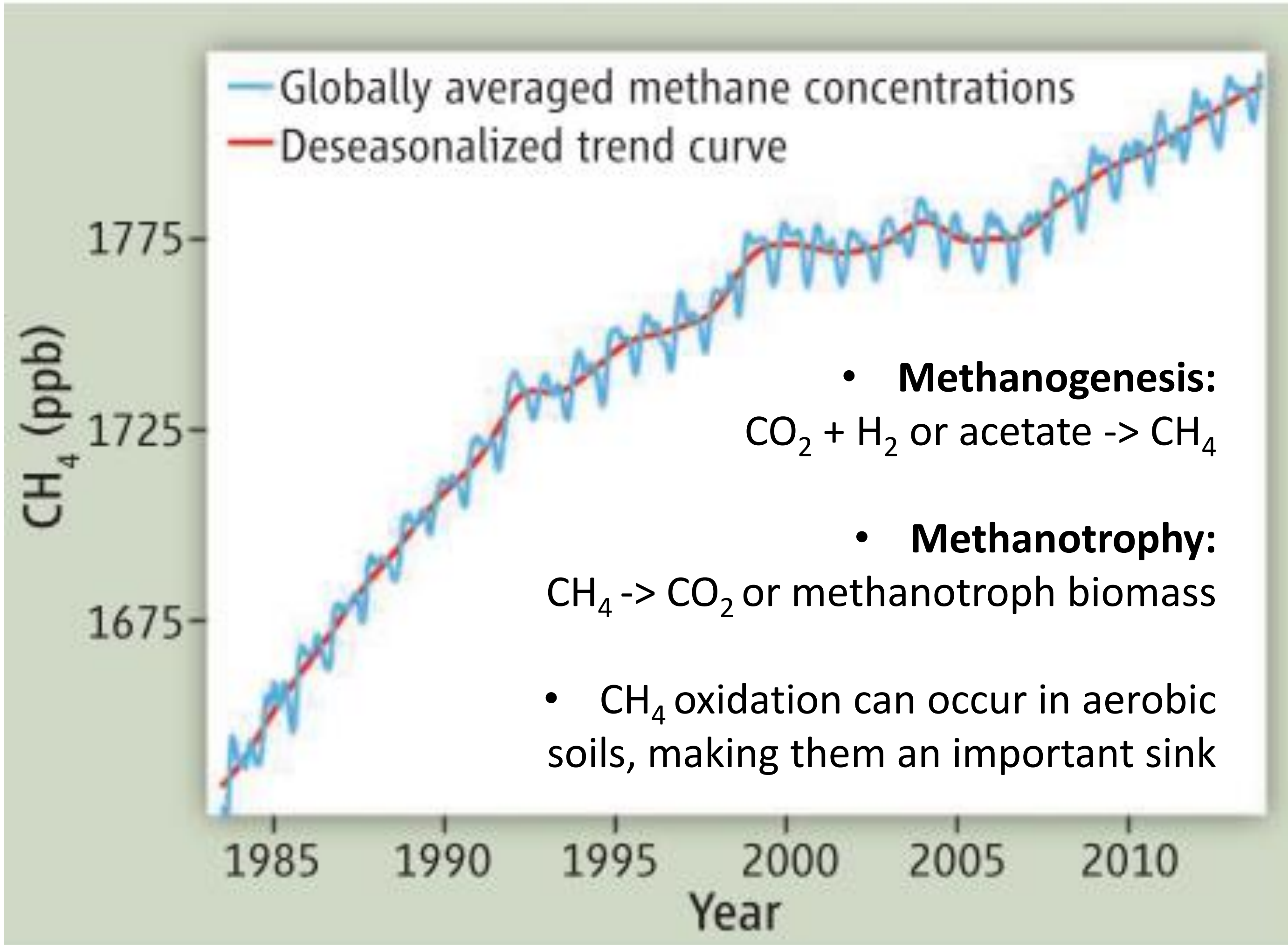


- Natural emissions account for 55% of total emissions
- Anthropogenic emissions account for 45% of total emissions
- Agriculture accounts for 60% of total anthropogenic emissions

Image Source: Syakila, A., & Kroeze, C. (2011).

Matson, P. A., & Harris, R. C. (1995); Firestone and Davidson (1989); Bond-Lamperty and Thomson (2010)

Methane (CH_4) Emissions



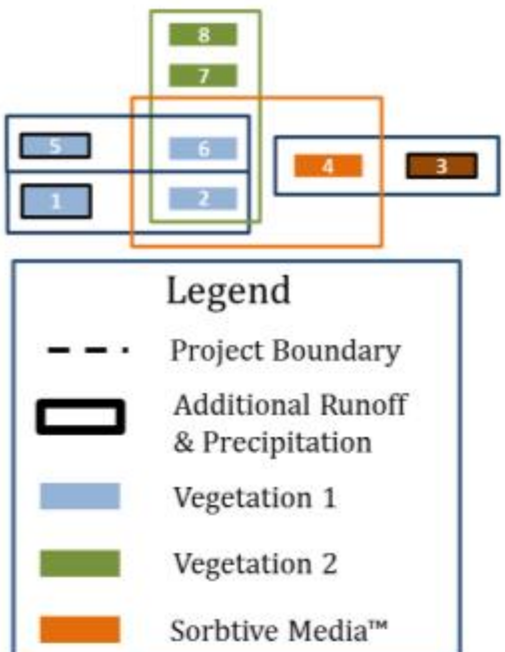
- **Methanogenesis:**
  $CO_2 + H_2$ or acetate -> CH_4

- **Methanotrophy:**
  CH_4 -> CO_2 or methanotroph biomass

- CH_4 oxidation can occur in aerobic soils, making them an important sink

Nisbet, E. G., Dlugokencky, E. J., & Bousquet, P. (2014). Atmospheric Science.

Experimental Design and Layout



Bioretention Cells	Paired Treatment	Abbreviation
1 and 2	Conventional Media + 20% vs. Conventional Media	CM20 vs. CM
(2 & 6) and (7 & 8)	Vegetation 1 vs. Vegetation 2	V1 vs. V2
(2 & 6) and 4	Conventional Media vs. Sorbtive Media ™	CM vs. SM
3 and 4	Sorbtive Media™ + Climate 60% Vs. Sorbtive Media™	SM60 vs. SM

Methods: Measuring Stormwater Quality

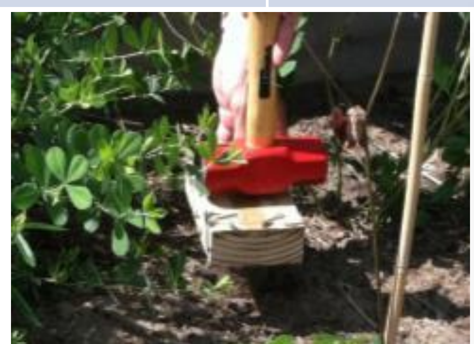
Equipment	Parameter	Sampling and Analysis Methods
• 6700 Series Automatic Samplers (Teledyne™) • Model 720 Differential Pressure Transducer	1. TP 2. NLP 3. SRP 4. TN 5. TKN 6. NO_3^- 7. TSS 8. Flow Rate	• Time Based • Discrete Samples • Based on the Hydrograph • Inflow = Every 2 min for 48 min (950 mL) • Outflow = Every 4 min for 96 min (500 mL) • Inflow to Outflow, 20-L increments (n = 6) • Outflow to Outflow, 20-L increments (n = 6) • Partial Event Mean Concentration (PEMC)




Methods: Measuring Bioretention Soil Media Characteristics

Equipment	Parameter	Sampling Method
• Soil auger • Soil core cylinder • Trowel • Decagon soil probes	1. NH_4^+ (n = 13) and NO_3^- (n = 13) 2. SRP (n = 7) 3. Bulk Density (n = 11) 4. Ca, K, Mg, Na, S, Mn, Al, Fe, Zn, Cu (n = 7) 5. Cation exchange capacity (CEC) 6. Organic matter content (n = 7) 7. Volumetric water content 8. Electrical conductivity 9. Soil temperature	1. 2 M KCl extraction 2. Modified Morgan 3. Change in mass /volume 4. Inductively coupled plasma spectroscopy 5. Ammonium acetate 6. Loss on ignition (375°C) 7. Every five minutes **3 composited sub-samples per cell**






Methods: Measuring Soil Gas Emissions

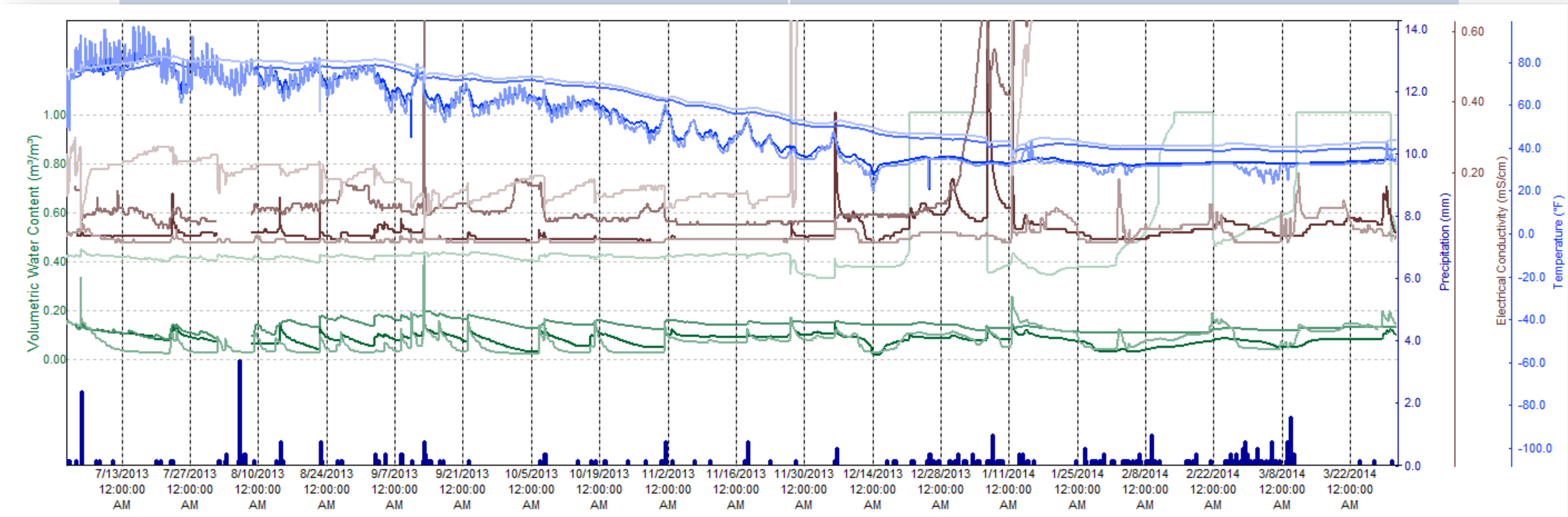
Equipment	Parameter	Sampling Method
• Permanent anchors • Closed chambers • 10 mL vials with self sealing septum • Syringes with nylon stopcocks	1. CO_2 2. CH_4 3. N_2O	1. Samples taken T_0, T_{15}, T_{30}, T_{45} 2. Weekly to bi-weekly 3. July to October 2014 4. Humidity minimized: short deployment time 5. Temperature disturbance: reflective mylar 6. Pressure disturbance: chamber vent tube 7. Sample time 10 am or 3 pm to minimize temporal disturbances




