Incorporating Internal Water Storage into Bioretention Design

Stormwater Engineering

Biological & Agricultural Engineering

NC STATE UNIVERSITY

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Based upon work by Robert Brown

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Rain Garden Design Workshop

All the Information Presented Available in 2 Docs

Underdrain Configuration to Enhance Bioretention Exfiltration to Reduce Pollutant Loads

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Abstract: The bioretention drainage configuration of raising the outlet to create an internal water storage (IWS) layer in the media was originally intended to promote denitrifying conditions. The goal was to reduce nitrate and total nitrogen concentrations in nutrient-sensitive watersheds. Two field studies in the Piedmont region of North Carolina, where the in situ soils typically have high clay content, showed this design feature had potential to enhance exfiltration and reduce drainage from bioretention. Two bioretention cells in Rocky Mount, North Carolina, were monitored for two year-long periods to measure the impact of varying IWS zone depths over sandier underlying soils. Nearly 99% of runoff entering the bioretention cell with sand underlying soil (sand cell) was never directly discharged to the storm water network. However, the hydraulic retention time (contact time) of runoff in the media was less than 3 h, and except for total suspended solids (TSS), minimal pollutant removal was achieved. The other bioretention cell had a sandy clay loam underlying soil (SCL cell); runoff from this cell was reduced by 87% during the monitoring period with a 1.03-m IWS zone depth and 75% when the IWS zone depth was 0.73 m. The underlying soil of the SCL cell had a lower hydraulic conductivity, so water would remain in the IWS zone for up to 7 days. The increased hydraulic retention time in the media resulted in lower outflow concentrations. For events monitored with drainage from the SCL cell, efficiency ratios of all the nitrogen species and TSS exceeded 0.5. As an additional metric of performance, the parking lot runoff and treated runoff from both the SCL and sand cells were compared to concentrations consistent with "good" and "fair" benthic macroinvertebrate health in streams. Using this metric, the parking lot runoff only met the "fair" standard for total nitrogen (TN) and total phosphorus (TP), and treated runoff from the SCL cell achieved the "good" standard for both TN and TP. However, because of the short hydraulic retention time of runoff in the media for the sand cell, this cell only maintained the "fair" standard for TN and did not achieve the "fair" standard for TP. **DOI:** 10.1061/(ASCE)EE.1943-7870.0000437.

CE Database subject headings: Water storage; Biological processes; Water quality; Drainage; Coastal environment; Sustainable development; Filtration.

Author keywords: Internal water storage (IWS) zone; Bioretention; Hydrology; Water quality; Drainage configuration; Coastal plain; Exfiltration; Low impact development.

Introduction

Low impact development (LID) practices are a new and evolving technology for storm water managers to restore the altered hydrologic condition of the landscape created by urbanization. A primary goal and treatment mechanism of LID is to infiltrate runoff near the source. Increasing infiltration reduces runoff and recharges shallow groundwater, which helps maintain stream baseflow. Additionally, reduced outflow volume results in decreased pollutant load discharged to the storm drain network. Because LID practices are still relatively new, researchers and designers continue to modify design features to increase pollutant removal, runoff reduction, and overall performance of the practice.

Bioretention is an example of an LID practice that has been researched intensively to determine the most efficient design with respect to media depth, media selection, vegetative cover, drainage configuration, ponding depth, and capture volume (Davis et al. 2009). Original bioretention designs included a conventional underdrain configuration, which consisted of lateral, perforated drains present in a gravel layer beneath the filter media. A drawback of this design configuration was that the filter media was predominantly aerobic, so organic nitrogen and ammonium that were captured during runoff events were transformed to nitrate and released as such in the effluent. Field-monitored bioretention cells with conventional drainage reported poor removal of nitrate, and in most cases, effluent nitrate concentrations increased (Davis et al. 2001; Hatt et al. 2009; Hsieh and Davis 2005; Hunt et al. 2006, 2008; Roseen et al. 2006).

The lack of nitrate reduction was a concern in initial bioretention research because many of the study sites were located in nitrogen-sensitive watersheds. Modifying the design to promote denitrification would improve the efficiency of bioretention cells in removing nitrogen from storm water runoff. Kim et al. (2003) first proposed a raised underdrain outlet to create a continuously submerged anaerobic zone to promote denitrification and improve nitrate and total nitrogen reduction. The results from pilot-scale bioretention studies were 70–80% mass removal rates of nitrate plus nitrite ($NO_{2,3}$-N) (Kim et al. 2003). A diagram of a bioretention cell with an elevated underdrain, also known as internal water storage (IWS) zone, is shown in Fig. 1. Despite promising laboratory results, later field studies by Dietz and Clausen (2006) and Hunt et al. (2006) were

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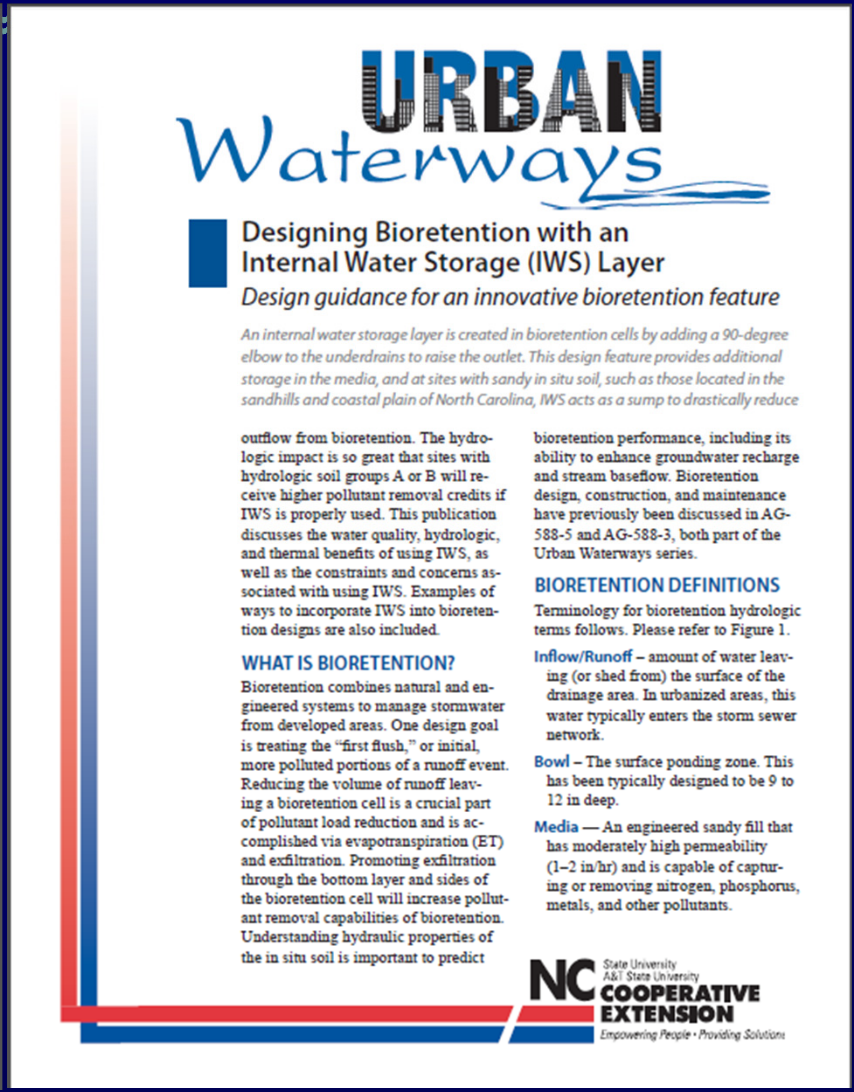

URBAN Waterways

Designing Bioretention with an Internal Water Storage (IWS) Layer

Design guidance for an innovative bioretention feature

An internal water storage layer is created in bioretention cells by adding a 90-degree elbow to the underdrains to raise the outlet. This design feature provides additional storage in the media, and at sites with sandy in situ soil, such as those located in the sandhills and coastal plain of North Carolina, IWS acts as a sump to drastically reduce

outflow from bioretention. The hydrologic impact is so great that sites with hydrologic soil groups A or B will receive higher pollutant removal credits if IWS is properly used. This publication discusses the water quality, hydrologic, and thermal benefits of using IWS, as well as the constraints and concerns associated with using IWS. Examples of ways to incorporate IWS into bioretention designs are also included.

WHAT IS BIORETENTION?

Bioretention combines natural and engineered systems to manage stormwater from developed areas. One design goal is treating the "first flush," or initial, more polluted portions of a runoff event. Reducing the volume of runoff leaving a bioretention cell is a crucial part of pollutant load reduction and is accomplished via evapotranspiration (ET) and exfiltration. Promoting exfiltration through the bottom layer and sides of the bioretention cell will increase pollutant removal capabilities of bioretention. Understanding hydraulic properties of the in situ soil is important to predict bioretention performance, including its ability to enhance groundwater recharge and stream baseflow. Bioretention design, construction, and maintenance have previously been discussed in AG-588-5 and AG-588-3, both part of the Urban Waterways series.

BIORETENTION DEFINITIONS

Terminology for bioretention hydrologic terms follows. Please refer to Figure 1.

Inflow/Runoff – amount of water leaving (or shed from) the surface of the drainage area. In urbanized areas, this water typically enters the storm sewer network.

Bowl – The surface ponding zone. This has been typically designed to be 9 to 12 in deep.

Media — An engineered sandy fill that has moderately high permeability (1–2 in/hr) and is capable of capturing or removing nitrogen, phosphorus, metals, and other pollutants.

