THE OHIO STATE UNIVERSITY

Effects of Design Characteristics on Bioretention Cell (Hydrologic) Performance

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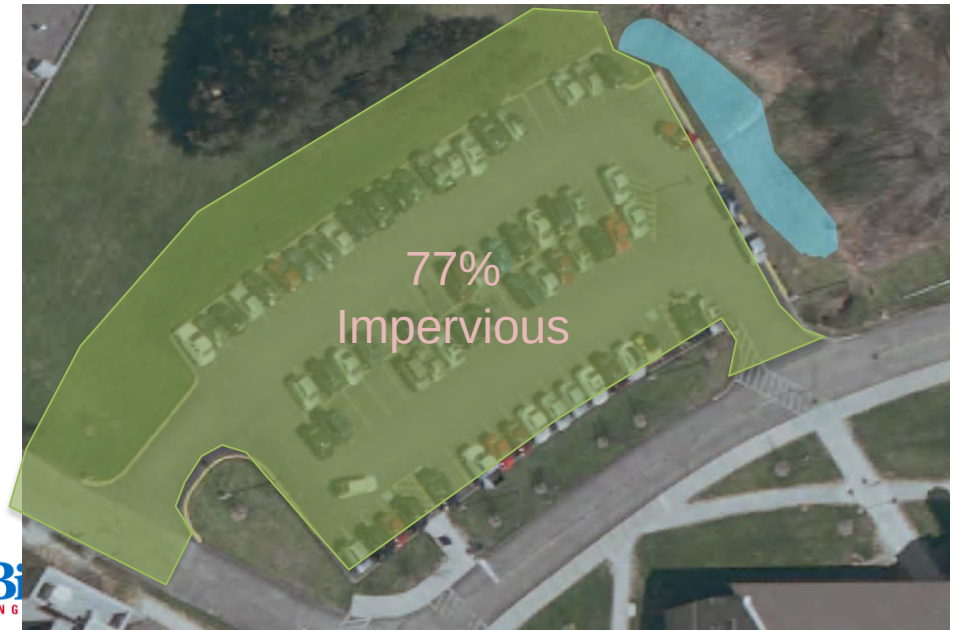
Toledo Green Infrastructure Workshop

4/14/2016

We've Monitored Bioretention Hydrology…

- At three cells in northeast Ohio
  - Clayey underlying soils
  - Internal water storage zones
  - Ohio media specification
  - Different planting palettes



But, what about…

- All of the thousands of other possible design configurations?
  - Media characteristics
  - Underlying soil K_{sat}
  - IWS depth
  - Media depth
  - Loading Ratio
  - Plants
  - Changing Climate

Long-Term Model Needed

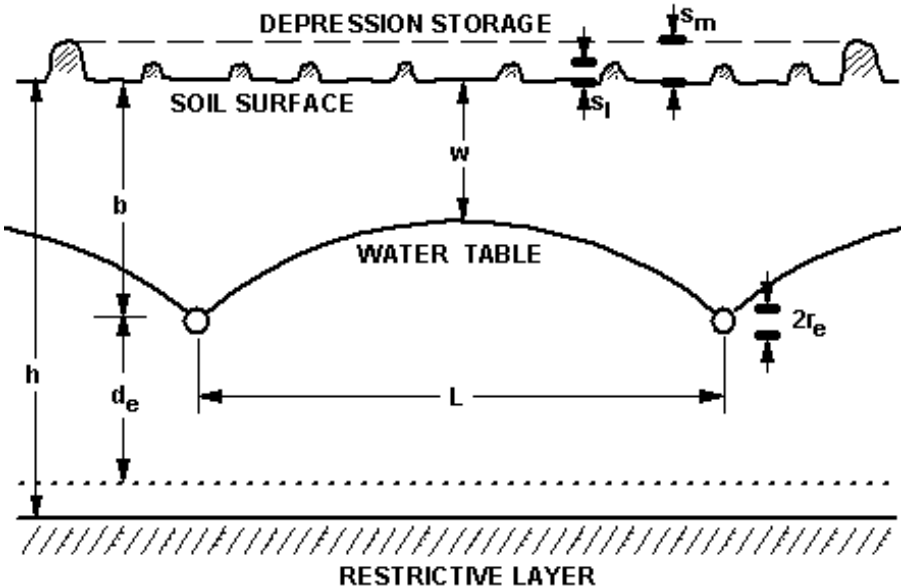
- Quantify bioretention hydrology for various design configurations
- Long-term water balance (treated drainage, untreated overflow/bypass, exfiltration/groundwater recharge)

Bioretention Models

- Many are single storm
- Do not incorporate IWS zone as a design feature
- Some current models do not accurately model underdrain flow for typical designs
  - Elementary drain calculation or only have 1 drain

What is DRAINMOD?