Parkin and Venterea (2010)

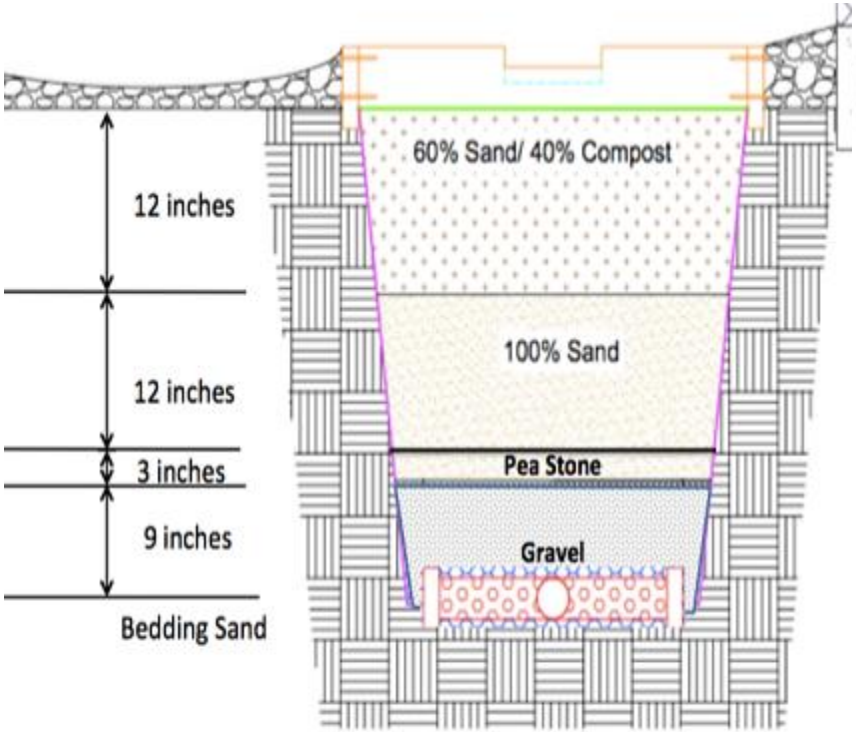
Methods: Soil Conditions

Equipment	Parameter
Decagon Probes (depths of 2” and 2’) High Resolution Rain Gauge	Soil temperature Moisture Conductivity Rainfall



Comparing Soil Media Treatments

Conventional Media (CM)



Sorbtive Media ™ (SM)

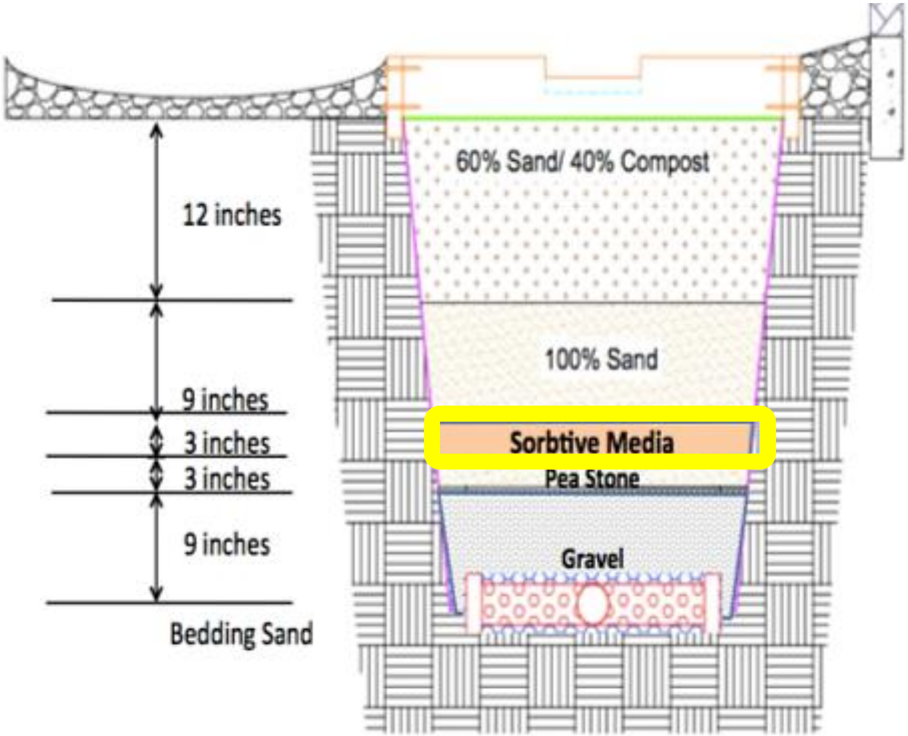


Image Credit: J. Schultz, C. Brackett, J. Nummy, O. Lapierre (unpublished).

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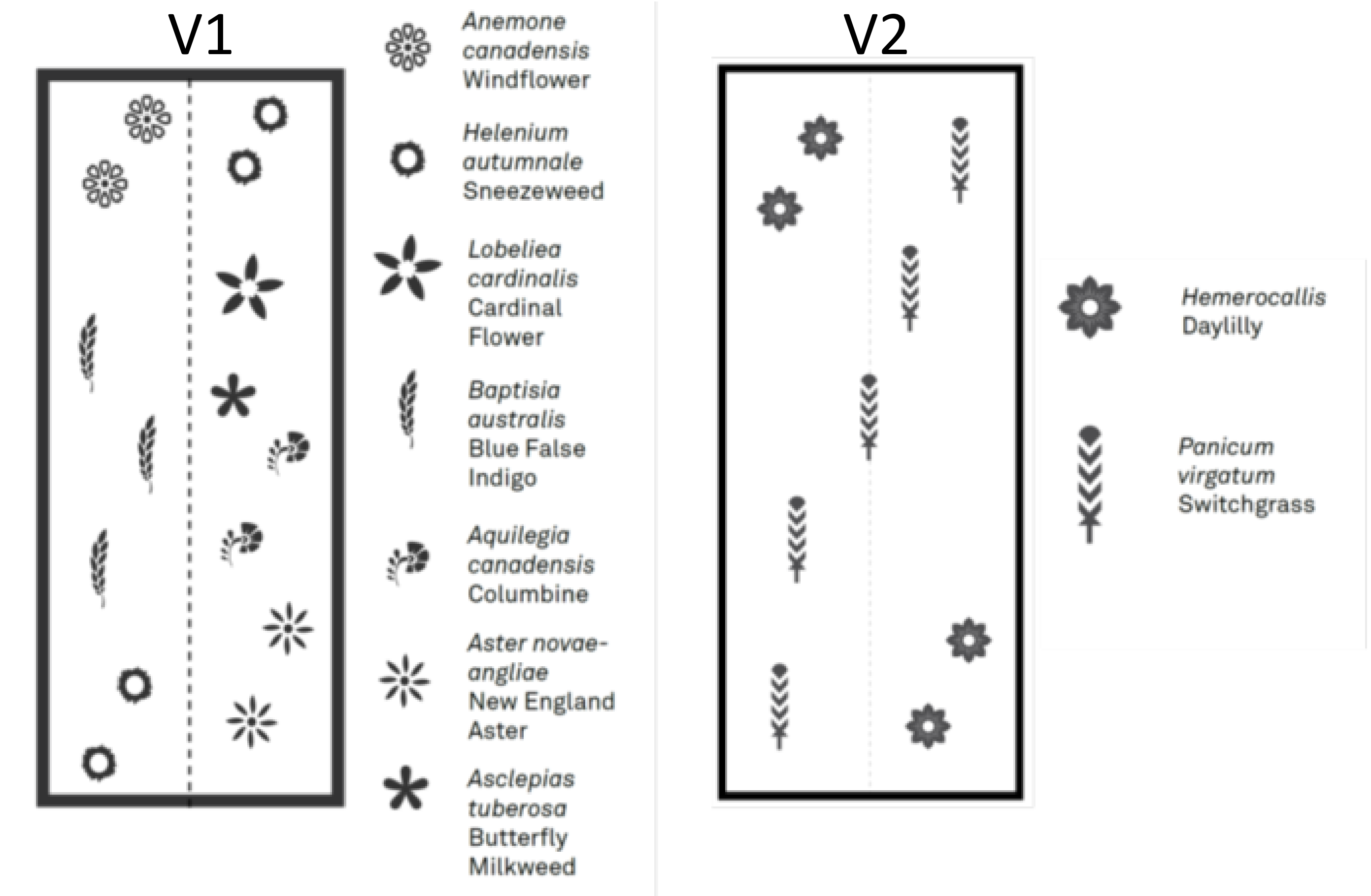
Comparing Vegetation Treatments



Planting Configuration: Vegetation Palette 1 (left) and Vegetation Palette 2 (right) (Diagram created by S. Hurley and A. Zeitz, unpublished).

Plant Pallet 1: High Species Diversity (7)

Latin Name	Common Name
Aesclepius incarnata	Butterflyweed, Milkweed 'Tuberosa'
Anemone canadensis	Windflower
Aquilegia canadensis	Columbine
Aster novae-angliae	New England Aster 'Purple Dome'
Baptisia australis	Blue False Indigo 'Caspian' and 'Midnight Prairiebliss'
Helenium autumnale	Sneezeweed 'Red + Gold'
Lobeliea cardinalis	Cardinal Flower

Plant Pallet 2: Low Species Diversity (2)

Hemerocallis spp.	Daylilies 'Stella d'Oro'
Panicum virgatum	Switch Grass 'Shenandoah'

Vegetation Planted: May 2013

Low Diversity (2 species) vs. High Diversity (7 species)

Established Vegetation: August 2013

Low Diversity (2 species) vs. High Diversity (7 species)

Vegetation 1 (V1)