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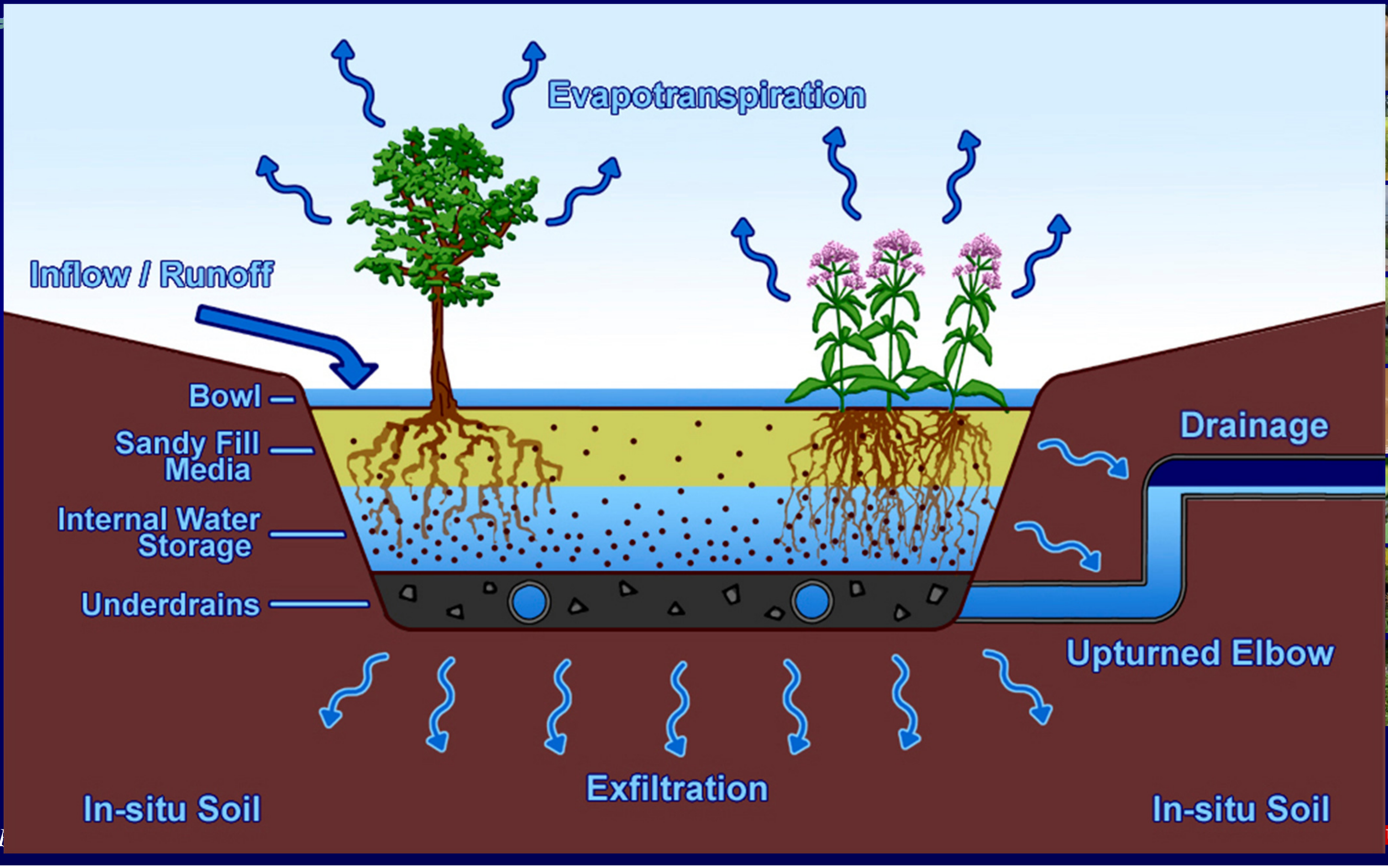
What is an Internal Water Storage Zone?

- Internal Water Storage = IWS
- Originally developed to improve nitrate reduction in N-sensitive watershed
  - Bottom of cell remains saturated → anaerobic conditions created to reduce nitrate TN
- Main benefit → “Infiltration Enhancer”
  - Biggest impact in sandy in-situ soils
    - Outflow → rare

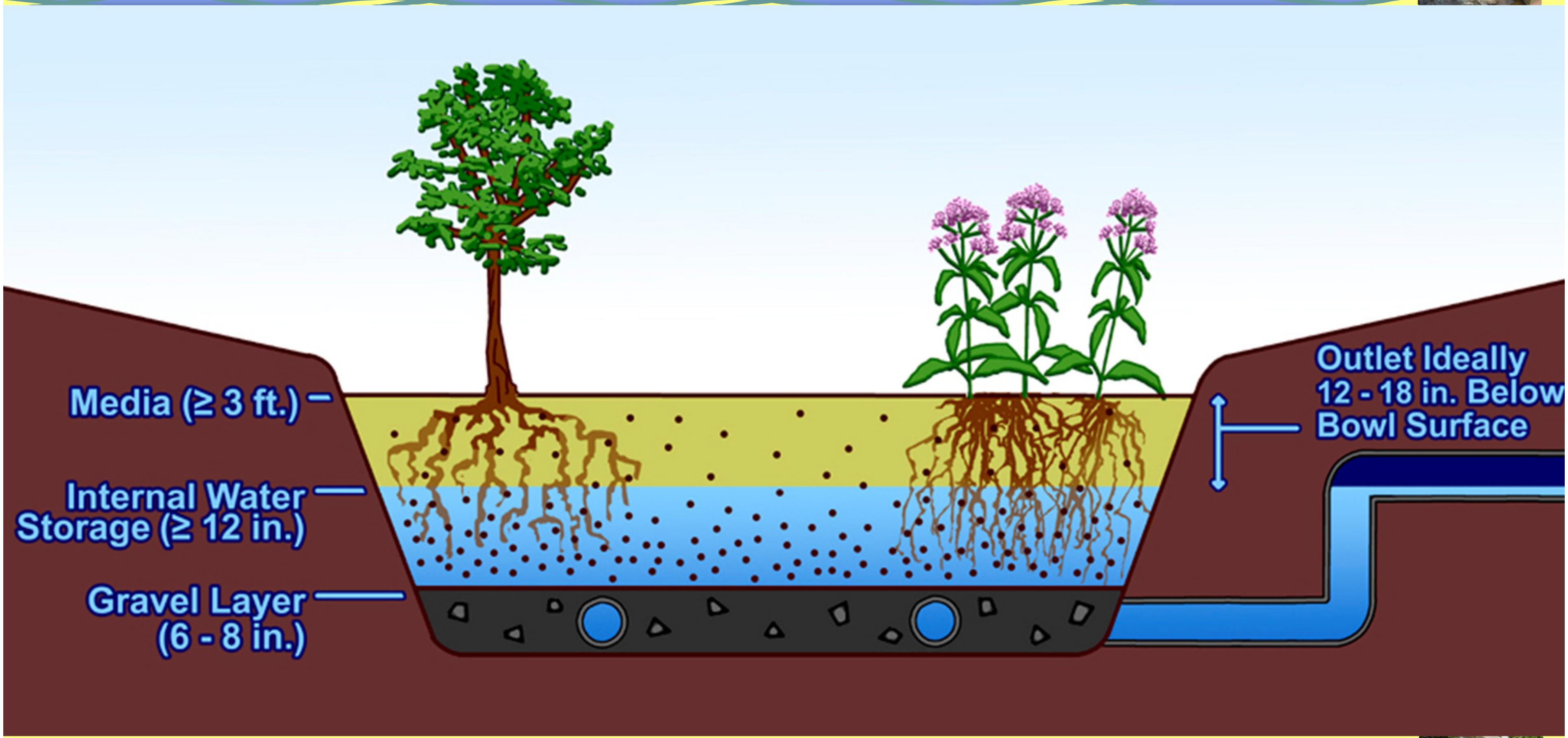
Bioretention Cell Schematic



Increased Pollutant Removal Credit for Bioretention w/ IWS

- Specifications
  - Applies to Sandhills, upper coastal plain, coastal plain, and barrier islands
  - Minimum media depth – 0.9m (3 ft)
  - Top of IWS no closer to surface of media than 30cm, but no shallower than 30cm above bottom of cell
  - *NC State Guideline* – pre-construction underlying soil permeability at least 25mm/hr

New NCDENR Design Guidance



Increased Pollutant Removal Credit for Bioretention w/ IWS

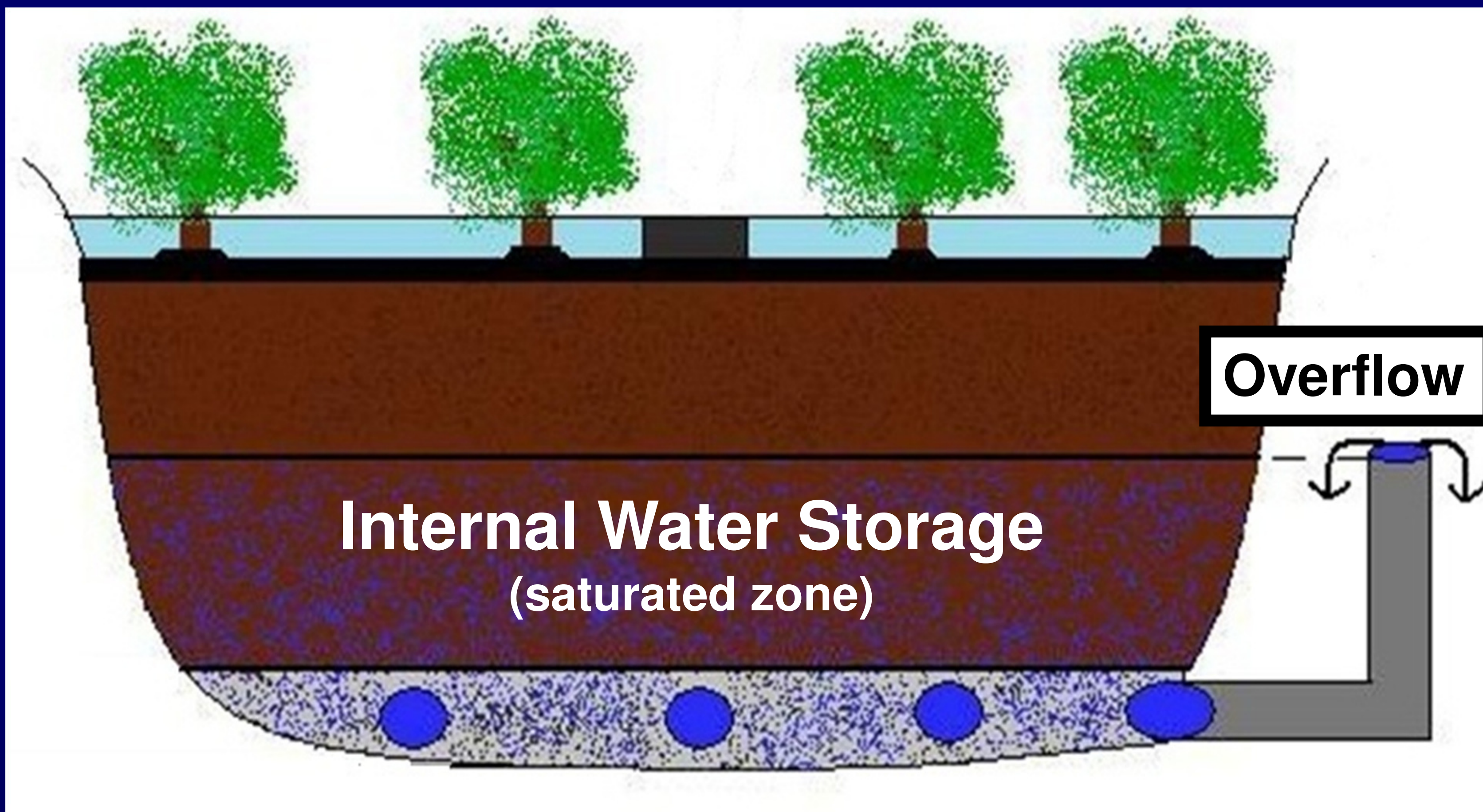
	Total Nitrogen	Total Phosphorus	TSS
Old NC DENR Credit (Statewide)	35%	45%	85%
Revised NC DENR Credit (Sandhills and Coastal Plain)	**60%**	**60%**	85%
Revised NC DENR Credit (Piedmont & Mts)	**40%**	45%	85%

In order to receive additional credit in Piedmont or Mtns, Cell must be constructed at site with a B Hydrologic Soil Group.