- Long-term Agricultural Drainage Model
- Developed in 1980s by Dr. R. Wayne Skaggs (N.C. State University)
- The USDA model for flat land, shallow water table applications

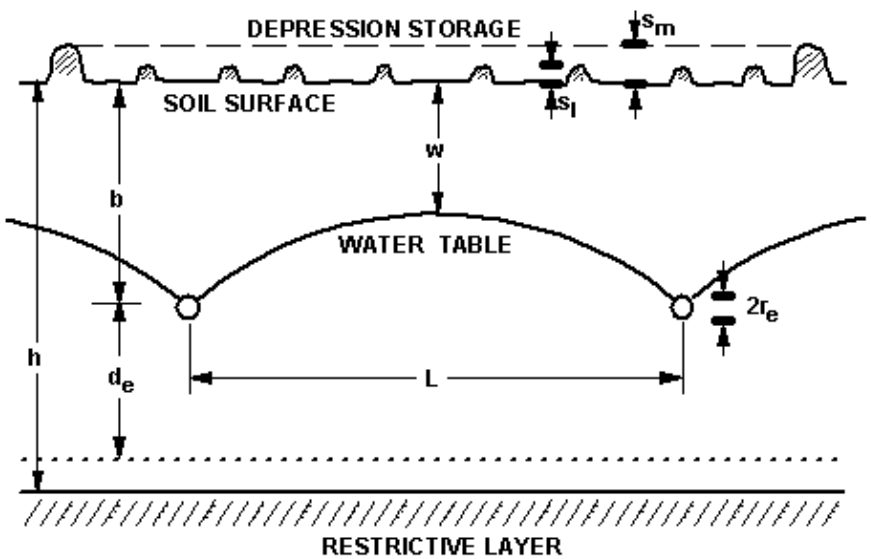


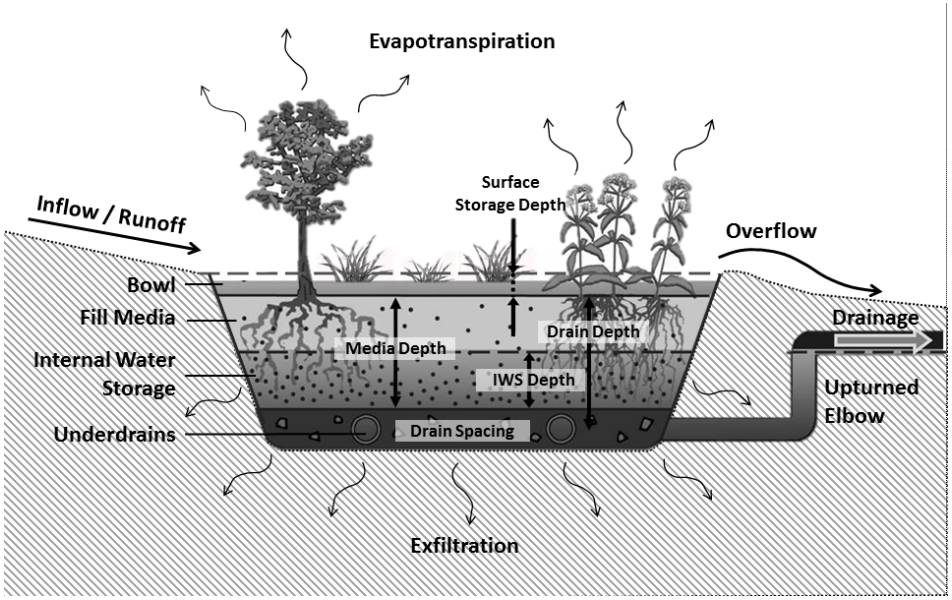
DRAINMOD Applications

- Ag drainage systems
- Controlled drainage
- Subirrigation
- Wetland hydrology
- Nitrogen dynamics and losses from drained soils
- Impacts of drainage system and irrigation management on soil salinity in arid regions
- On-site wastewater treatment