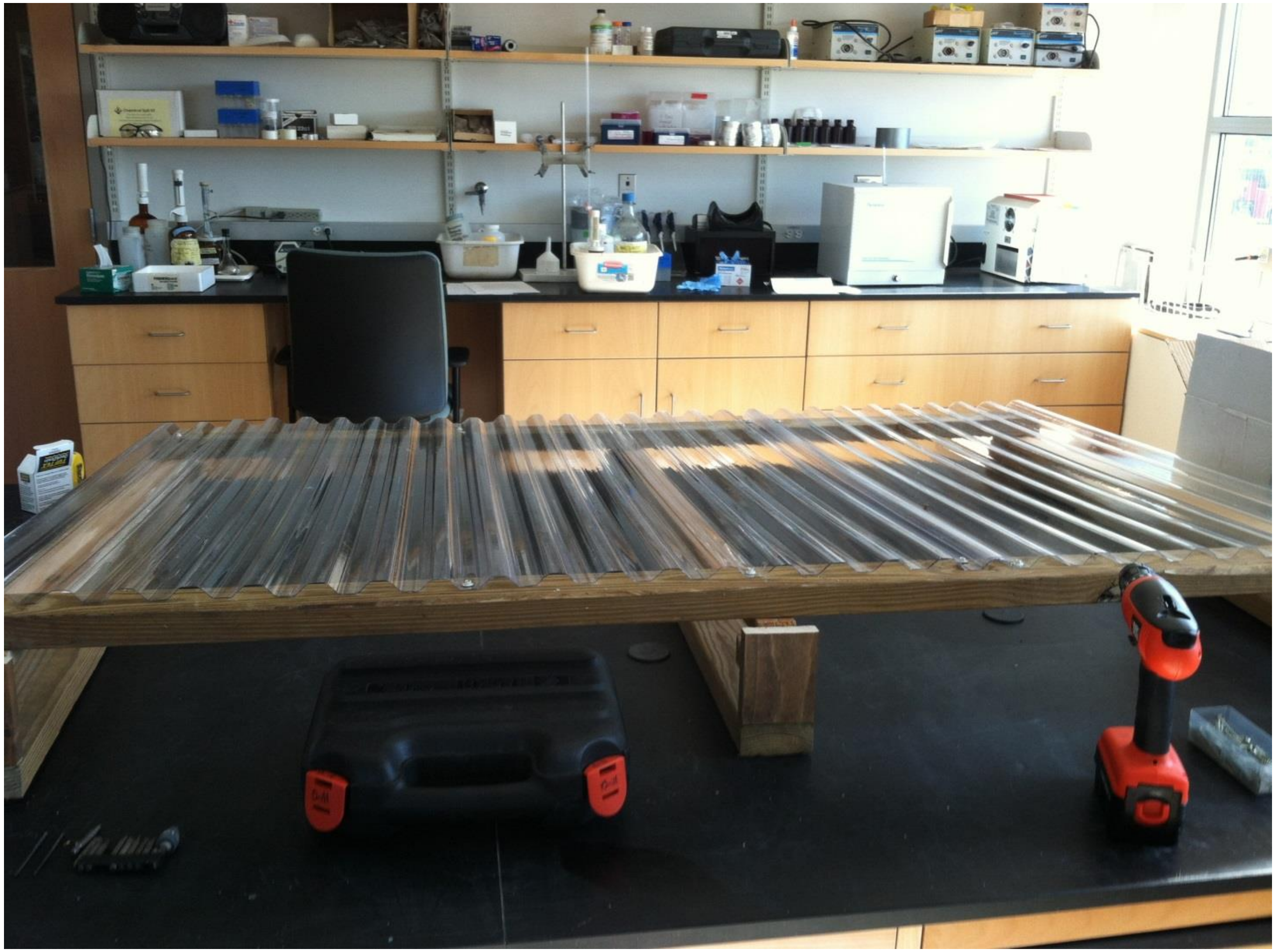
Vegetation 2 (V2)

Precipitation Treatments, CM20 and SM60

1. Precipitation was added with a simulation device = rain pan
2. Runoff was added by increasing the size of the drainage area

- CM20 received 20% more precip via rain pan + drainage area 20% larger than CM
- SM60 received 60% more precip via rain pan + drainage area 60% larger than SM

Simulating Precipitation



Simulating Precipitation

Methods: Greenhouse Gas Emissions

1. Measured bi-weekly May-October
2. CO_2 , CH_4, N_2O three locations per plot, (T_0, T_{15},T_{30})
3. Inorganic soil N, moisture, temperature, and bulk density, as covariates for N_2O fluxes

Conclusions

1) Bioretention consistently reduce peak stormwater flow rates and volumes.

2) Non-labile nutrient and sediment removal is considerable as a result of physical filtration.

3) Deep rooted, fine textured roots (*Panicum Virgatum*) provided greater soil stability and access to soil nutrients throughout the profile.

4) Organic amendments (compost) added labile nutrient mass loads which far exceed loads from stormwater from a medium traffic paved road surface, and need to be limited.

5) Sorbtive Media™ was extremely effective at removing SRP, and may have influenced nitrate removal, although mechanisms are not fully understood.

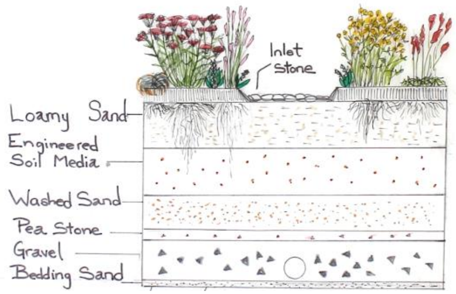
6) Nitrate reduction through extended retention time in an anaerobic zone can provide significant denitrification but optimal conditions necessary are yet to be determined.

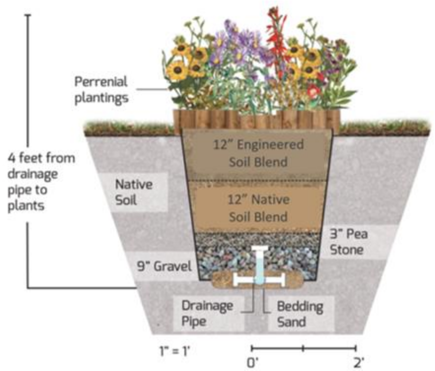
7) Increased precipitation and runoff may have been linked to increased transport of fine sediment, and partial clogging of the underdrain, but may be site specific.

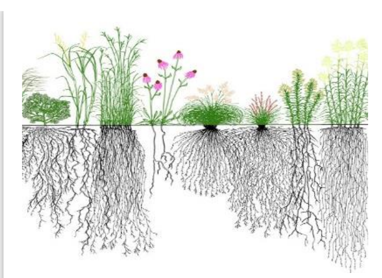
8) Bioretention cells were a small source of N_20 but not likely significant in the global context.

9) Bioretention could be a small sink for CH_4 if the media above the saturated zone is aerobic, but warrants further research given different depths and saturation durations.

Future Research Needs



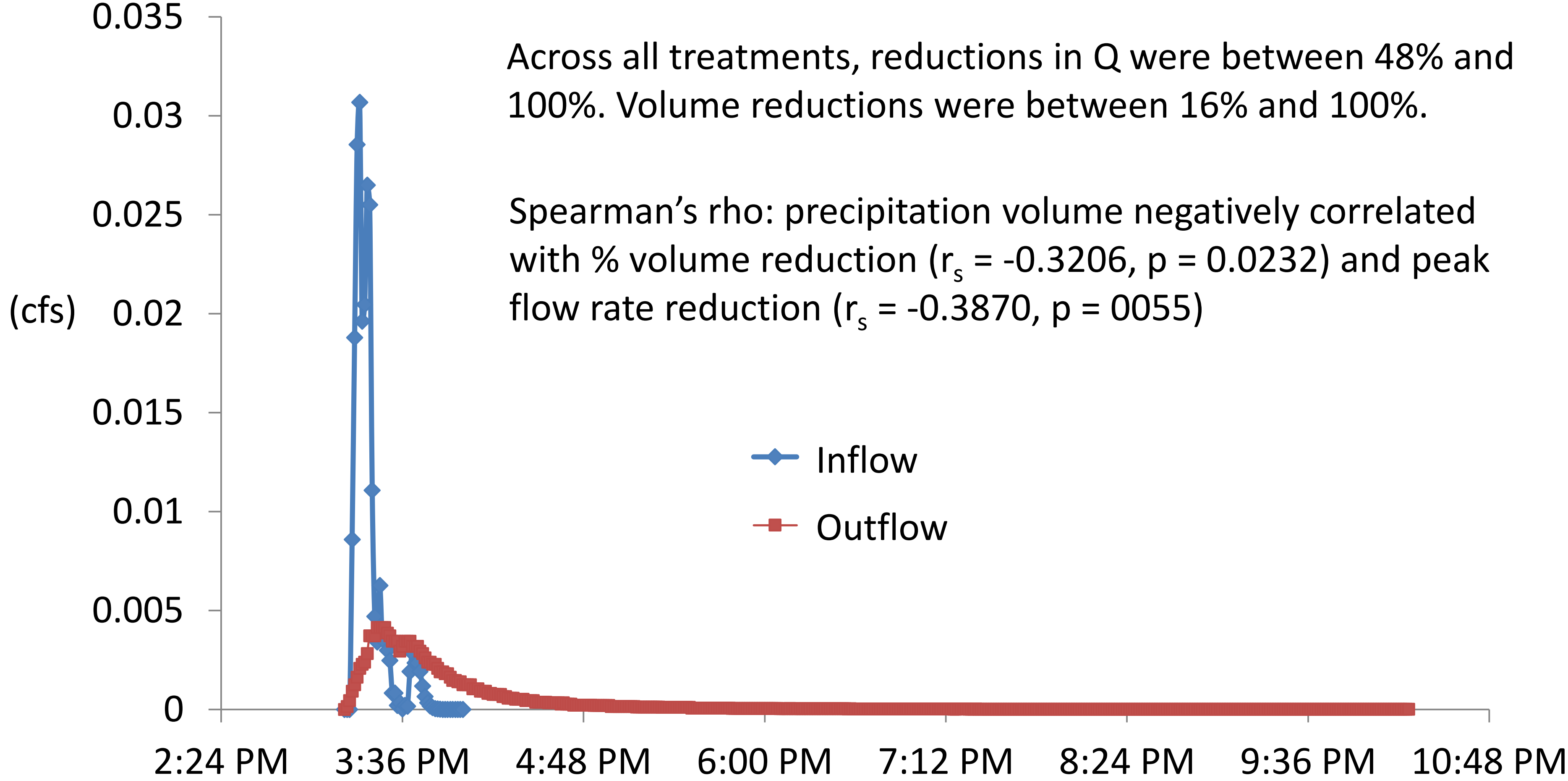




1. Chemical characteristics of soil media to minimize soluble N and P contributions (compost, mulch, soil), but achieve target infiltration rate?
2. Retention time, carbon requirements for thorough denitrification in different medias?
3. Planting options to achieve maximium soil stability and pollutant uptake, given soil conditions (#1) above?

Images: Drawing: A. Cording (2016) Unpublished, (Middle) Cording, A., Hurley, S., Adair, E., Ross, D. (In Preparation). *Evaluating critical bioretention designs features in the context of climate change*. (Bottom) 2012 Nature Education, Conservation Research Institute, Heidi Natura.