Employing an IWS in Oz. Called: Saturated Zone

Drains force water to within 100mm of surface

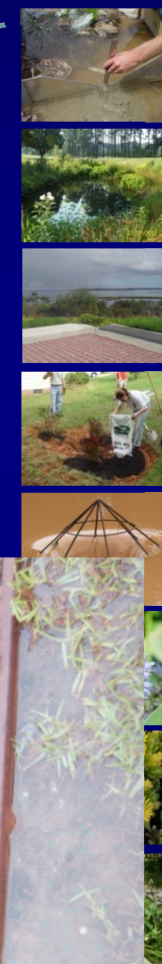
Bioretention Cell Schematic



How is an Internal Water Storage Zone Created?

- Elevating the outlet with a 90º PVC elbow to force water to be ponded in bottom layer.

Most Common Install Method: Upturned Pipe in Outlet

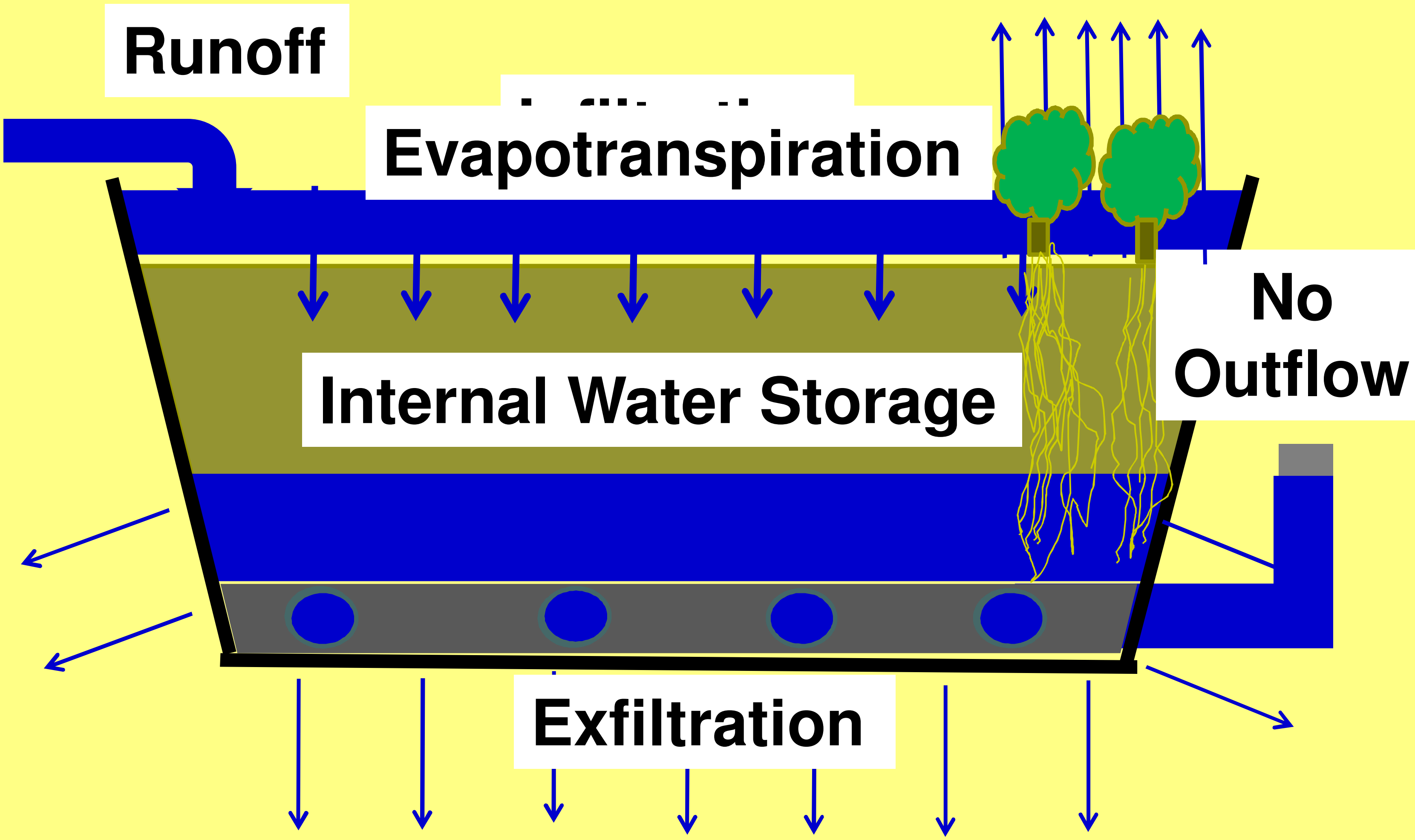


Looking down into the Overflow Basin

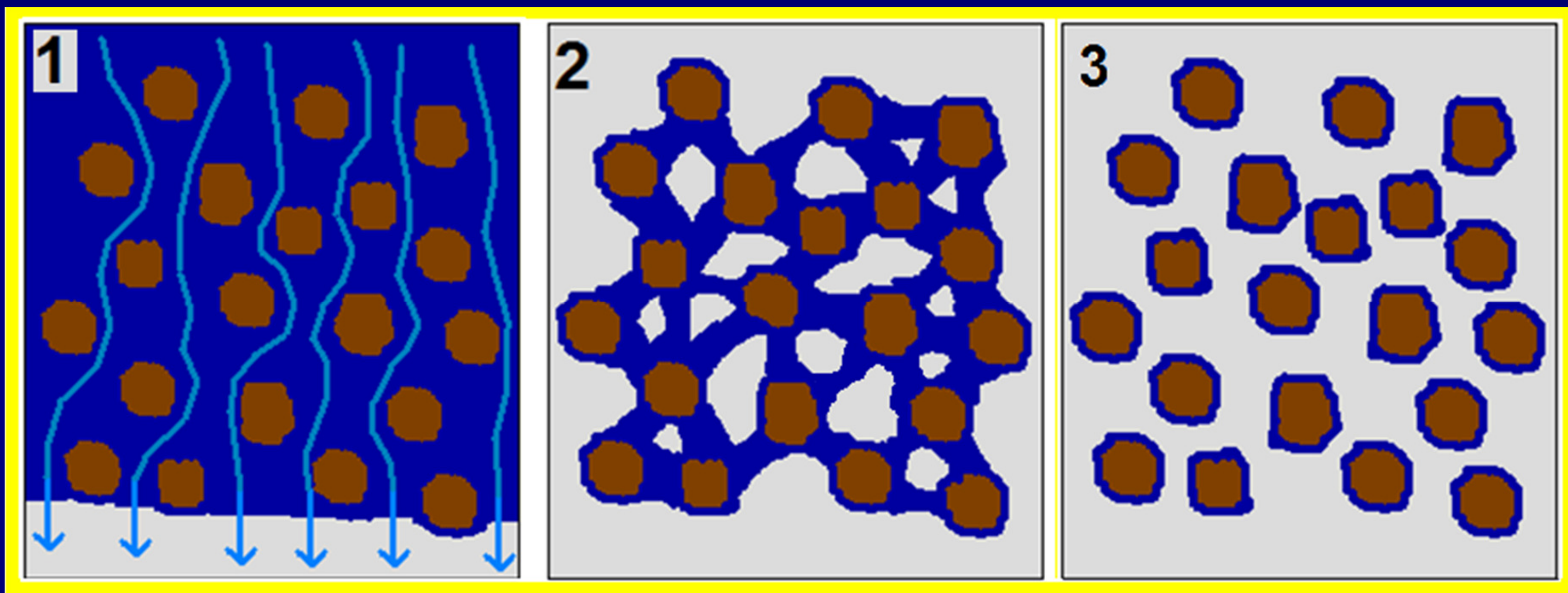
Benefits

- Hydrological
- Thermal
- Cost
- Retrofit Ease
- Water Quality

Hydrological Benefit



Effective Porosity



1. Gravitational Water (freely draining by gravity)
2. Capillary Water (held by surface tension between particles, plant-available water)
3. Hygroscopic Water (held tightly, not plant available)

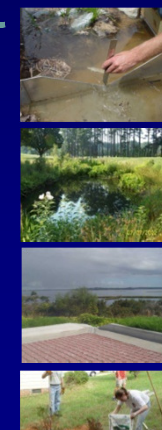
Storage Availability in IWS: Example Calculations

- 0.9m media w/ underdrain & 20cm gravel layer

IWS Depth in Media	60 cm	45 cm	30 cm
Available Water Storage (units of depth)	23.4 cm	18.8 cm	14.2 cm
Typical Storm Size Captured (100% impervious, 8.4:1 ratio)	25.7mm	20.8mm	16.0mm