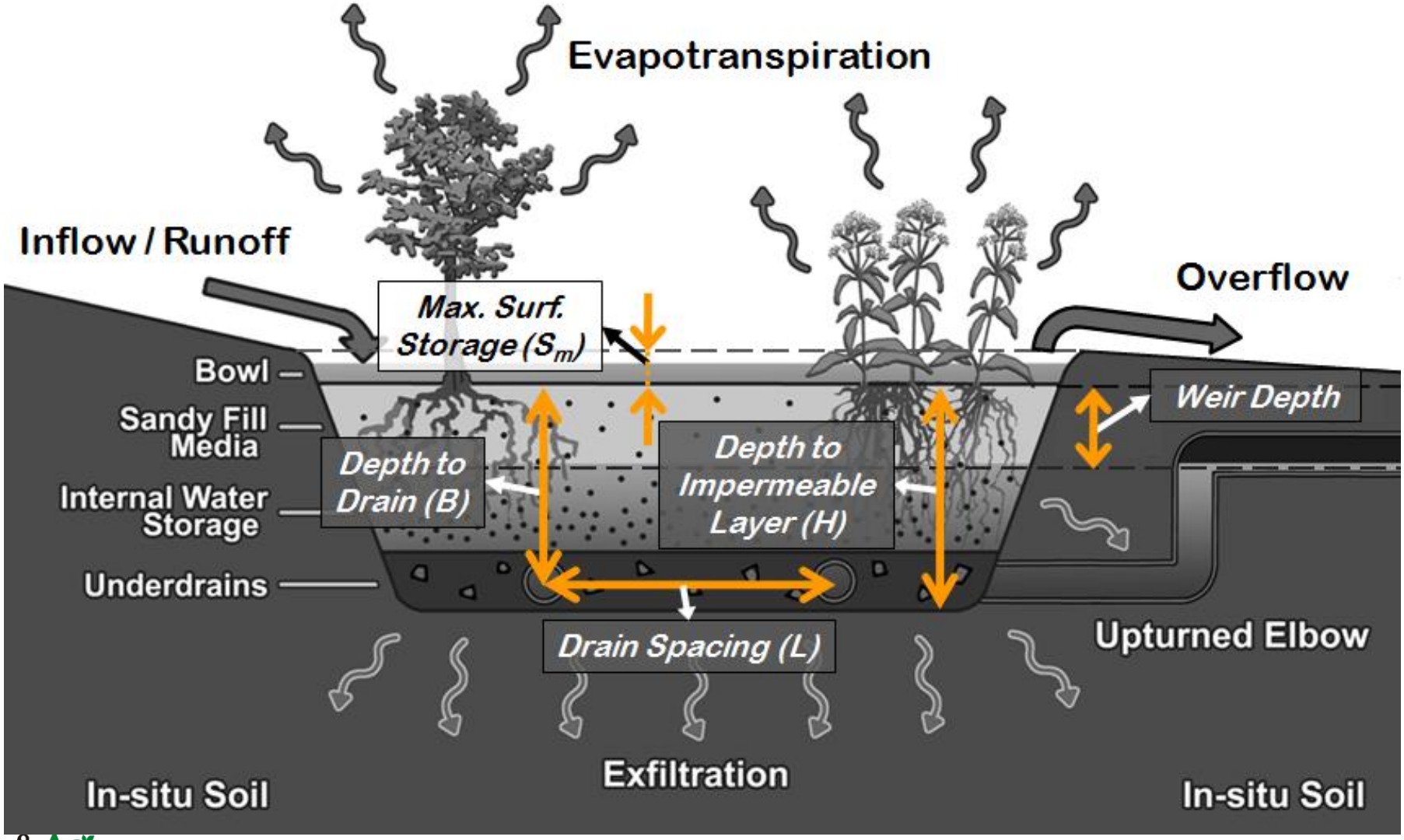
Bioretention Modeling in DRAINMOD

- Concepts of water movement in BRCs are very similar to Ag. fields with drain tiles
- Most bioretention design specifications correspond directly to DRAINMOD inputs





Bioretention Diagram



Why DRAINMOD?