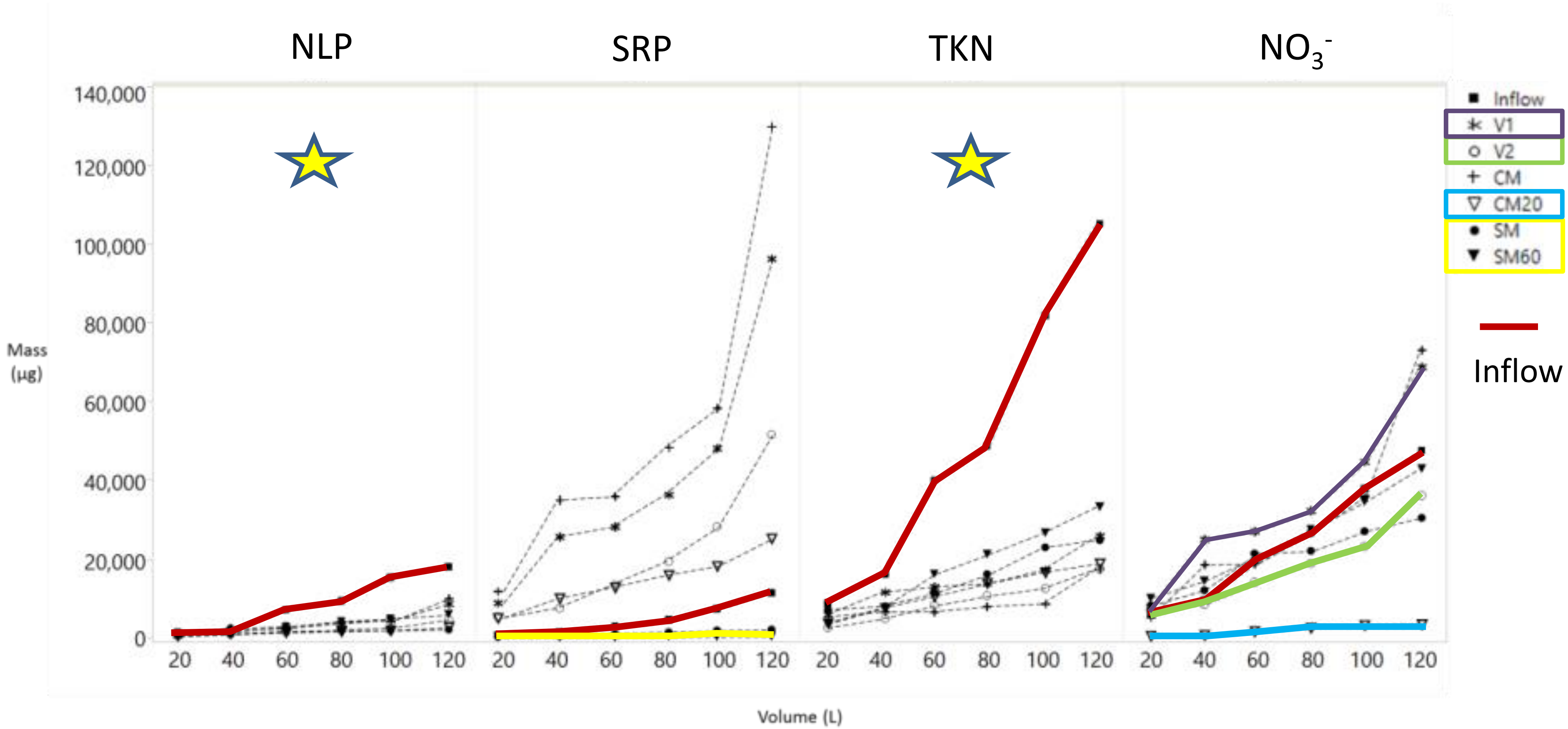
Results:
Flow Rate Reduction Performance



Across all treatments, reductions in Q were between 48% and 100%. Volume reductions were between 16% and 100%.

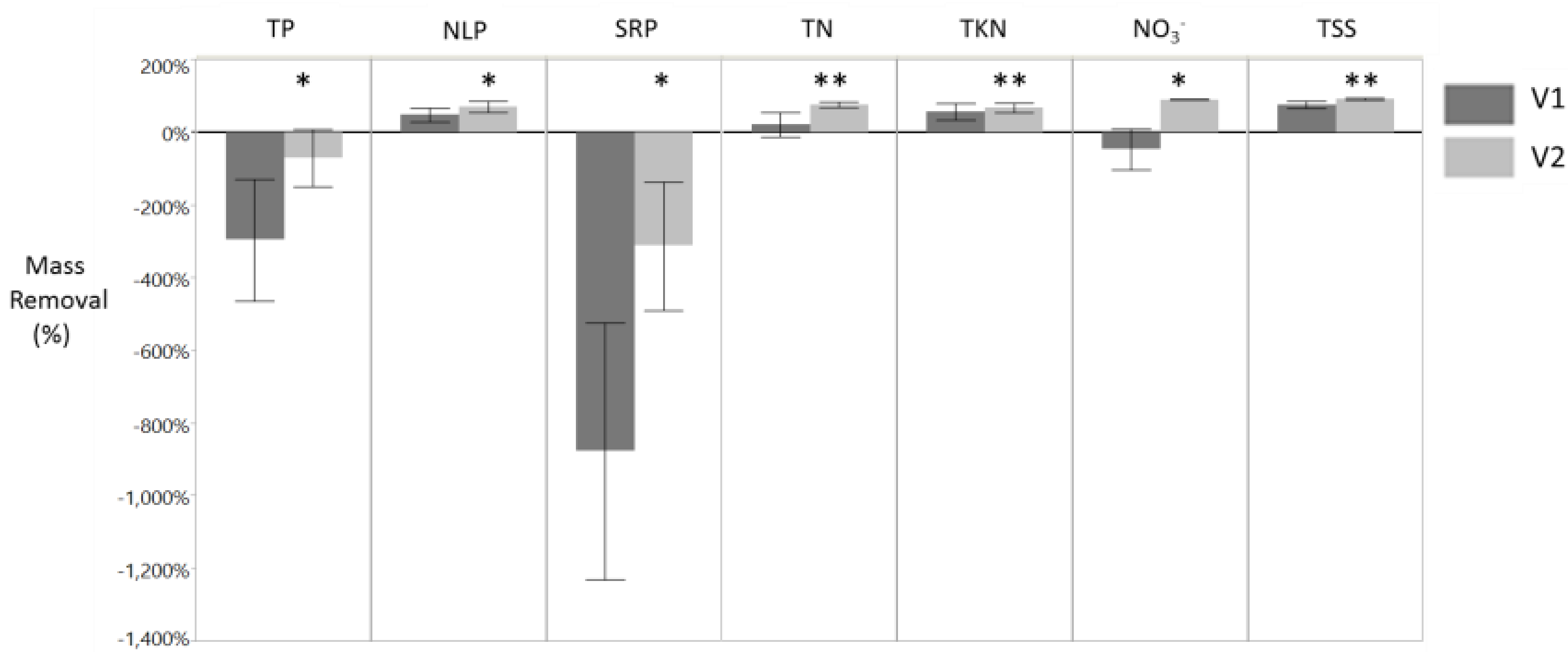
Spearman's rho: precipitation volume negatively correlated with % volume reduction (r_s = -0.3206, p = 0.0232) and peak flow rate reduction (r_s = -0.3870, p = 0055)

Results:
Mass Removal within Each Treatment



The SRP mass load was significantly increased from inflow to outflow in all treatments, except those containing Sorbtive Media (i.e., SM and SM60).

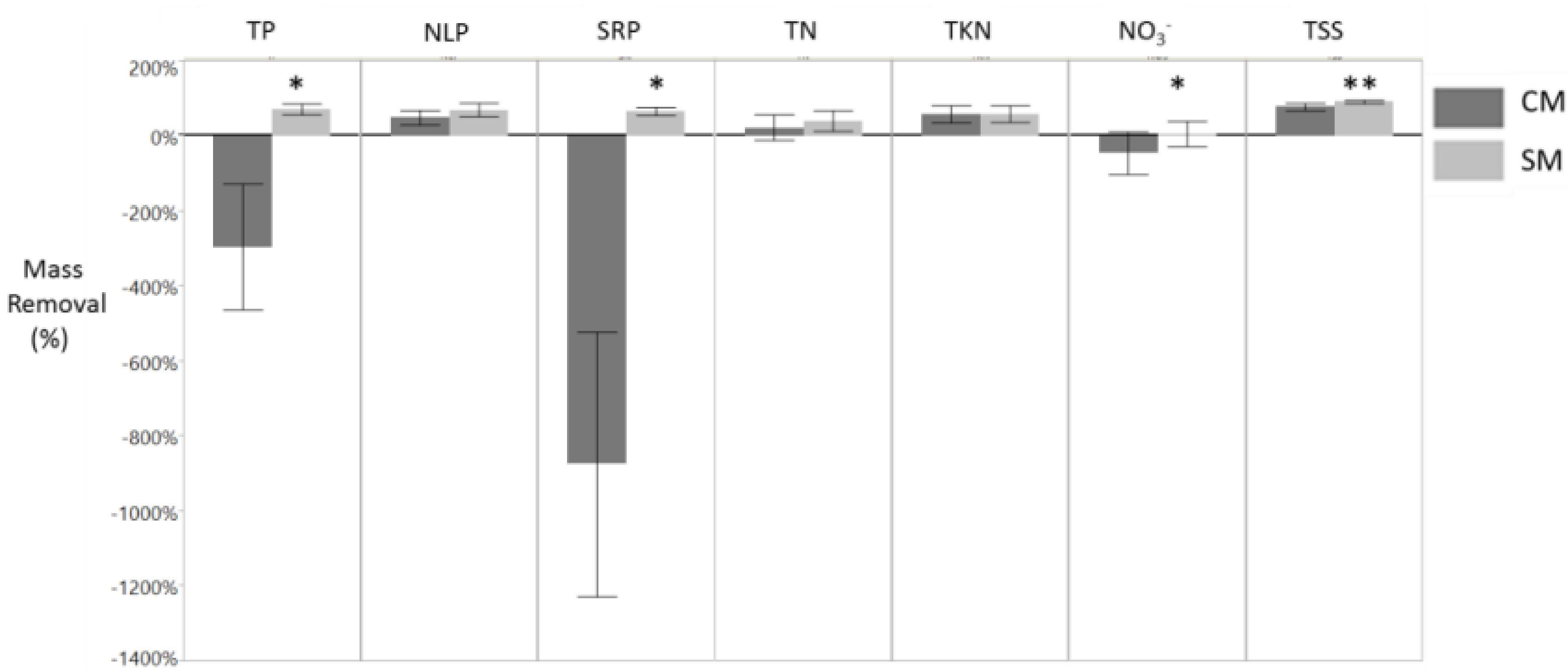
Results:
Outflow Mass between Vegetation Treatments



ns = p > 0.05, * = p ≤ 0.05, ** = p ≤ 0.01, *** = p ≤ 0.001, **** = p ≤ 0.0001.