Monitoring Hydrologic Benefits

Rocky Mount

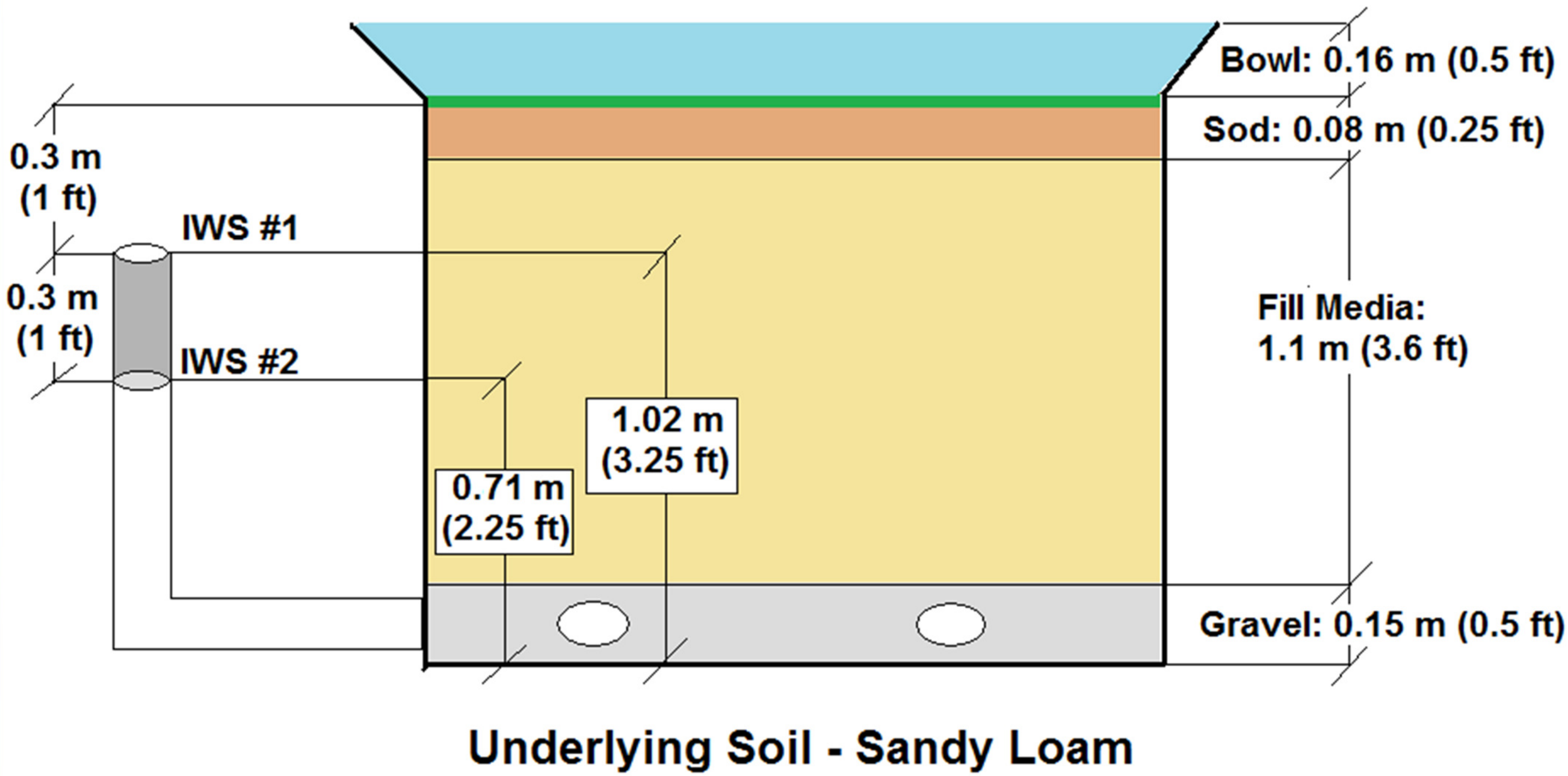


- Imperial Centre: Museum & Performing Arts
- Grassed Cell (*sandy loam underlying soil*)
- Mulched/Shrub Cell (*sand underlying soil*)

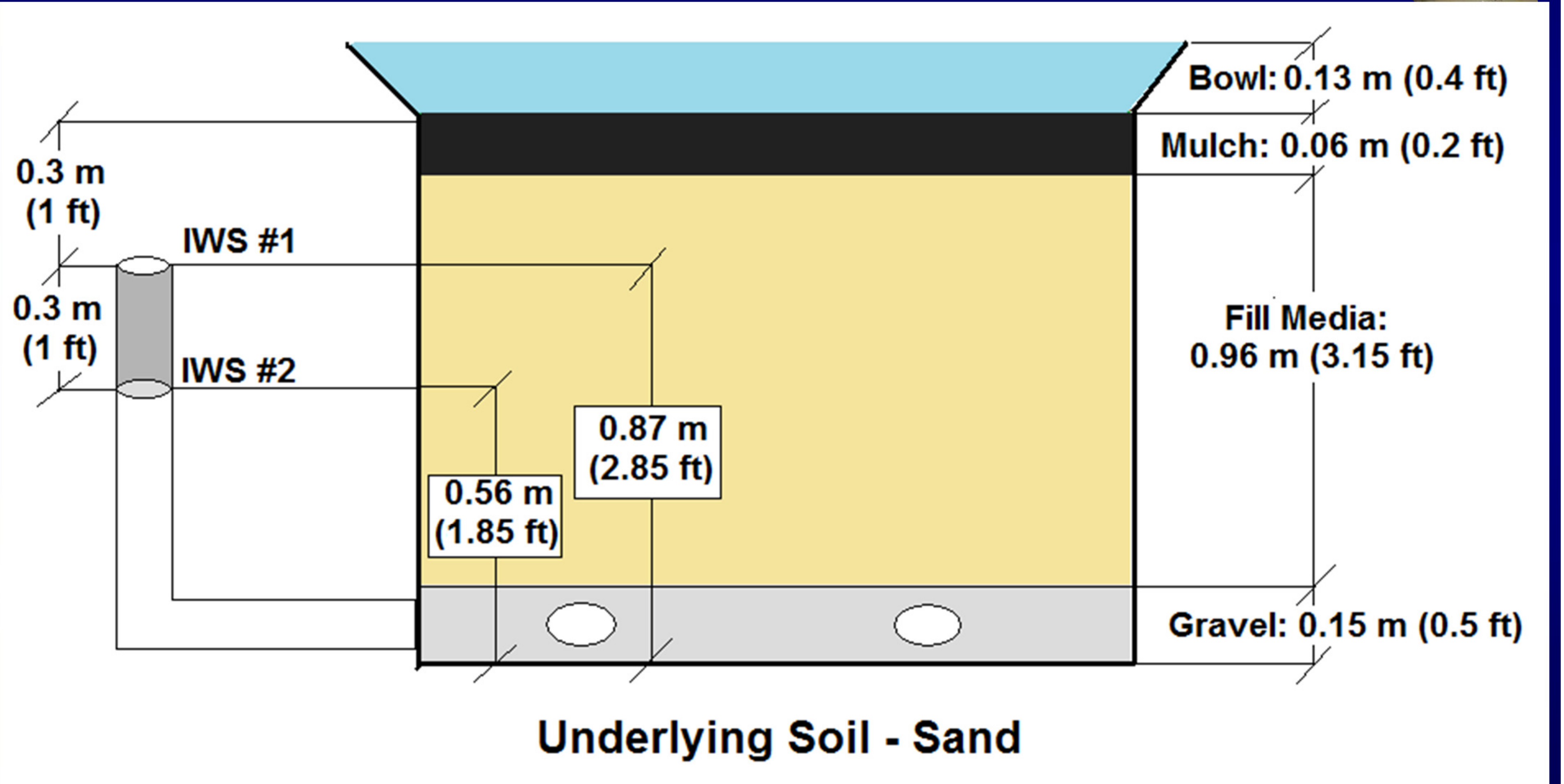
Rocky Mount Characteristics

Characteristics	“Sandy Loam”	“Sand”
Vegetative Cover	**Grass**	**Shrub/Perennial**
Subsoil	**Sandy Loam**	**Sand**
Exfiltration Rate	8-10 mm/hr	150-300 mm/hr
Drainage Area	0.22 ha	0.25 ha
Impervious Area	76 %	72 %
Bioretention Surf. Area	139 m^2	150 m^2
Media	Sand (96% sand, 4% silt & clay)	

Sandy Loam Cell (Grass)



Sand Cell (Mulch/Shrub)