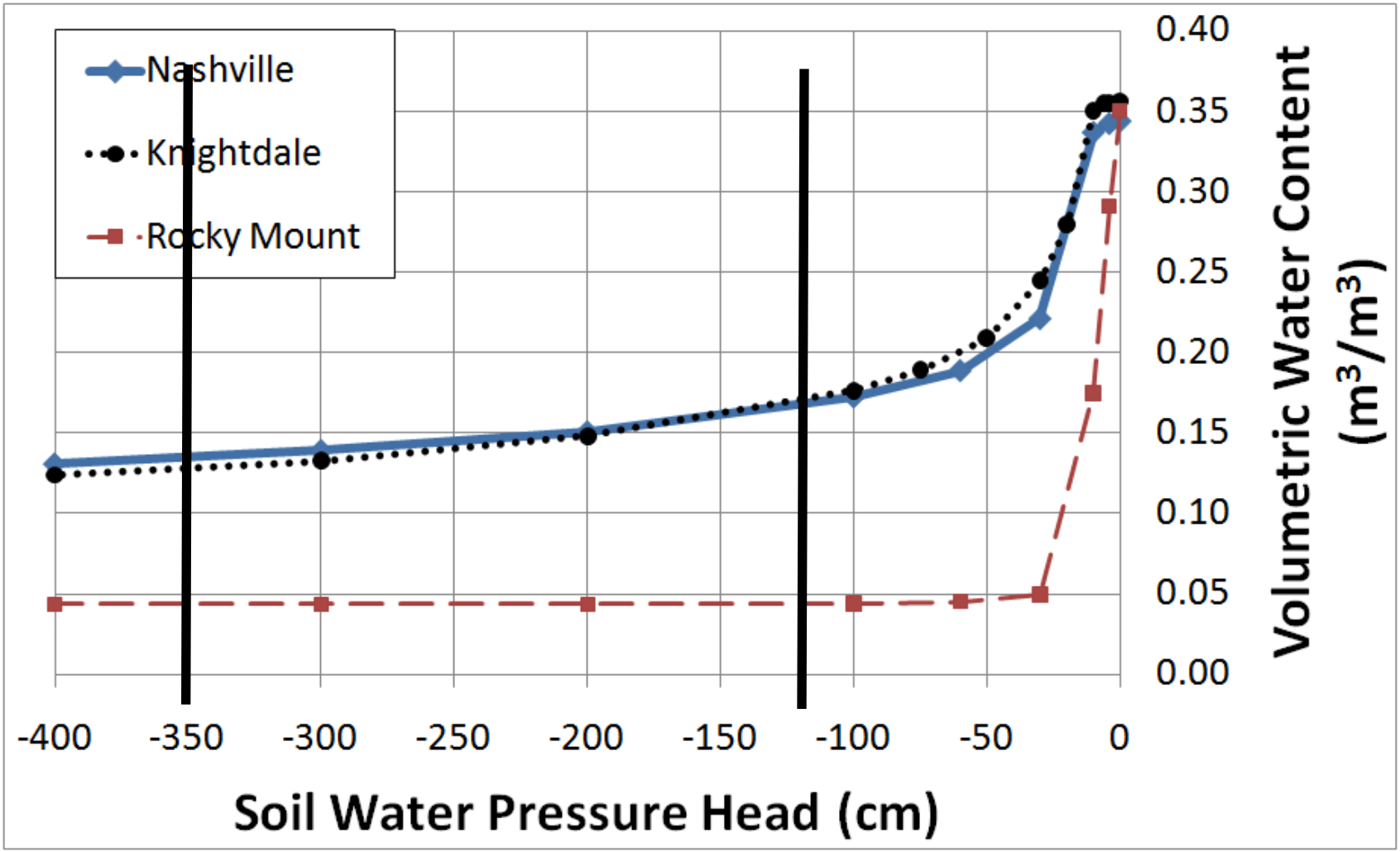
1. Runs continuous, long-term simulations
   - Accounts for antecedent moisture conditions
   - 30 years or more
2. Drain calculations are based on Kirkham's Eqn. & Hooghoudt Eqn.
3. Calibrated from actual bioretention cells with underdrains
4. Models IWS zone configuration

Biggest Benefit of DRAINMOD

5. DRAINMOD predicts water stored in media/soil based on water table depth and soil-water characteristic curve

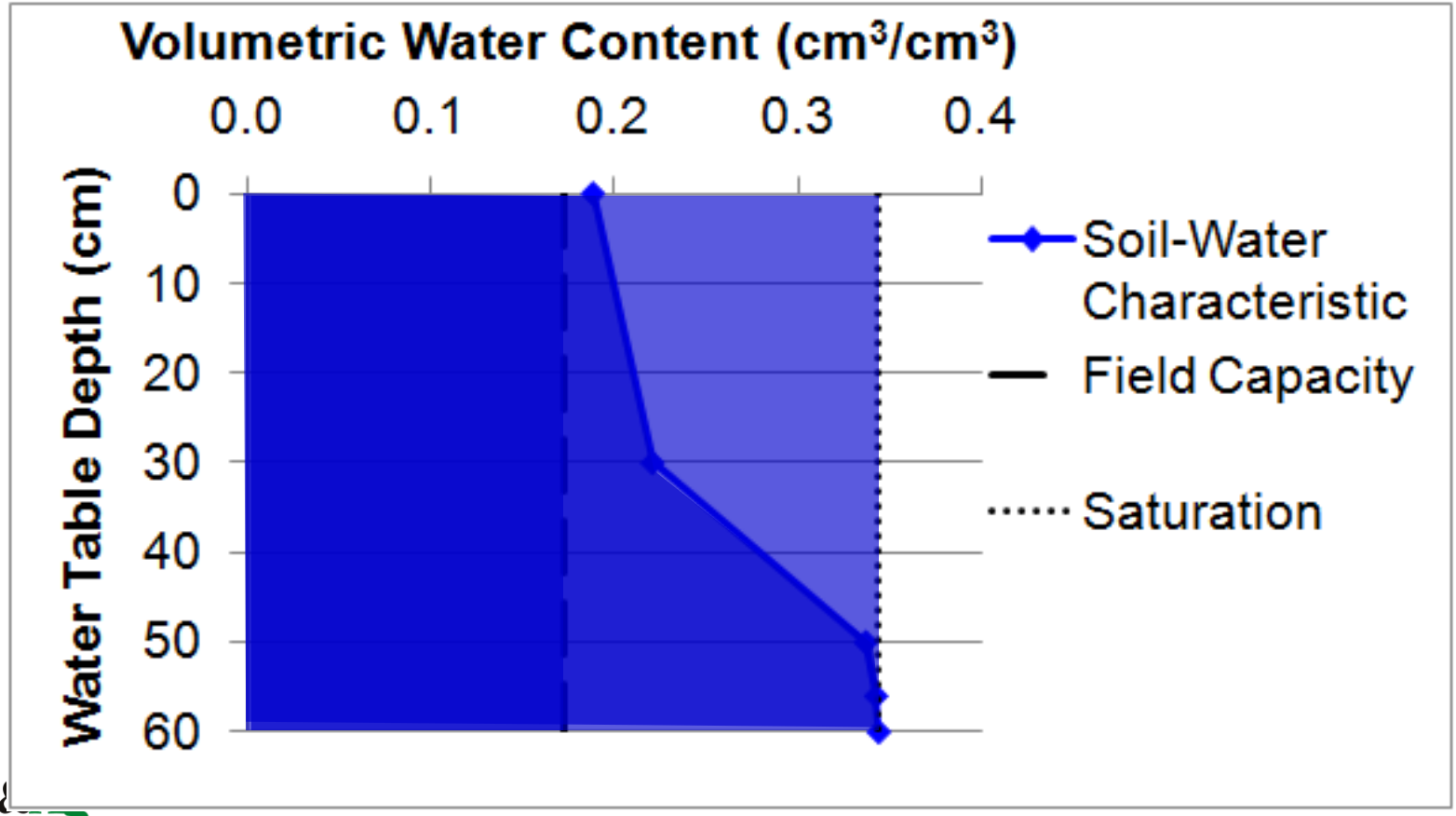
- All other BRC models use field capacity when soil is not saturated
  - Field capacity is ***not*** a soil water constant. More valid approximation in deep, well drained soils
    - Smith, R.E., and A.W. Warrick (2007). "Chapter 6: Soil Water Relationships" *Design and Operation of Farm Irrigation Systems*, 2nd Edition. ASABE, St. Joseph, Mich.
  - Invalid when water table is close to the surface