Paired t-test (n = 6) results indicate that outflow mass from V2 was significantly lower than V1 for all constituents

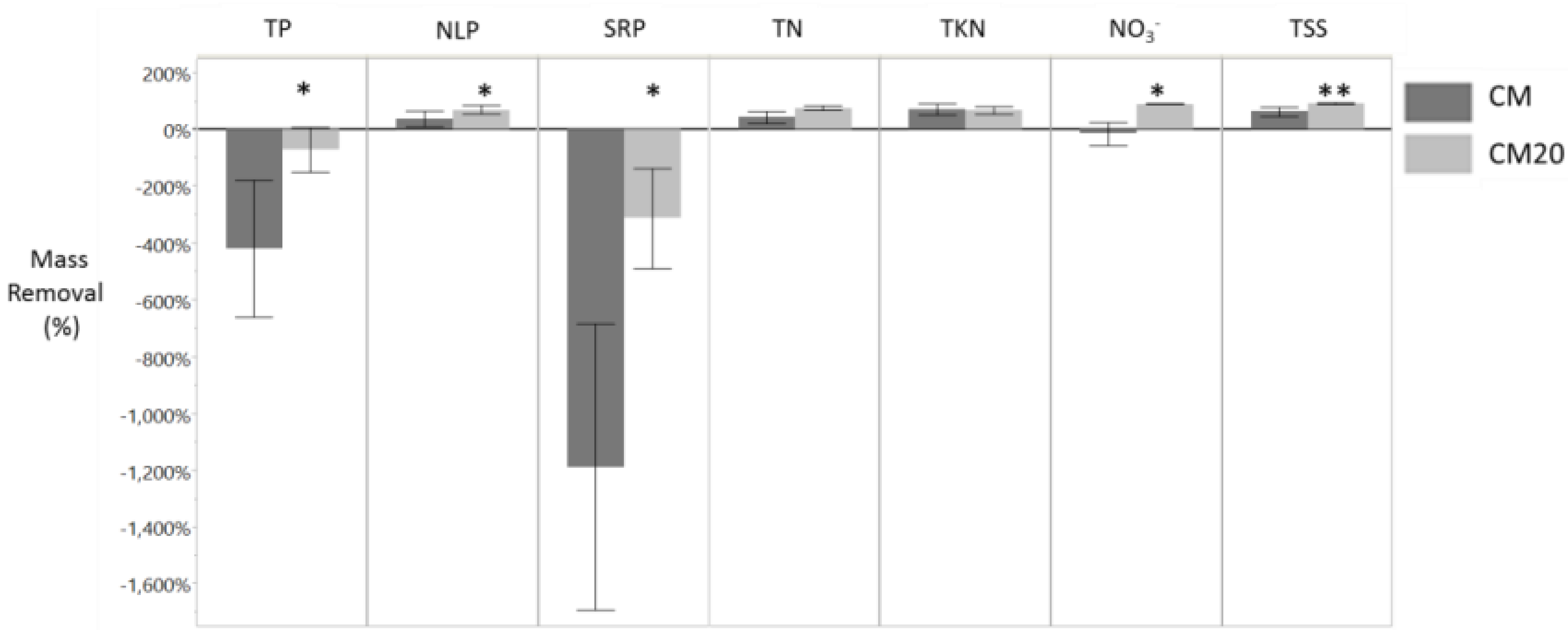
Results:
Outflow Mass Between Soil Media Treatments



ns = p > 0.05, * = p ≤ 0.05, ** = p ≤ 0.01, *** = p ≤ 0.001, **** = p ≤ 0.0001.

Outflow mass from SM was lower than the CM for all constituents except NLP and TKN, which were equal between treatments

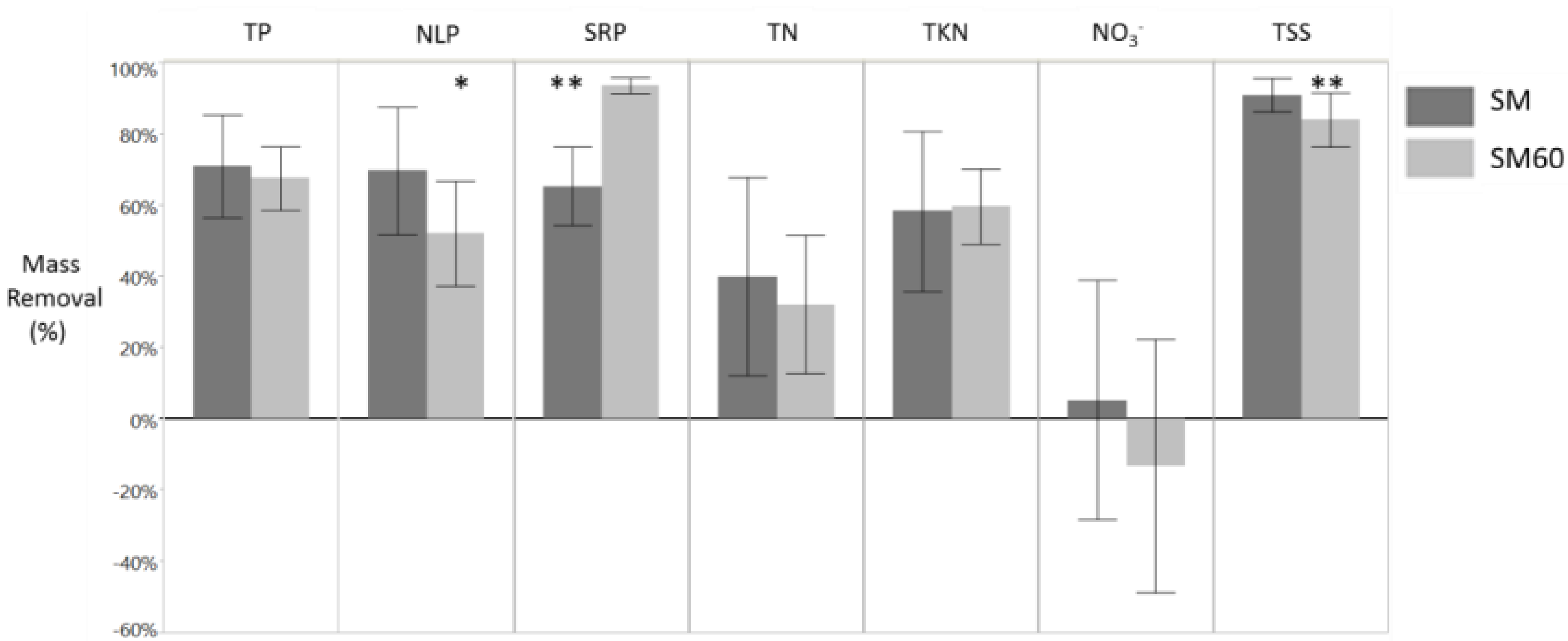
Results:
Outflow Mass Between Climate Change Treatments: 20% Increase in Precipitation to Conventional Media



ns = p > 0.05, * = p ≤ 0.05, ** = p ≤ 0.01, *** = p ≤ 0.001, **** = p ≤ 0.0001.

Outflow mass from CM20 was lower than CM for all constituents except TKN, which was found to be equal between treatments

Results:
Outflow Mass Between Climate Change Treatments: 60% Increase in Precipitation to Sorbtive Media™



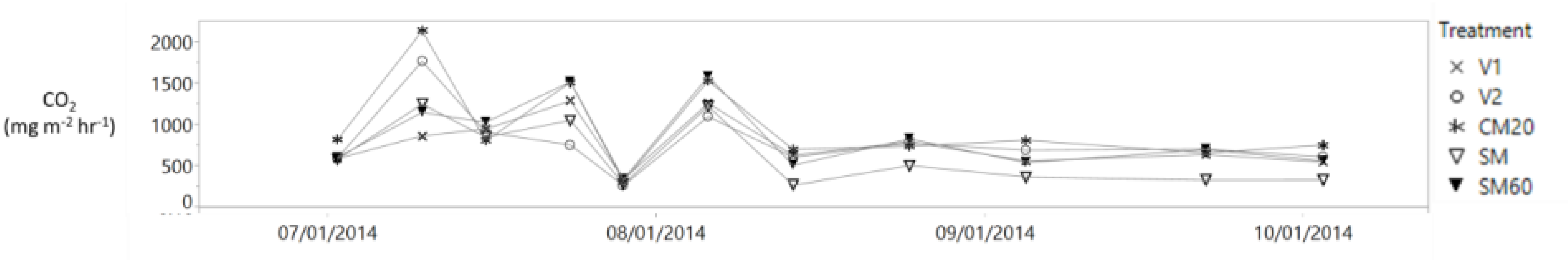
ns = p > 0.05, * = p ≤ 0.05, ** = p ≤ 0.01, *** = p ≤ 0.001, **** = p ≤ 0.0001.

Outflow SRP mass from the SM60 was lower than the SM

NLP and TSS mass from SM60 was higher than from SM

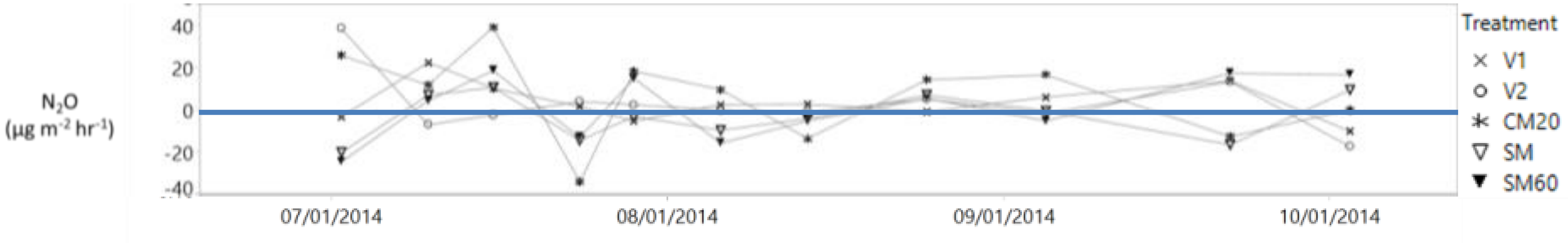
TKN or NO_3^- mass equal between treatments

Results (CO_2): GHG Emissions by Treatment



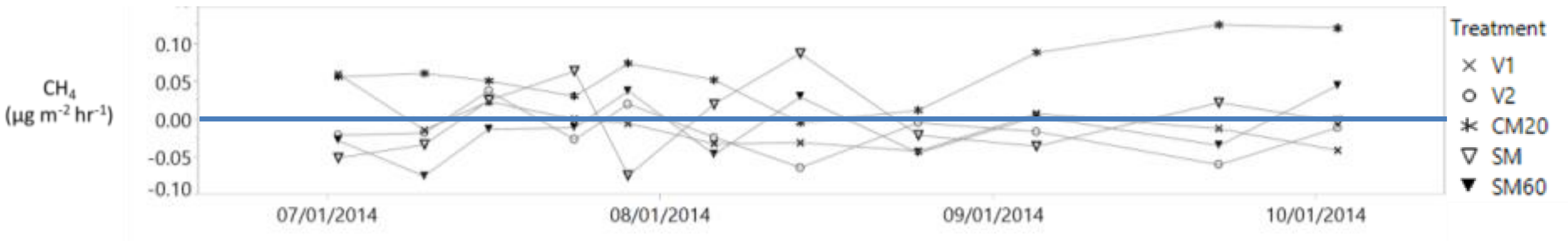
- CO_2 emissions (n = 77), minimum 251 mg m^{-2} hr^{-1} and max 2,650 mg m^{-2} hr^{-1}
- Adviento-Borbe et al. (2010) CO_2 ranged 13 mg m^{-2} hr^{-1} to 1,015 mg m^{-2} hr^{-1}
- CO_2 positively correlated with soil temperature ($r_s = 0.2545$, $p = 0.0255$)
- CO_2 negatively correlated with antecedent precip ($r_s = -0.5333$, $p < 0.0001$) and water filled pore space ($r_s = - 0.5400$, $p = 0.0065$).
- CO_2 from SM60 was greater than SM ($t(10) = 4.17$, $p = 0.0019$)

Results (N_2O): GHG Emissions by Treatment



- N_2O emissions ranged (n = 77) from -33.94 µg m^{-2} hr^{-1} to 65.80 µg m^{-2} hr^{-1}
- Grover et al. (2013) found N_2O emission 13.8 µg m^{-2} hr^{-1} to 65.6 µg m^{-2} hr^{-1}
- The SM was a sink for N_2O overall, with an average (n = 11) of -3.06 µg m^{-2} hr^{-1}

Results (CH_4):
GHG Emissions by Treatment



- CH_4 emissions ranged (n = 77) from – 0.1014 µg m^{-2} hr^{-1} to 0.1259 µg m^{-2} hr^{-1}
- All treatments were a small sink for CH_4 on average (n = 11) except CM20
- CM20 emissions (0.0608 µg m^{-2} hr^{-1}) greater than CM ($t (10) = 3.64$, $p = 0.0046$)
- Smith et al. (2003) predict that CH_4 emissions less than 1.6 µg m^{-2} hr^{-1} where depth to saturation > 50 cm, due to negative correlation with depth to "groundwater".