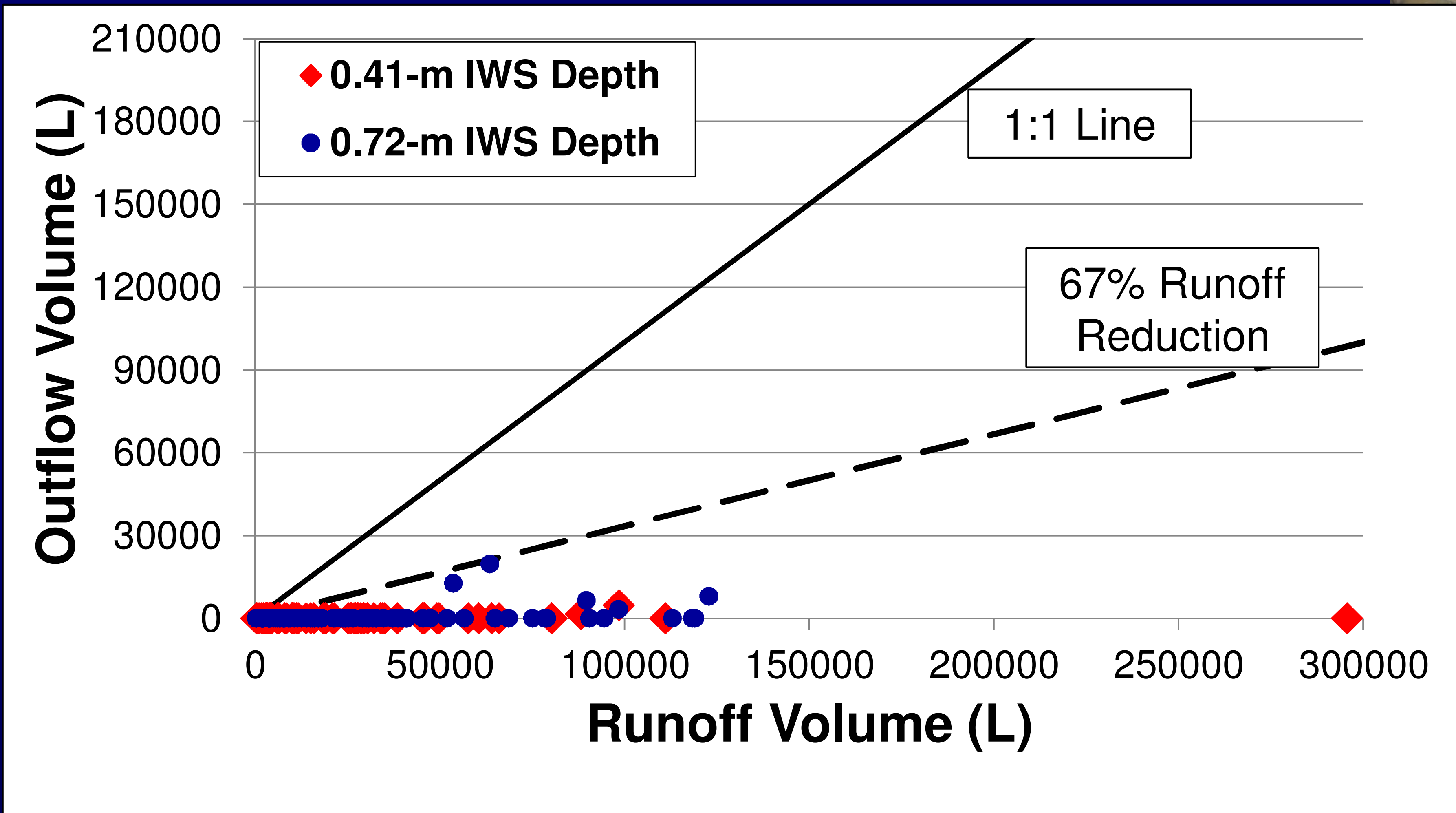


Rocky Mount

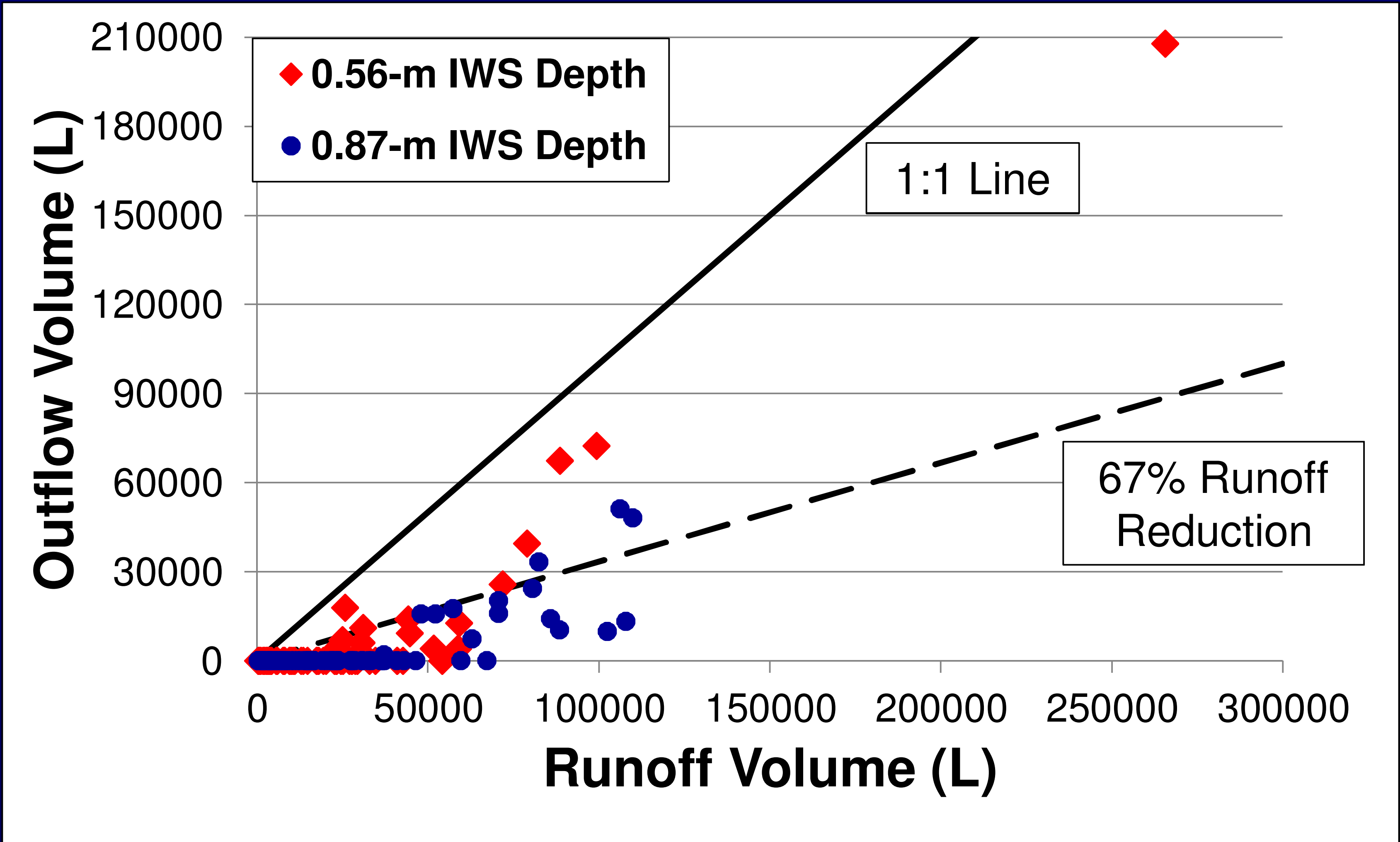
IWS Depth	Dates	n	Events > 25mm	Sandy Loam Cell Drainage	Sand Cell Drainage
Deep	9/15/07 to 1/13/09	78	15	5 events	4 events
Shallow	1/14/09 to 1/11/10	73	8	16 events	2 events

- Shallow IWS monitoring period
  - Fewer intense & large storms

Outflow vs. Runoff
(Sand underlying soil)



Outflow vs. Runoff
(Sandy loam underlying soil)



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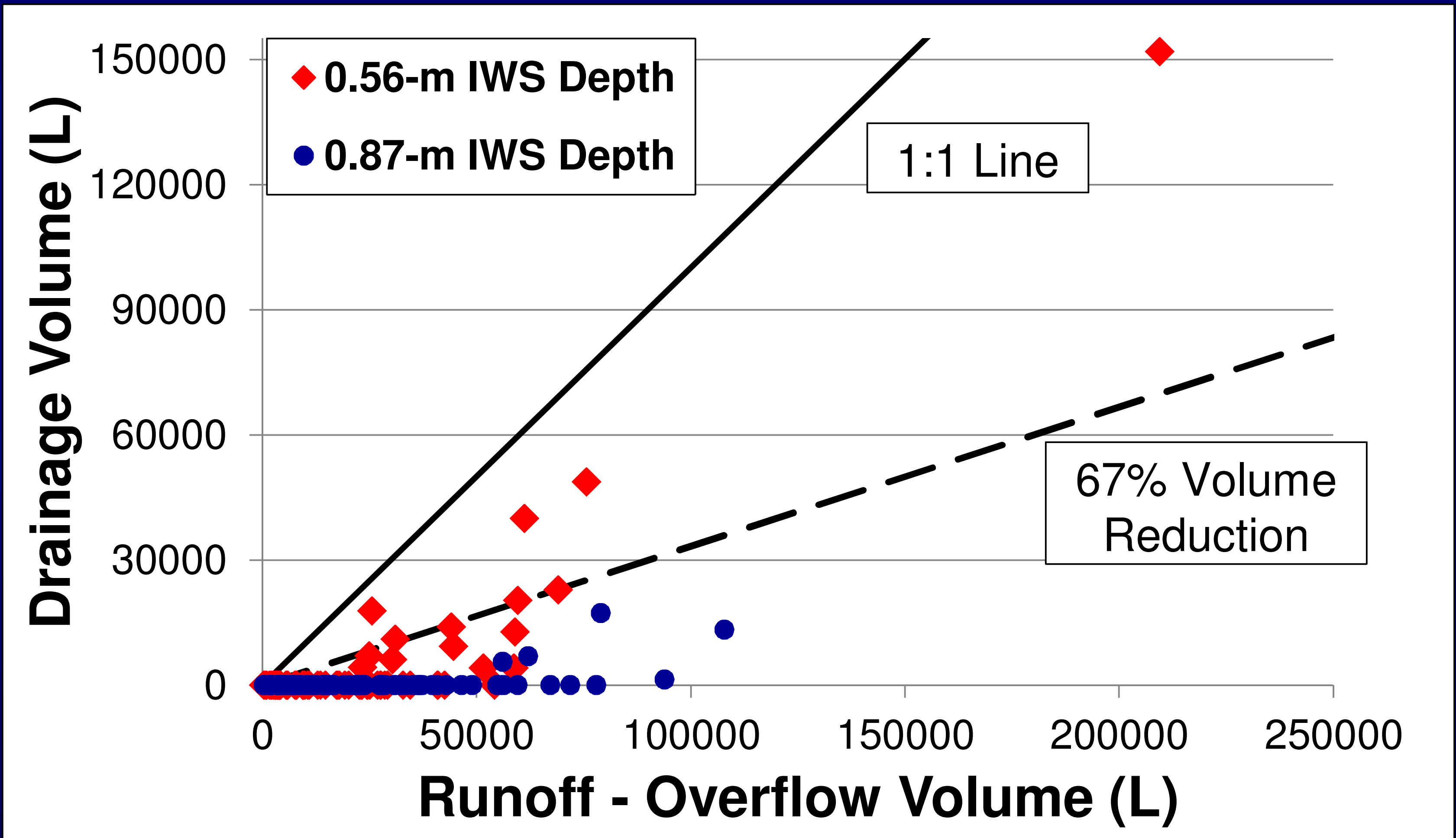
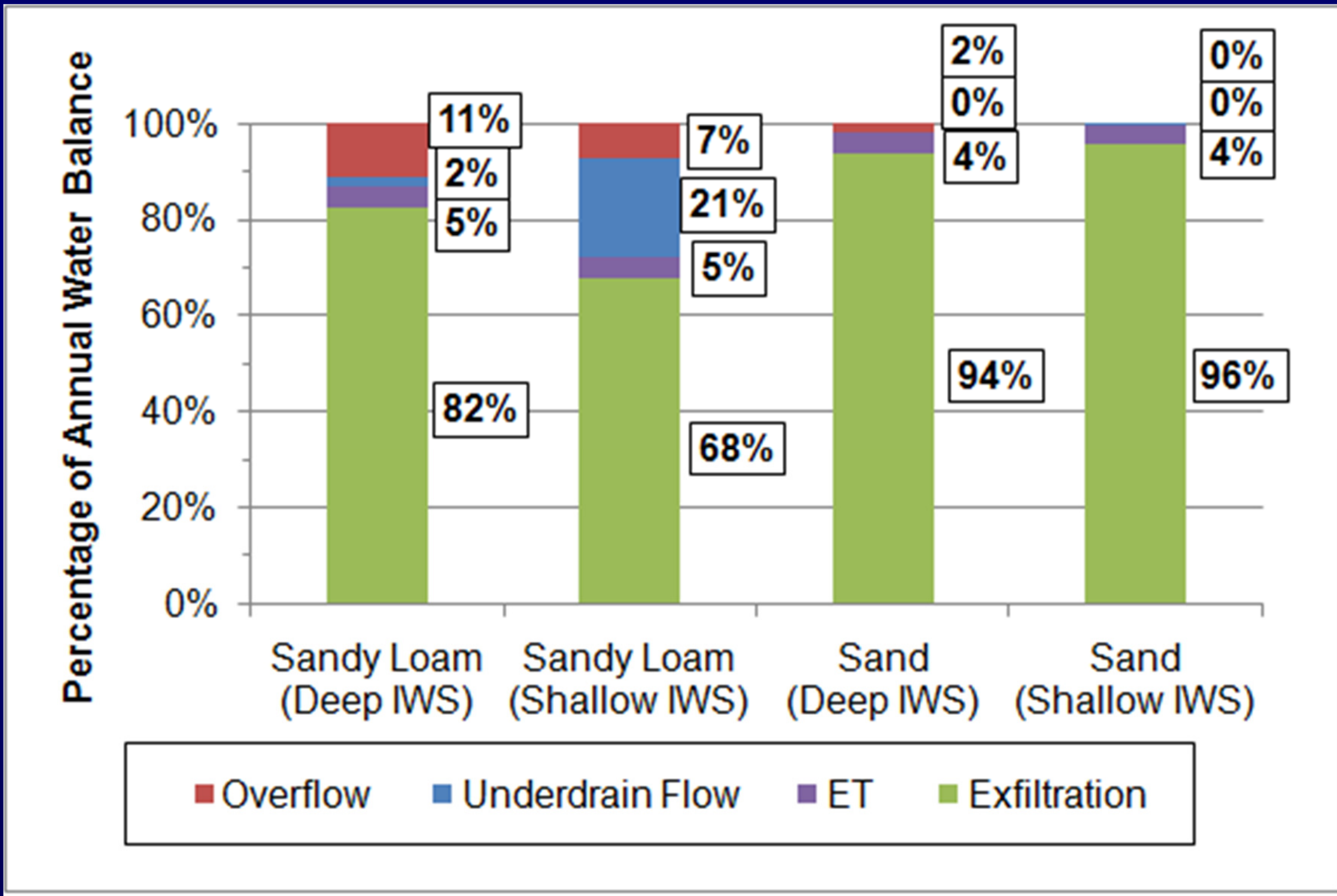
Drainage vs. (Treated) Runoff
(Sandy loam underlying soil)