Soil-Water Characteristic



Calculating Water Stored in Profile

- Standard Ohio Bioretention Media
- Water Table Depth = 2 ft



DRAINMOD Water Balance

$$\Delta V_a = D + ET + DS - F$$

where ΔV_a = change in air volume (cm)

D = lateral drainage from section (cm)

ET = evapotranspiration (cm)

DS = deep seepage (cm)

F = infiltration entering the section in Δt

**Calculated on an hourly basis*

Uses for DRAINMOD Outputs

- Evaluate hydrologic performance based on a number of design parameters and site conditions
- Creates an annual water balance
  - Used to estimate effluent pollutant load
- Quantifies:
  - Groundwater recharge
  - Percent of runoff infiltrating into the specialized media (“treatment”)

Modeling Bioretention Hydrology

1. Contributing runoff from parking lot
2. Utilities
   - Contributing Runoff
   - Weather (Temperature & Rainfall)
   - Soil
3. Enter BRC design characteristics
   - Drain depth & spacing
   - Soil layers (Ksat, depths)
   - Subsoil characteristics (seepage)

Soil

- Measured:
  - Soil Water Char. Curve
    - Tension table (pressure plate)
  - K_{sat}
    - Const. head permeability test
- DRAINMOD Soil Prep. Program:
  - Water Table – Vol Drained – Upward Flux
  - Green-Ampt Infiltration parameters

Weather Files

- DRAINMOD inputs:
  - Daily maximum air temperature
  - Daily minimum air temperature
  - Hourly rainfall depth
    - Measured at each site (weather station)

Potential Evapotranspiration (PET)

- PET can be user-supplied, or the model uses the Thornthwaite method
  - Not as precise as other methods
  - Fewest inputs → mean monthly air temp.
  - Heat index (I)
    - T_i is the mean monthly temp.
      - Degrees Celsius

$$I = \sum_{i=1}^{12} \left(\frac{T_i}{5} \right)^{1.514}$$

  - Daily PET values were estimated using the daily maximum and minimum temperatures and the calculated heat index.