Discussion: Vegetation Treatments

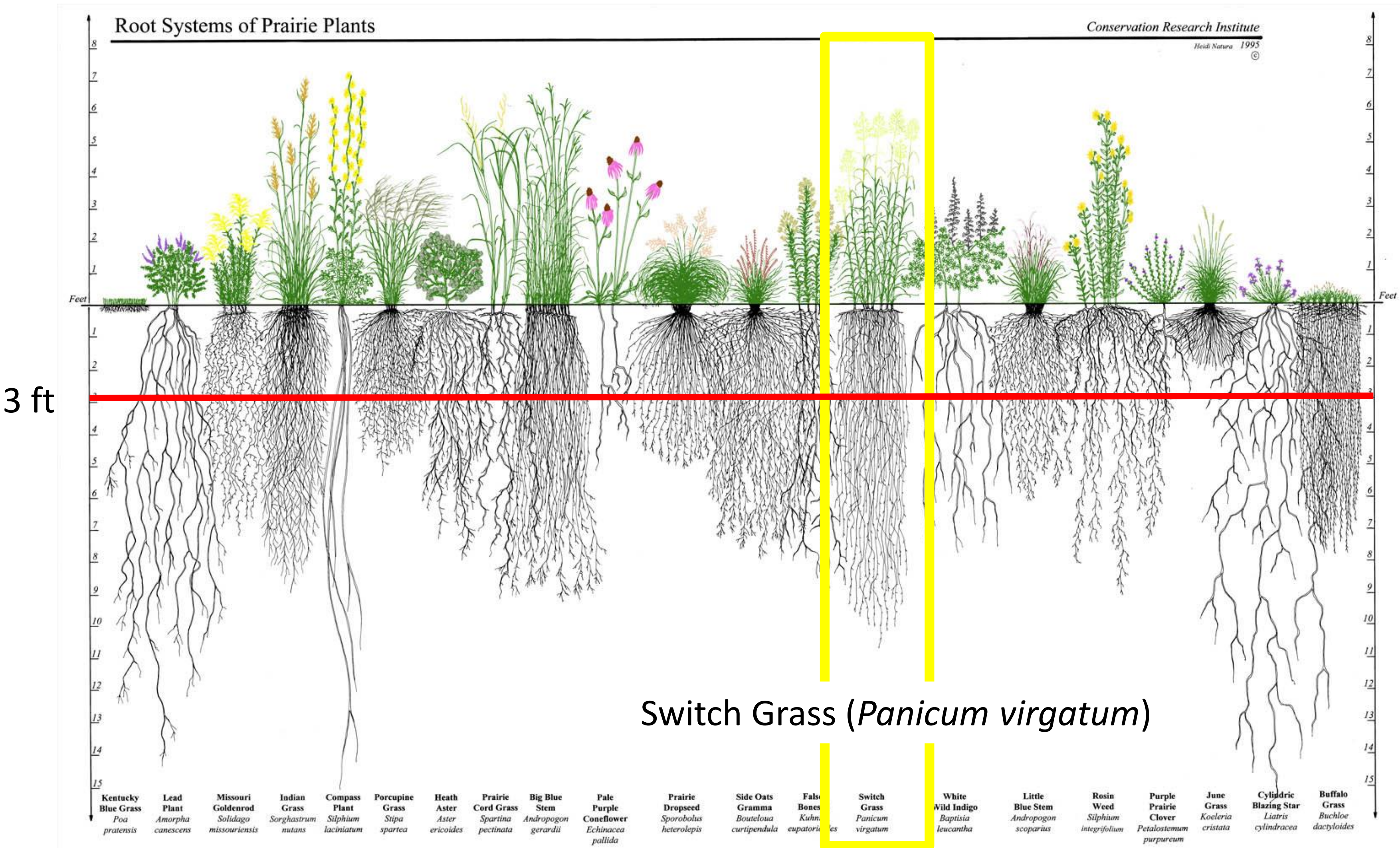
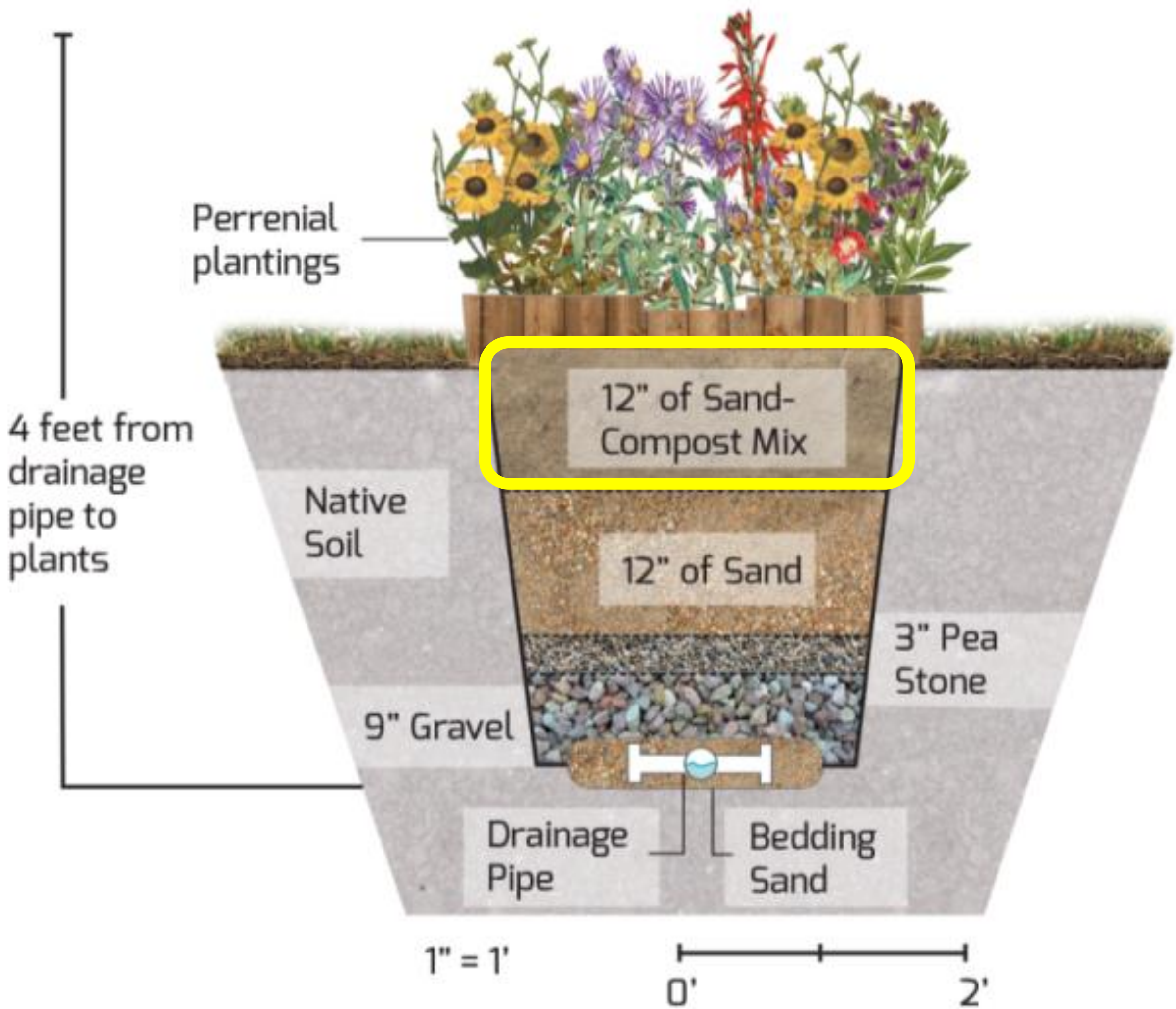


Image Source: Conservation Research Institute; Mann et al. (2013)