Water Balance



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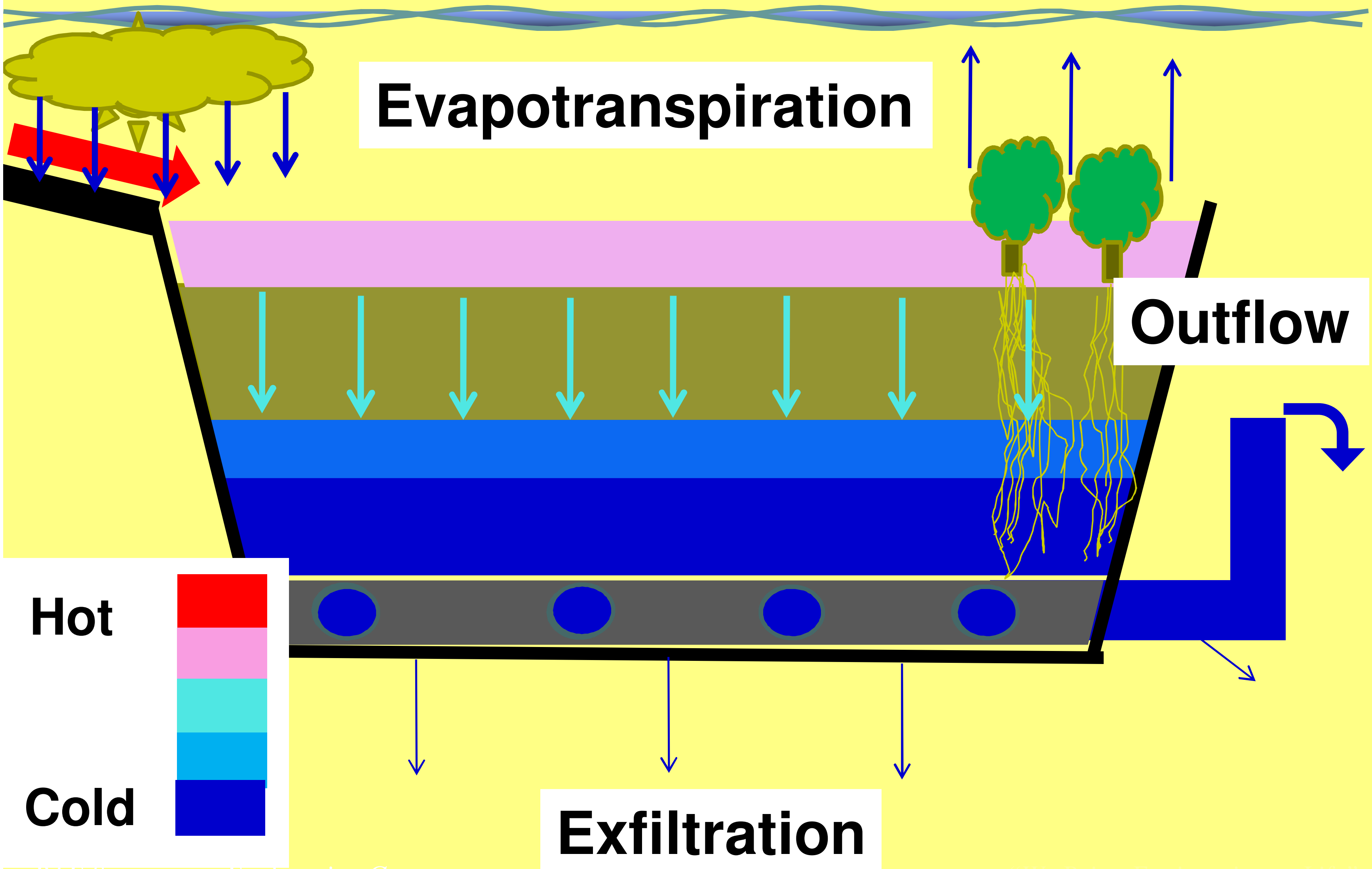
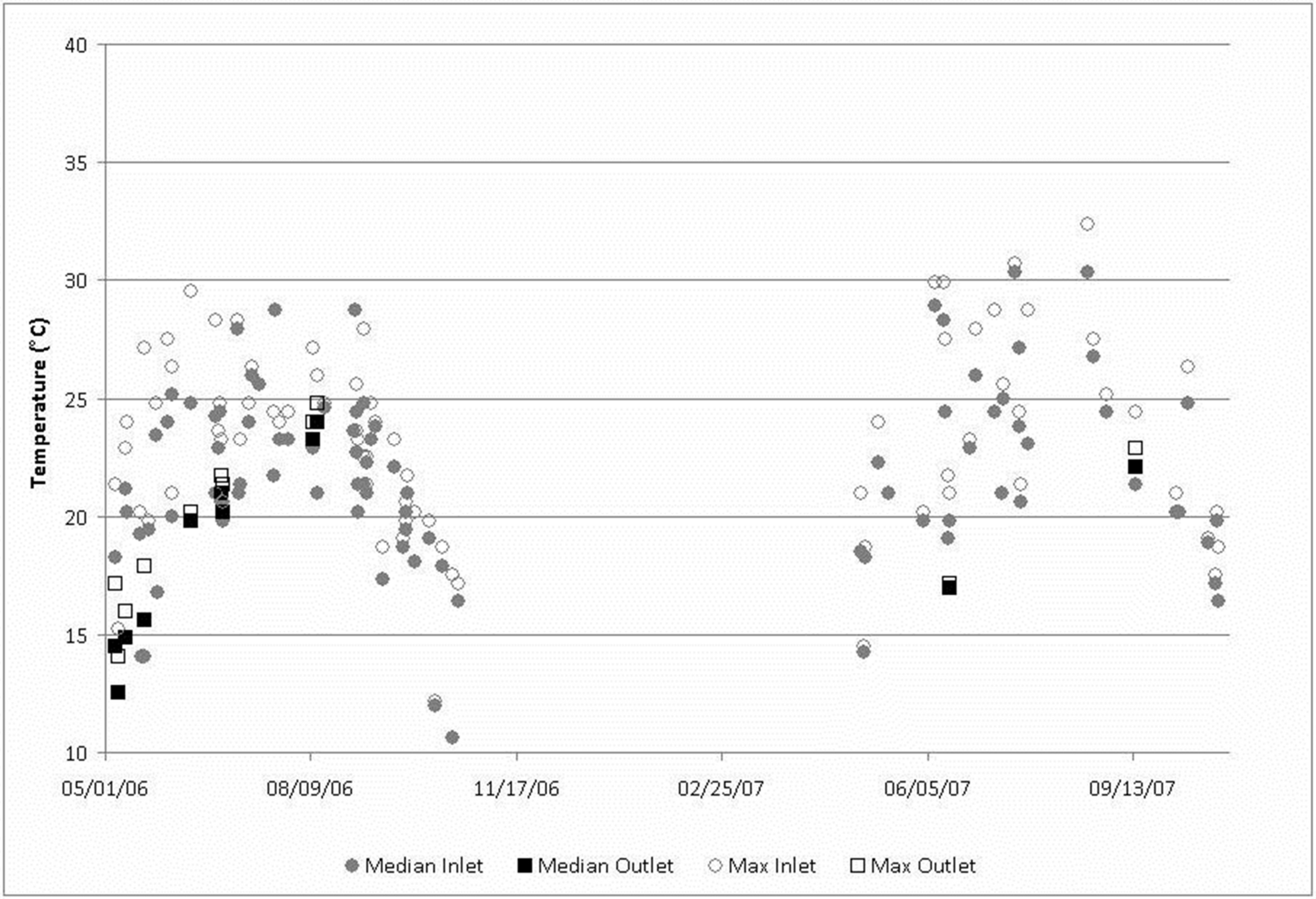
Thermal Benefit

- Draws water from bottom of media profile
  - Location of coolest water
  - Experiences smallest changes in temp. during storm events
- Volume decreased → thermal load decreases

Thermal Benefit



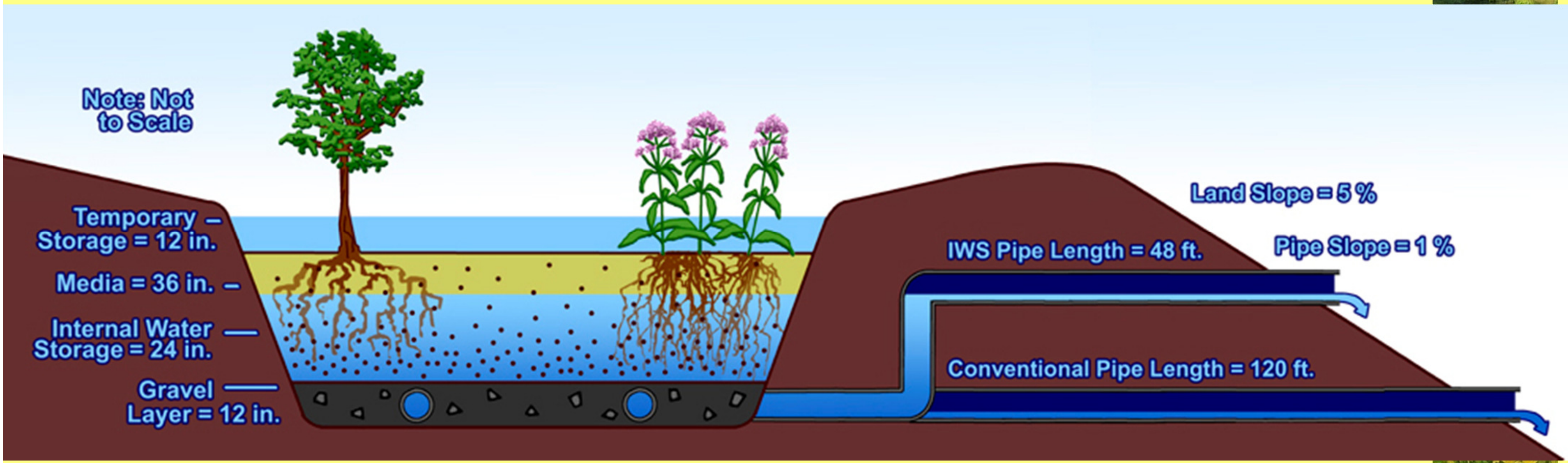
Inlet V. Outlet Temps: Asheville



Cost Savings

- Tie into existing landscape easier b/c elev. drop from underdrain to outlet is less
  - Fewer materials (pipe/drain tube)
  - Length of trench to outlet underdrain is shorter
- Best applied in where little change in elevation is accessible
  - Coastal plain (flat lands)
  - Retrofits