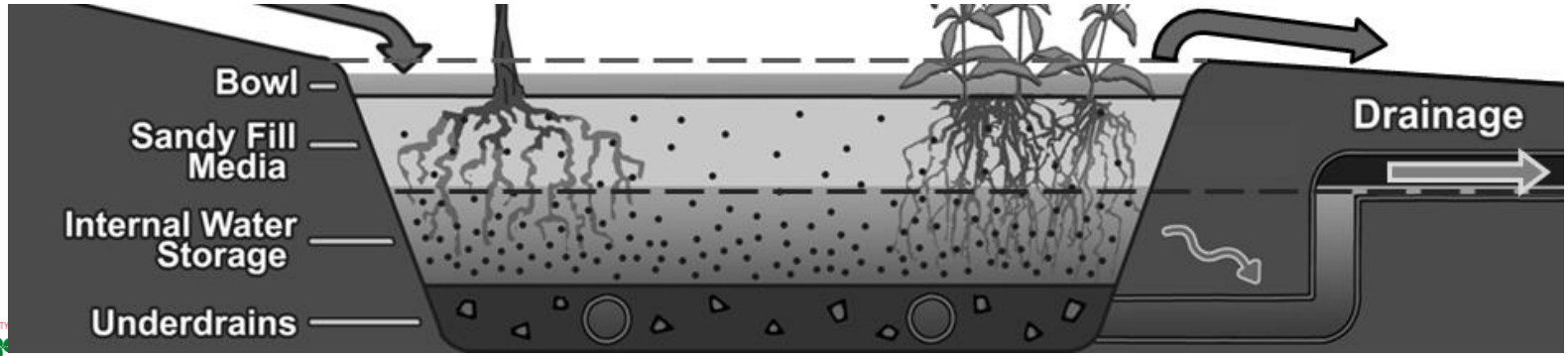
DRAINMOD Outputs: Water Balance

YEAR	RAINFALL	INFILTRATION	ET	DRAINAGE	RUNOFF	VERTSP
2009	1752.52	1484.75	95.57	861.64	267.77	532.19
AVG	1752.52	1484.75	95.57	861.64	267.77	532.19

DRAINMOD Outputs	Potential Meaning for Bioretention
ET	Evapotranspiration ***(volume eliminated)***
Drainage	Underdrain flow volume ***(treated volume)***
Runoff	Overflow volume ***(untreated volume)***
Seepage	Exfiltration ***(volume eliminated)***

Calibration Methods

1. **Site specific surveys**
   - Catchment area
   - Surface area & average ponding depth
   - Media depth & soil-water characteristic curve
   - Gravel & sand layer depths
   - Underdrain depth, spacing, and radius
   - Internal water storage zone depth



Calibration Methods

2. **Measured water level**
   - In media (at midpoint between drains)
3. **Measured / estimated flow volumes**
   - Runoff (estimated)
   - Drainage (measured)
   - Overflow (measured)
   - Exfiltration/ET (measured)

Calibration and Validation

- **Calibration Period**
  - Storms during even months
- **Validation Period**
  - Storms during odd months

- Brown et al. (2013) – split data set into first & second halves
  - Believe this even/odd months better captures seasonal variations in performance

Quantifying Agreement

- Percent difference between predicted and measured volumes
- Coefficient of determination (R^2)
  - 1.0 perfect agreement
- Nash-Sutcliffe Coefficient
  - 1.0 perfect agreement

$$R_{NS}^2 = 1 - \frac{\sum_{i=1}^{N}\left(Vol_{i,measured} - Vol_{i,predicted}\right)^2}{\sum_{i=1}^{N}\left(Vol_{i,measured} - Vol_{average}\right)^2}$$