Discussion: Conventional Bioretention Design

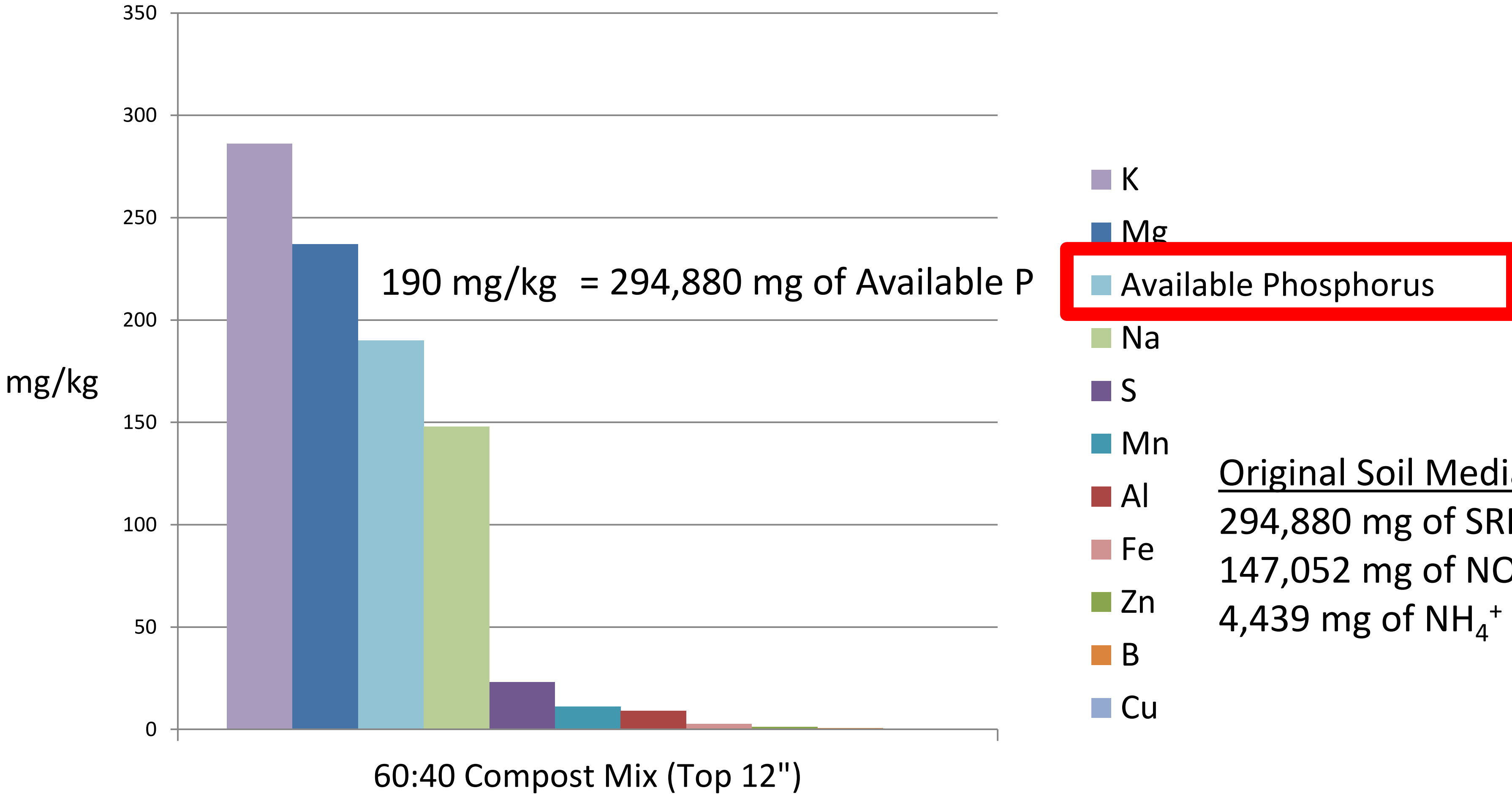


<u>Recommended By:</u>

1. Vermont Agency of Natural Resources (2002)
2. Washington State University Pierce County Extension (2012)
3. Center for Watershed Protection

Image Credit: Hurley, S., Zeitz, G.,(unpublished)

Conventional Bioretention Design: 60:40 Sand Compost Mix



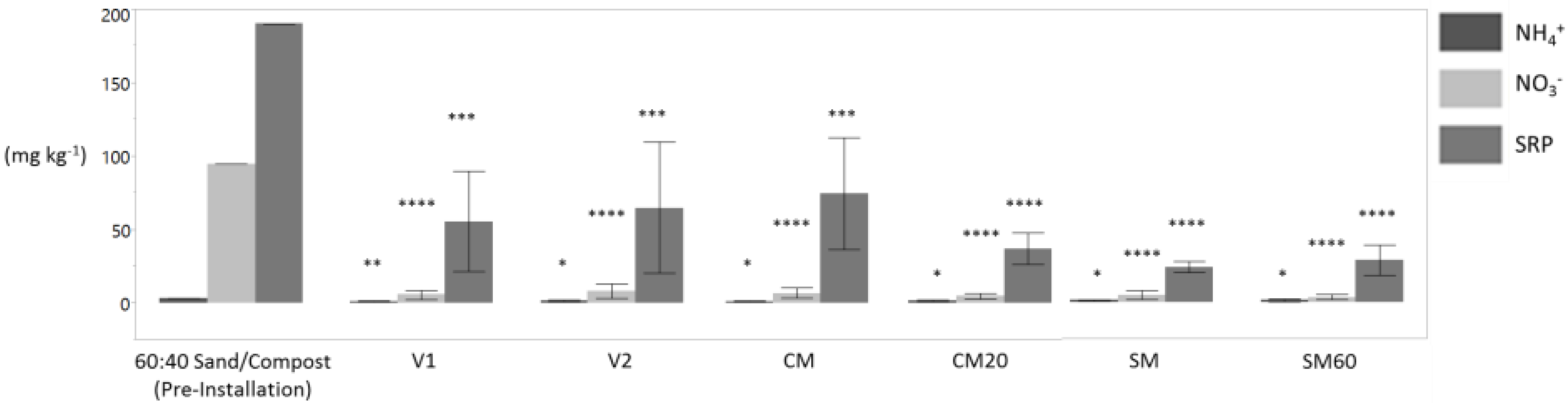
<u>Original Soil Media:</u>

294,880 mg of SRP

147,052 mg of NO_x

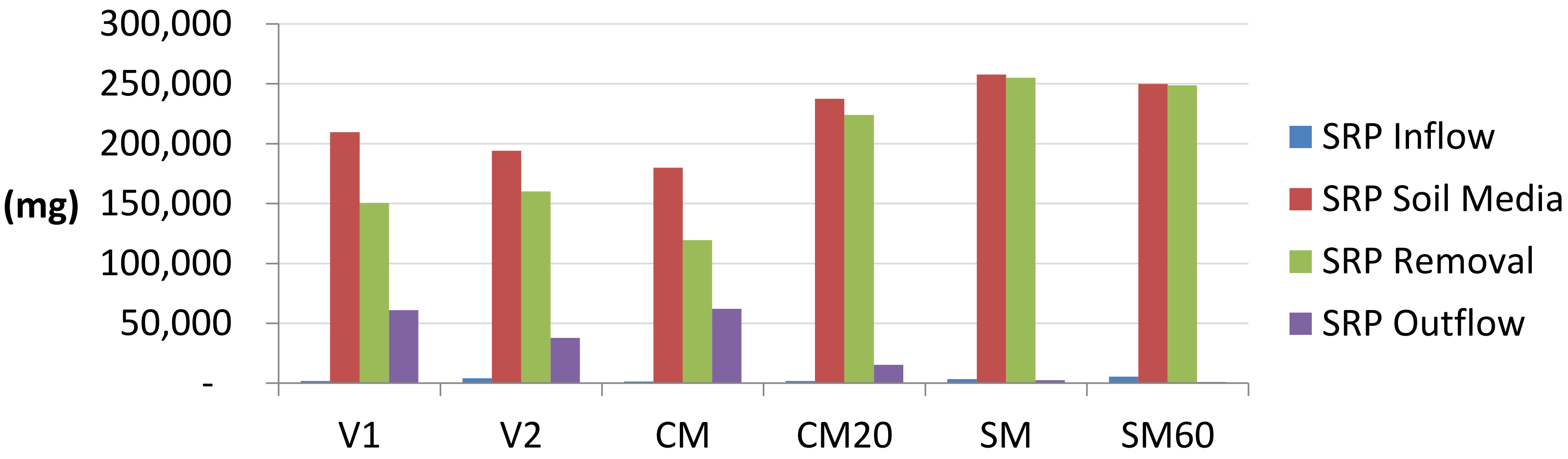
4,439 mg of NH_4^+

Comparing Nutrient Content in 60:40% Sand and Compost Mixture from Pre-Installation to Average After Two Years



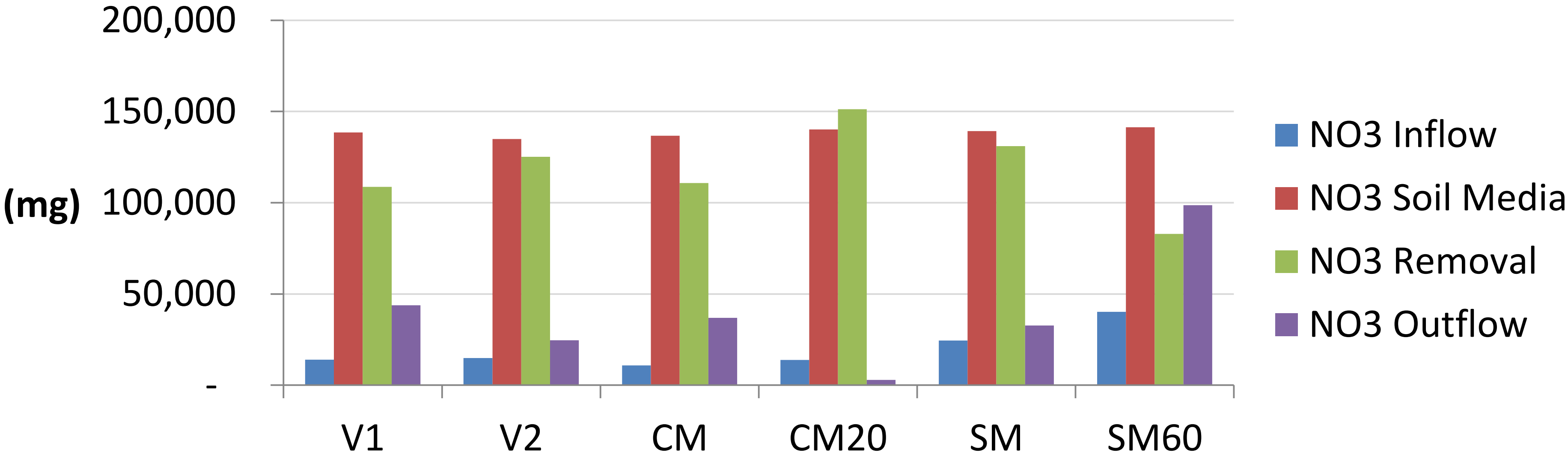
Dunnett's Control: NH_4^+, NO_3^-, and SRP significantly decreased from the original pre-installation mix after two years, in all treatments (n = 7)

SRP Mass Balance



- In the first two years of installation (n = 7) the SRP content decreased by between 66% (201 g) and 87% (257 g) across all treatments.
- Stormwater runoff contributed between 1% and 2% of the total SRP load to the cells, with the remainder coming from the compost mixture.

NO_3^- Mass Balance



- In the first two years of installation (n = 7) NO_3^- decreased between 92% (135 g) and 96% (141 g).
- NO_3^- mass from stormwater contributed between 9% and 22% of the total load.

Mass Balance: SRP and NO_3^-

- Of the total SRP and NO_3^- mass released from the compost and stormwater, approx. 70% was found to be removed by vegetation in V1 and 30% was released to the effluent.
- 80% of the mass load was removed by plant uptake in V2, releasing 20% to the outflow.
- Approximately 1% of the SRP from stormwater + compost mixture was released to the effluent from SM and SM60.