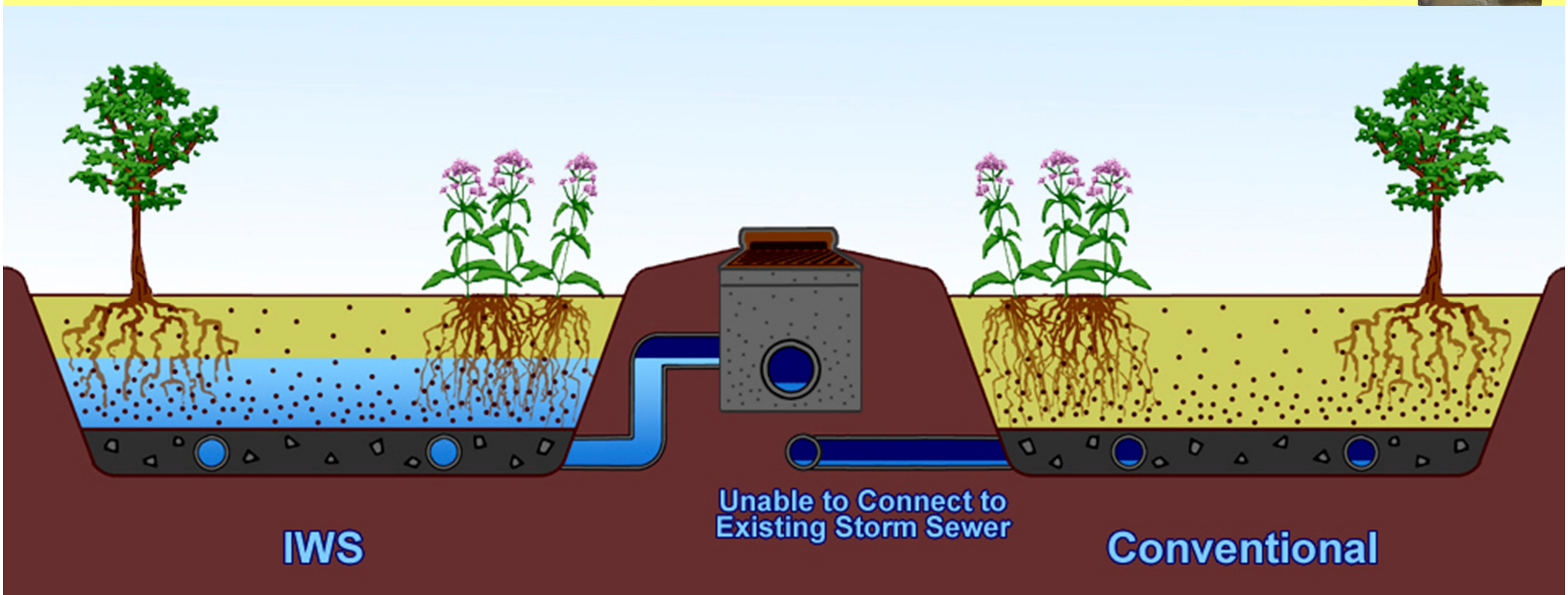
Retrofit Ease / Cost Savings

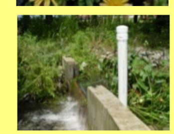


Retrofits

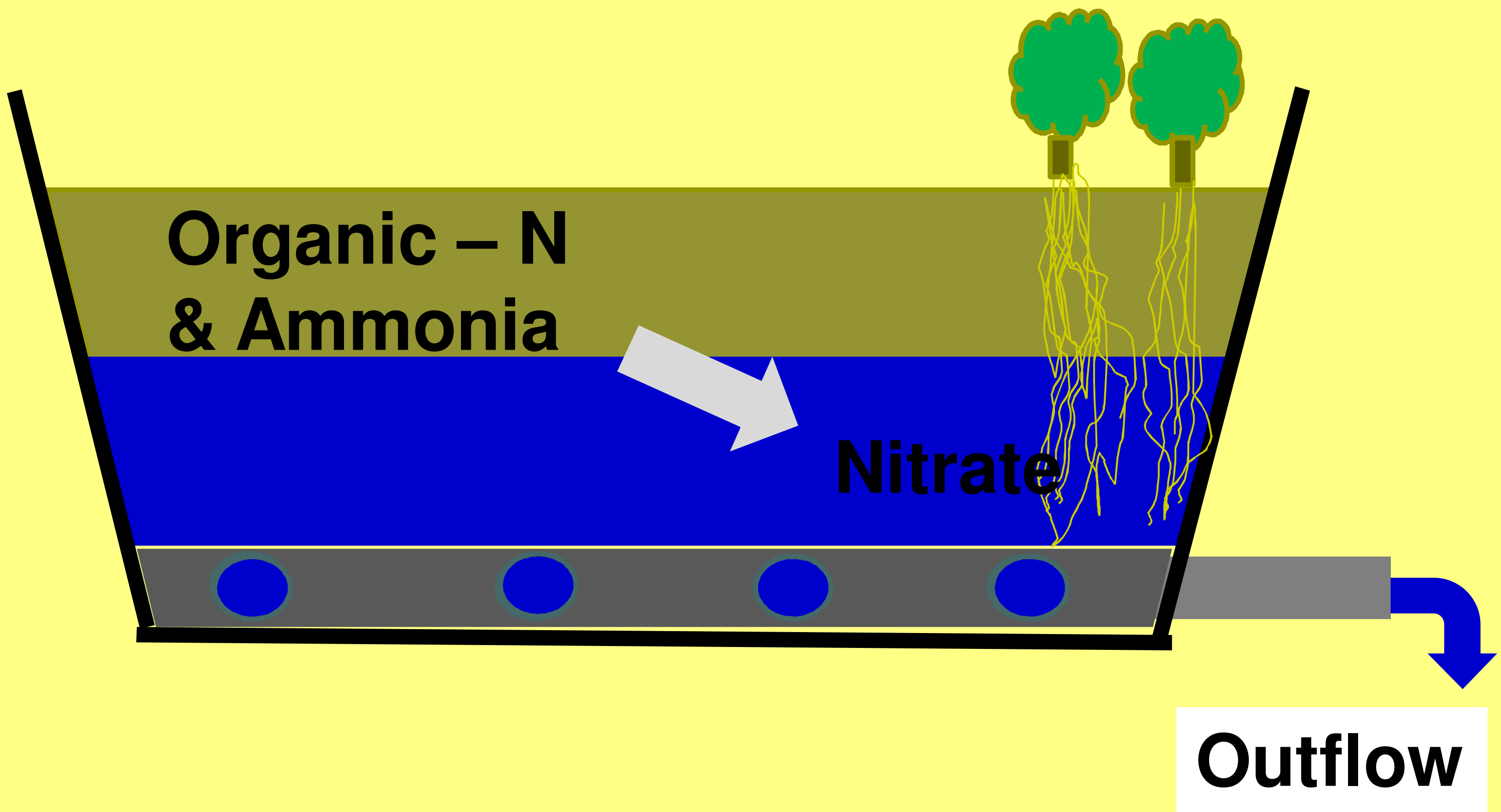
- Easy to tie in underdrain outlet
  - Less elevation change to worry about
  - Save $$$ on trenching and pipe cost
  - Avoid underground power lines (often 1m deep)
- Incorporating IWS makes some design scenarios feasible

Retrofit Ease / Cost Savings

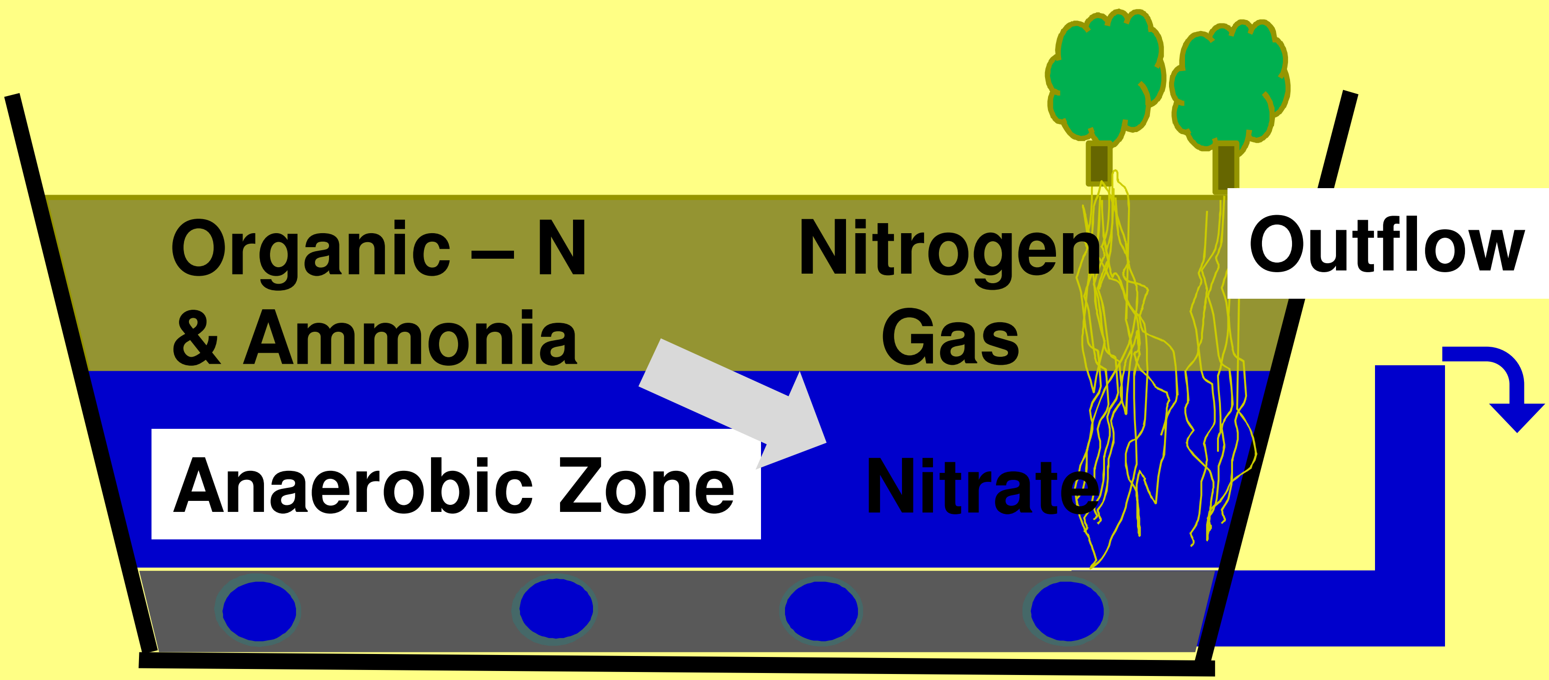




In theory…
Conventional Drainage



In theory…
IWS Water Quality Benefit



Sand Cell: Water Quality

- All samples (drainage [3] & grab [5]), n=8
  - Both monitoring periods; units: **mg/L**
- Time for IWS to fully drain: < 3 hours

	TKN	NH_3-N	NO_3 + NO_2	TN
Inflow	1.18	0.34	0.46	1.65
Sand Cell	0.86	0.07	0.53	1.40
Efficiency Ratio	**27%**	**78%**	**-15%**	**15%**
NC Credit (pollutant load removal)				**35%**
Statistical Sig.	none	(–)	none	none

Sandy Loam Cell: Water Quality

- Samples with drainage, n=11
  - Both monitoring periods; units: **mg/L**
- Time for IWS to fully drain: 3 to 5 days