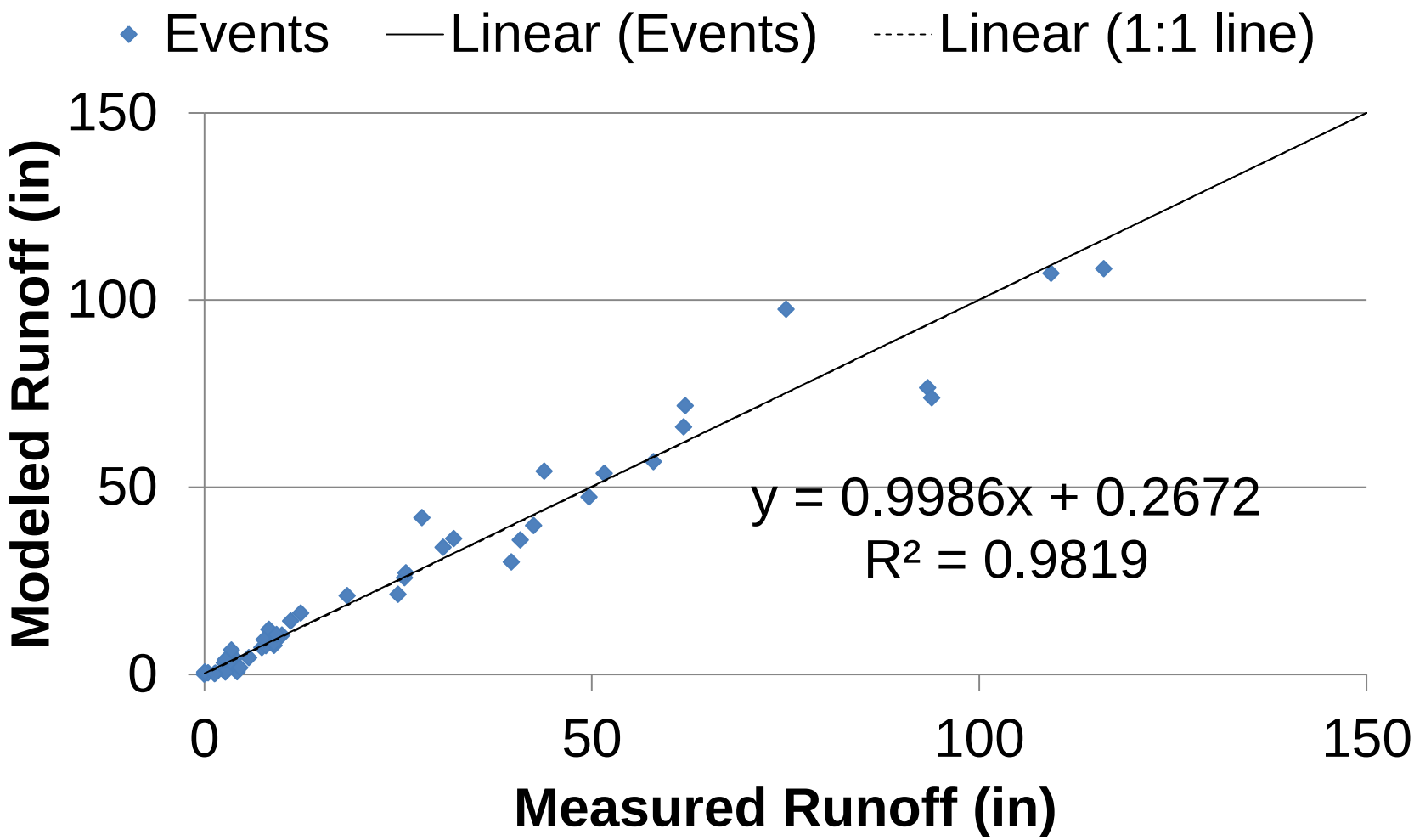
Modeling Parking Lot Runoff

- Create soil file for asphalt
  - Adjust Green-Ampt infiltration parameters
- Wide drain spacing
- Small surface storage (Sm)
  - Vary depending on surface cover

Nash-Sutcliffe Coefficients for Runoff/Inflow			
Monitoring Period	Ursuline	Holden South	Holden North
Calibration	0.99	0.99	0.99
Validation	0.99	0.96	0.96

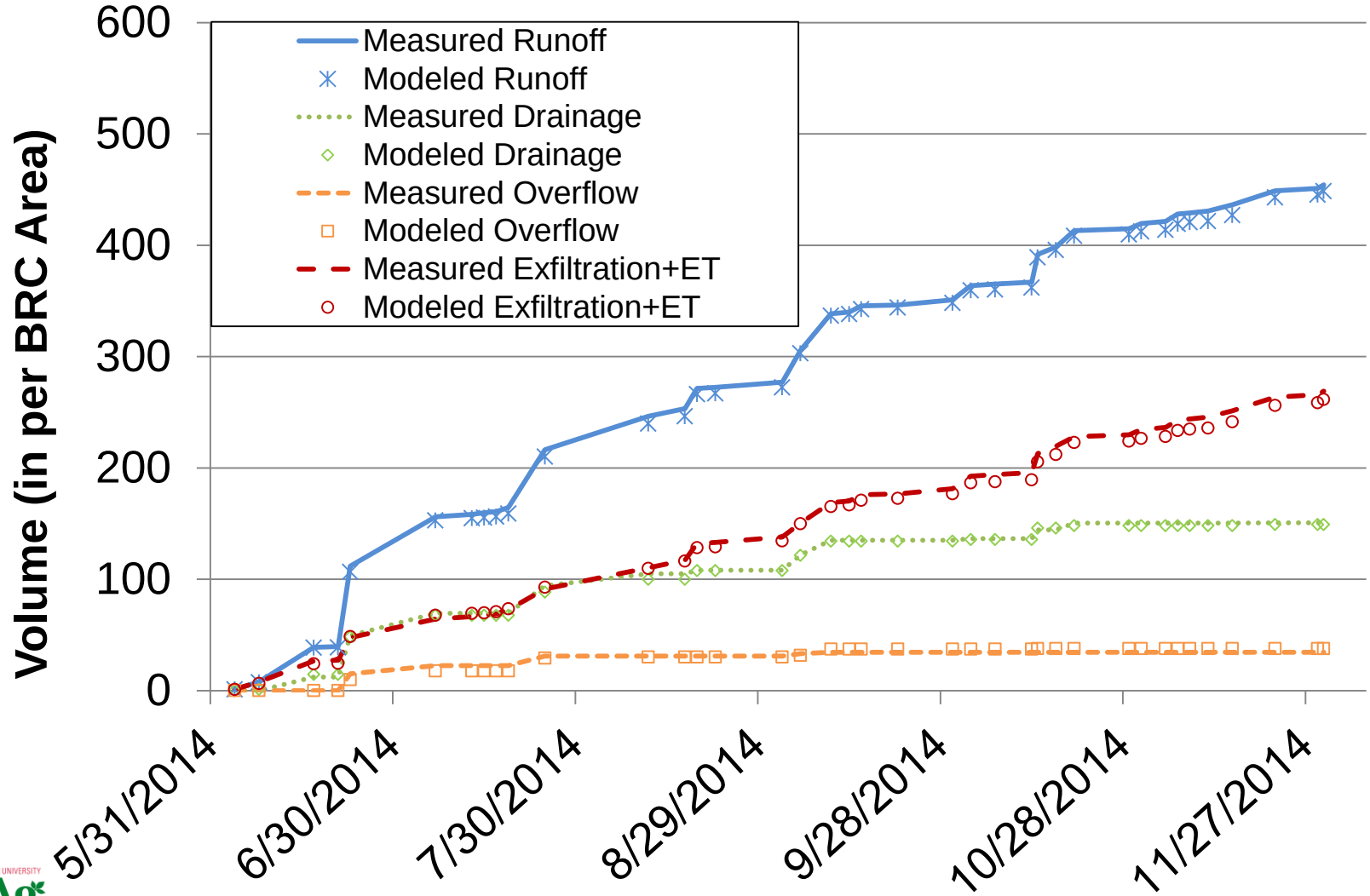
- Modeled pervious and impervious portions of each watershed separately
- Summed results of these models to determine runoff/inflow
- Improved calibration vs. lumped pervious/impervious runoff model