Effective Bioretention Requires the Right Soils

<u>Considerations</u>

Textual Class
Infiltration Rate
CEC/AEC
Fe, Ca, or Al
pH

Availability
Cost

FIGURE 2.2 - SOIL TEXTURE TRIANGLE

Source: University of Arkansas Community Design Center

Cation Exchange Capacity

FIGURE 2.2 - SOIL TEXTURE TRIANGLE

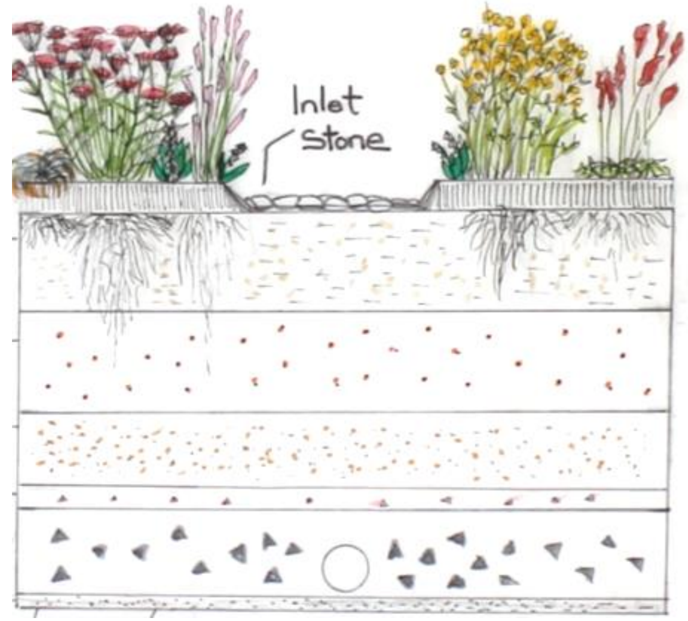
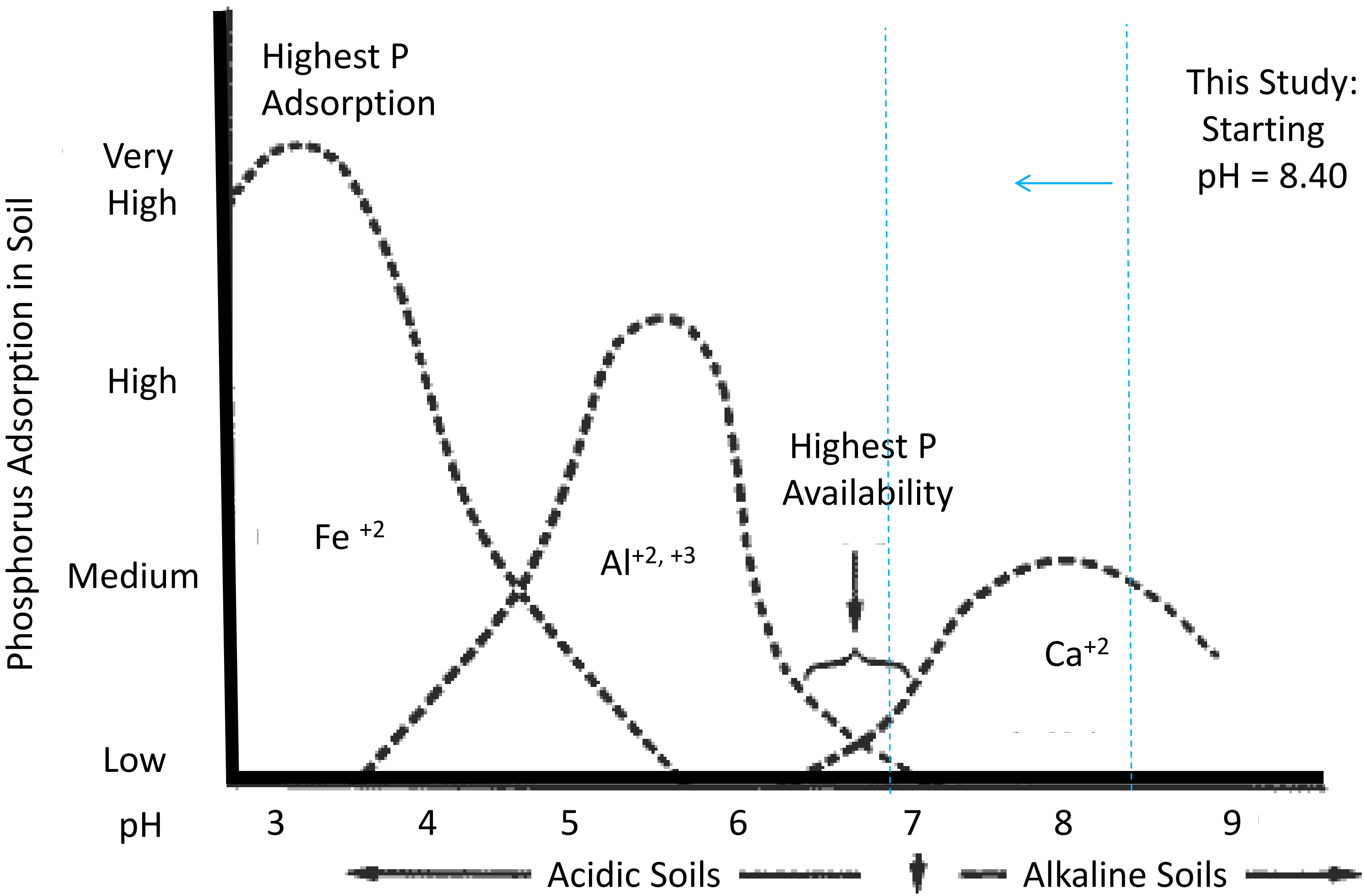
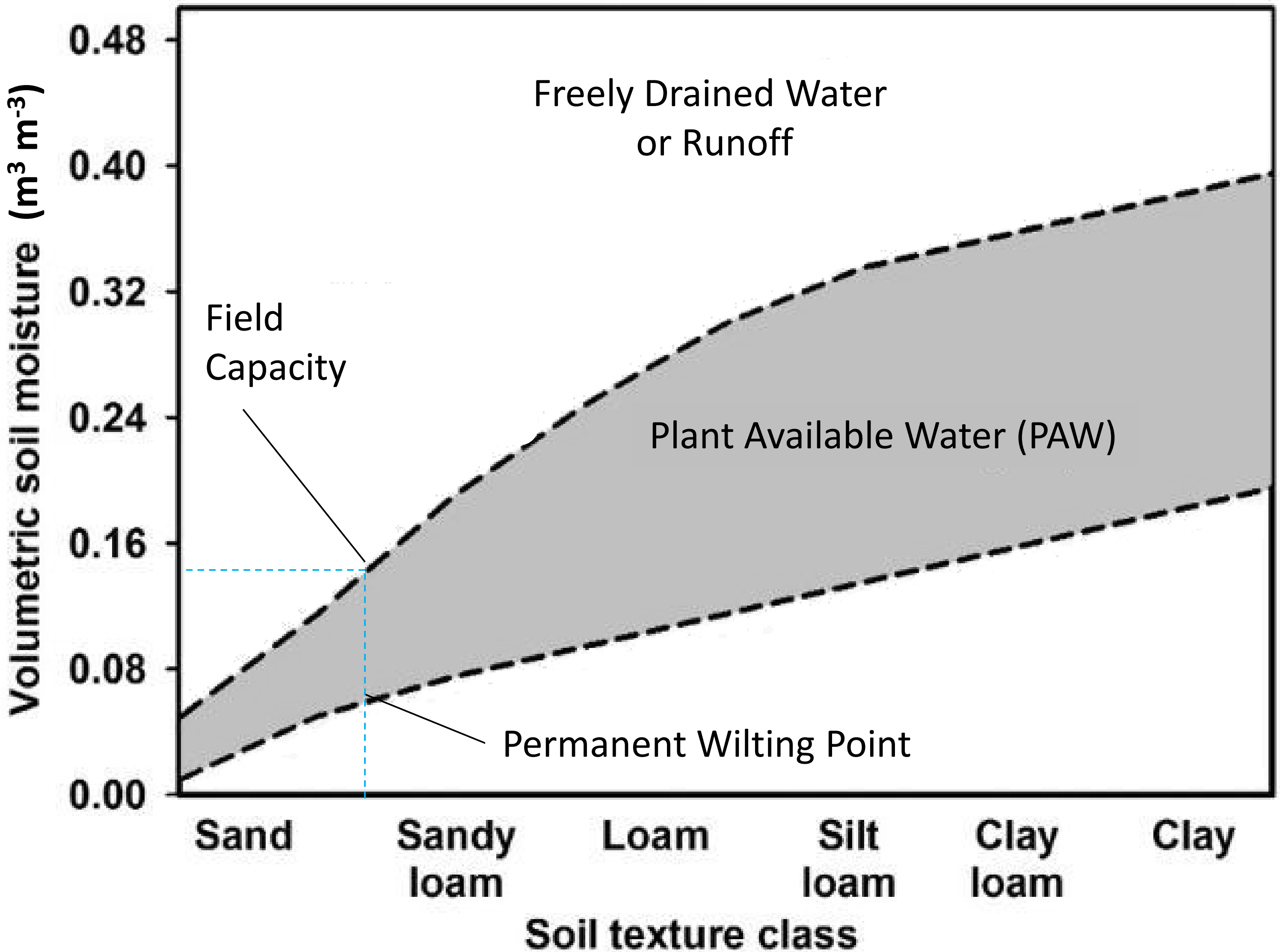


Table 1. Soil textures and CEC (Sonon et al. 2014).

Soil Texture	CEC (meq/100g)
This Study	6.30
Sand	1-5
Fine Sandy Loam	5-10
Loam	5-15
Clay Loam	15-30
Clay	> 30

Phosphorus Sorption and pH




Freely Drained Water
or Runoff
Field
Capacity
Plant Available Water (PAW)
Permanent Wilting Point
Volumetric soil moisture (m3 m-3)
0.48
0.40
0.32
0.24
0.16
0.08
0.00
Sand
Sandy
loam
Loam
Silt
loam
Clay
loam
Clay
Soil texture class

Average Outflow Concentrations Compared to the Literature

Parameter	This Study	Literature	Reference
NLP	18 µg L^{-1} (CM20) to 53 µg L^{-1} (CM)	40 – 800 µg L^{-1} ★	Hunt et al. (2006)
SRP	164 µg L^{-1} (CM20) to 568 µg L^{-1} (CM)	210 – 670 µg L^{-1} ☑	Geosyntec (2008)
SRP	4 µg L^{-1} (SM60) to 24 µg L^{-1} (SM)	140 µg L^{-1} ★	Chardon et al. (2005) (Iron Coated Sand)
		< 10 µg L^{-1} ☑	O'Neill and Davis (2011) (WW Treat. Residual)
TKN	149 µg L^{-1} (CM20) to 376 µg L^{-1} (SM)	1,240 – 1,780 µg L^{-1} ★	Geosyntec (2008)
NO_3^-	44 µg L^{-1} (CM20) to 464 µg L^{-1} (SM60)	300 – 400 µg L^{-1} ☑	Dietz and Clausen (2006)
TSS	3.03 mg L^{-1} (CM20) to 10.20 mg L^{-1} (CM)	15 – 33 mg L^{-1} ★	Geosyntec (2008)

Publications:

Cording, A., Hurley, S., Whitney, D. (**Submitted**) Monitoring methods and designs for evaluating bioretention performance. Journal of Environmental Engineering.

Cording, A., Hurley, S., Adair, E., Ross, D. (**In Preparation**). *Evaluating critical bioretention designs features in the context of climate change*.

Cording, A. (**In Preparation**). *Investigating pollutant mass mobilization and speciation during the stormwater first flush*.

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(808) 372 - 5719

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