	TKN	NH_3-N	NO_3 + NO_2	TN
Inflow	0.74	0.23	0.28	1.02
Sandy Loam Cell	0.31	0.06	0.12	0.43
Efficiency Ratio	**58%**	**74%**	**58%**	**58%**
NC Credit (pollutant load removal)				**35%**
Statistical Sig.	(–)	(–)	(–)	(–)

Pollutant Load Reduction

- Overall pollutant load reduction to stormwater network (pipe)
  - Sand Cell: TN (99%) & TP (99%)
    - Volume Reduction – 99%
  - Sandy Loam Cell: TN (89%) & TP (85%)
    - Volume Reduction – 80%
  - Data from both monitoring periods combined

Take Home Points

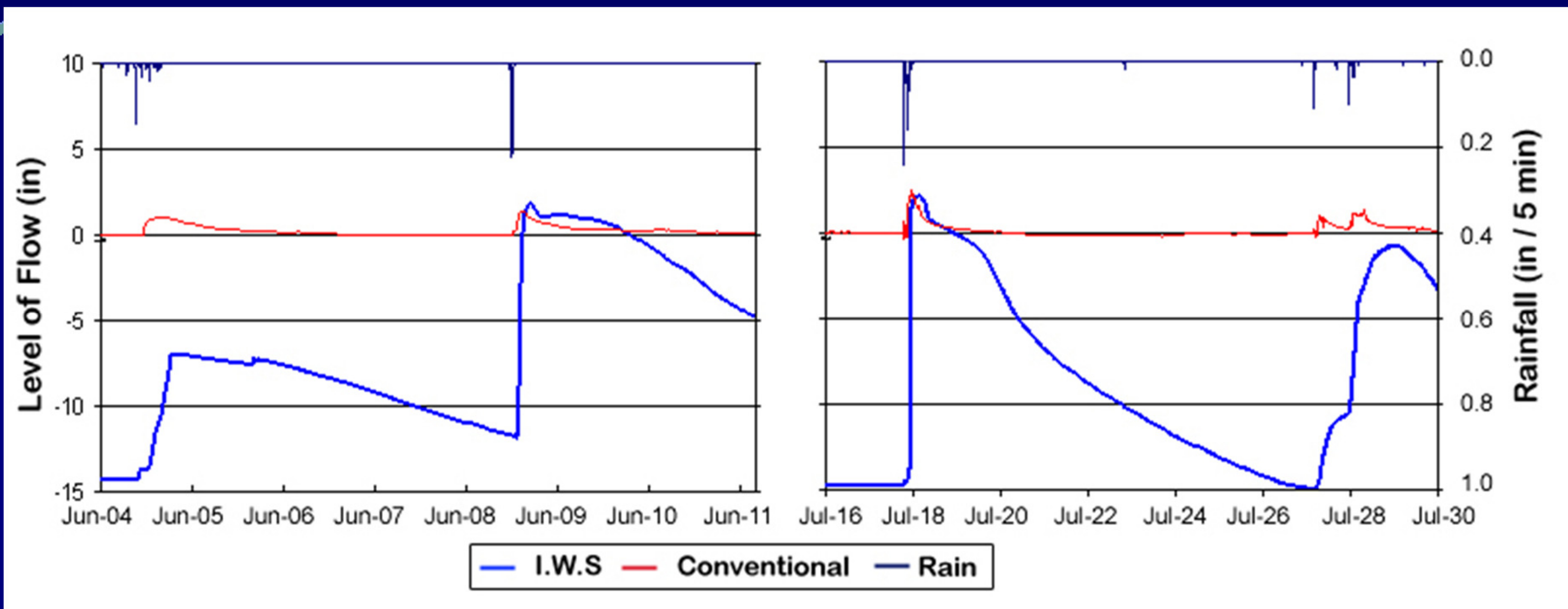
- Improves water quality
  - Primarily through load reduction
- If contact time in IWS is long enough
  - Has benefits from denitrification

- Remember, when soils get too clayey (tight)…
  - Reduced hydrologic benefit
  - However, improved concentration reduction

Drawbacks

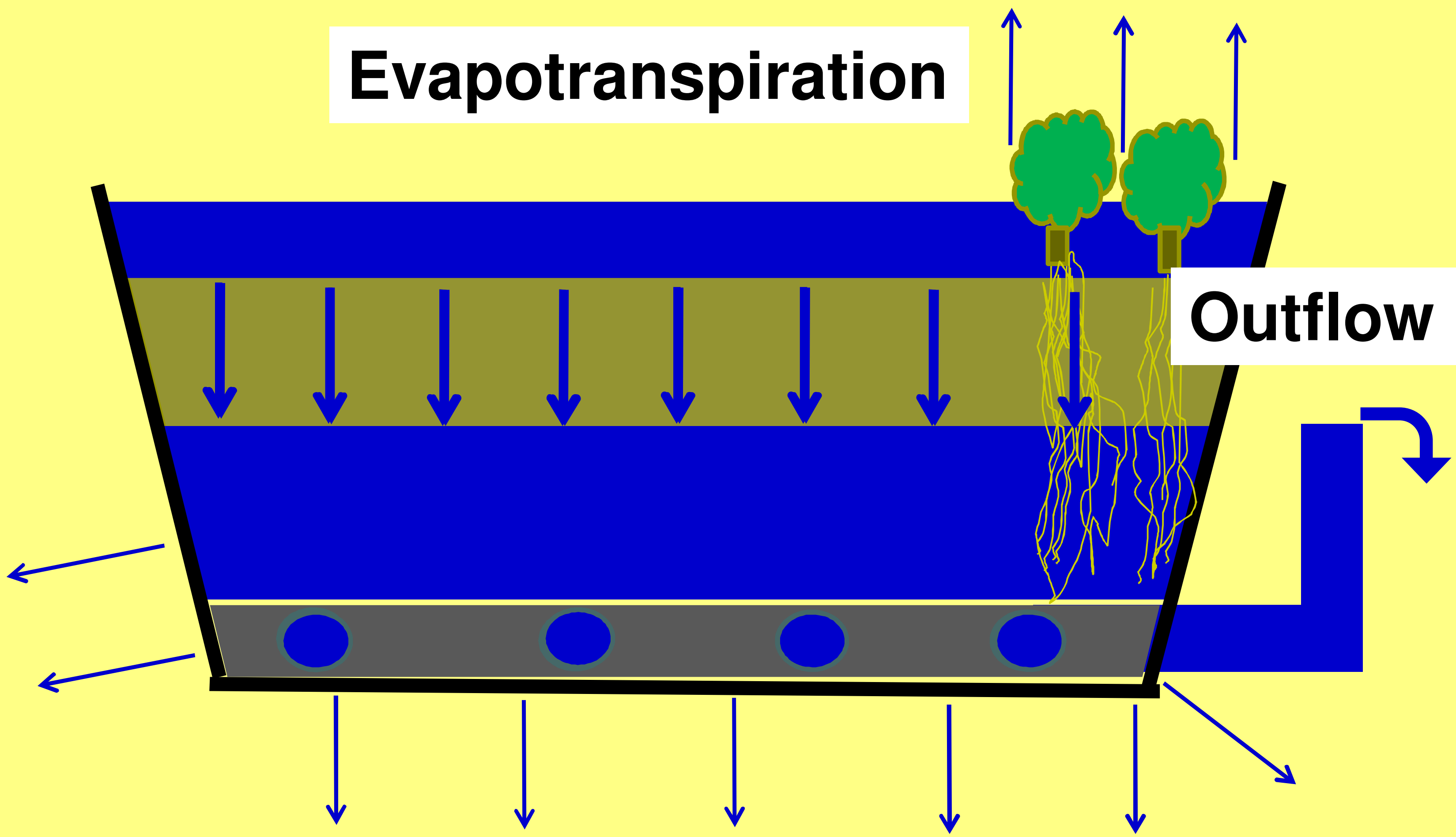
- Reduced performance for consecutive events
- Performance reduced in clay in-situ soils

Reduced Performance for Consecutive Events



Date	Rainfall (mm/in)	Inflow (L)	Bypass (L)	Drain G-1 (L) (2 ft IWS)	Drain G-2 (L) (No IWS)
6/4-5/04	22.6/0.89	41,800	2,100	0	3,200
6/8/04	25.4/1.00	47,500	7,700	4,600	3,200
7/17/04	63.2/2.49	124,100	84,300	6,600	11,800
7/27-28/04	30.5/1.20	53,900	0	0	4,900

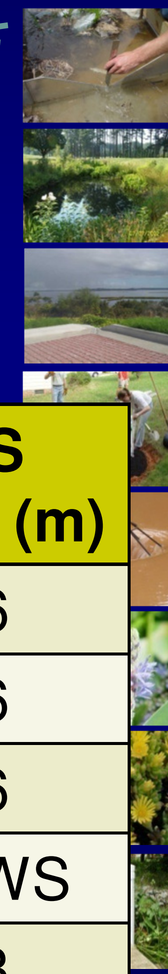
Consecutive Events



Reduced Performance in Clayey in-situ Soils

- Rocky Mount (sand): Upper Coastal Plain
- Greensboro (clay): Piedmont
- Graham: (N) loamy-clay & (S) sandy-loam

Site	# Events Monitored	# Events w/ Outflow	Media Depth (m)	IWS Depth (m)
RM Grass	78	5	0.9	0.6
RM Mulched	78	4	0.9	0.6
Greensboro 1	63	18	1.2	0.6
Greensboro 2	63	40	1.2	No IWS
Graham (N)	40	34	0.6	0.3
Graham (S)	40	22	0.9	0.6



Clay in-situ Soils

- Media depth – 0.9m
- IWS depth – 0.6m media & 0.3m gravel

Soil Type	Exfiltration Rate (mm/hr)	Drawdown Time (days)
Loamy Sand	62.5	0.6
Sandy Loam	25	1.5
Loam	12.5	3
Clay	2.5	15
Compacted Clay	1.3	30

Little benefit of IWS in Hydrologic Soil Group D

- Tight clay & Muck
- High Shrink/Swell

- Almost no potential for infiltration

IWS Depth Recommendations

- **Very sandy sites** – Hydrologic Soil Group (HSG) A, and sandy HSG B sites
  - Maximize IWS depth, drawdown of IWS not an issue
    - Set IWS outlet 12 in. from surface of media
- **More clayey sites** – HSG C, and tighter HSG B sites
  - Drawdown from IWS might not be as fast, and having a large enough aerobic zone is important
    - Set IWS outlet 18-24 in. from surface of media

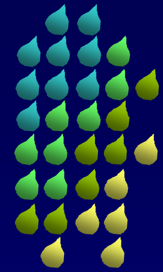
Take Home Points

- Best to use in areas of sandy in-situ soils – acts as a sump (outflow rare)
  - Coastal plain
- Easy retrofit
- Not much extra $$$, could even save some $$$ by using IWS
- Improves water quality and thermal impact
  - Load reduction
  - Contact time = N benefit, too.

Be Careful!!!

- For clay in-situ soils, exfiltration is slower, so media storage might not drain completely between events.
- For large successive events, even in sandy in-situ soils, the media storage will only be partially available.
- No hydrologic benefit in soil group D
    - IWS not necessarily better; may be worse
- Avoid seasonally high water tables!!!

Questions



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