Calibration of Runoff/Inflow: Holden North



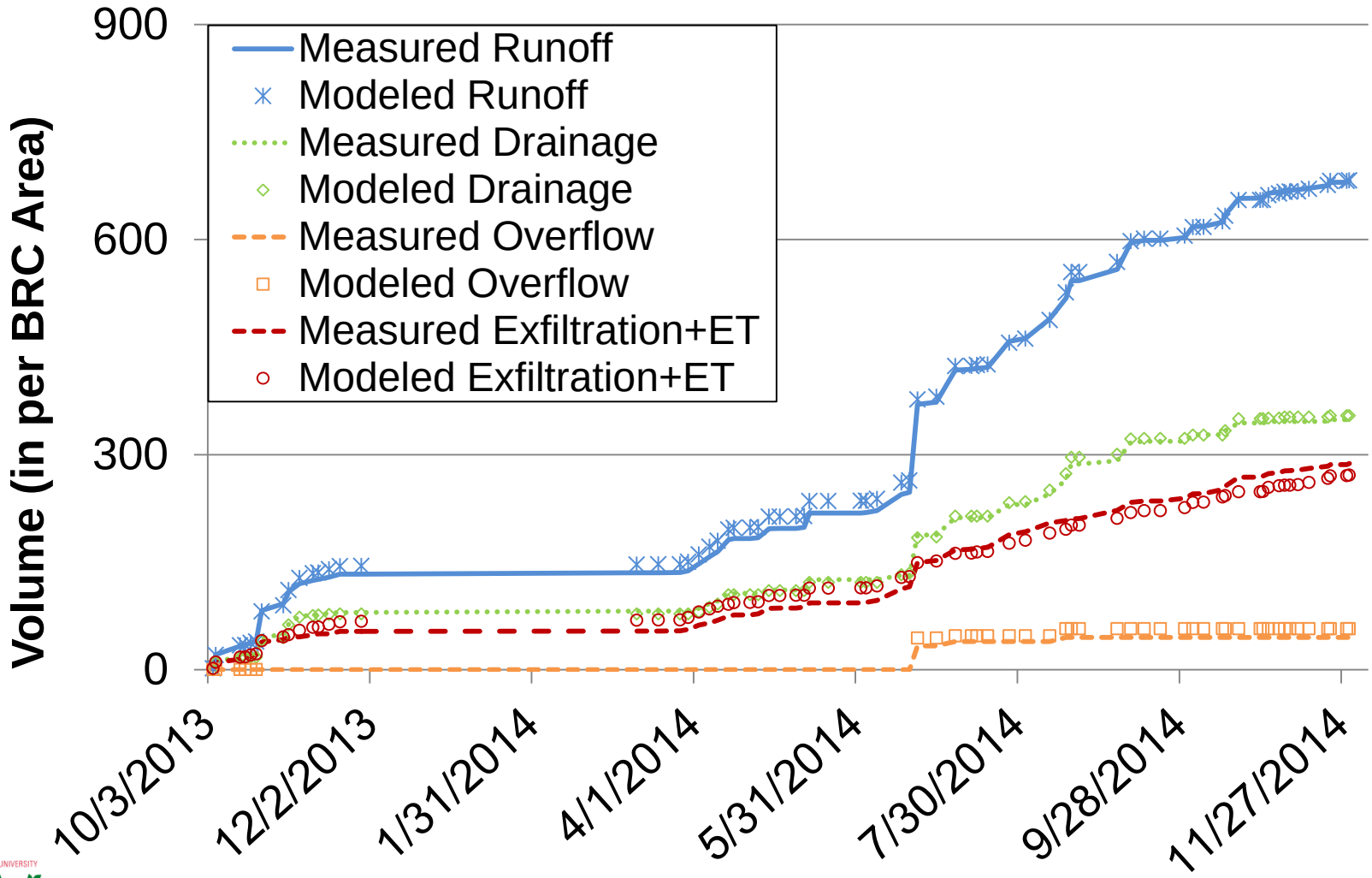
UC: Overall Water Balance

Measured vs. Modeled



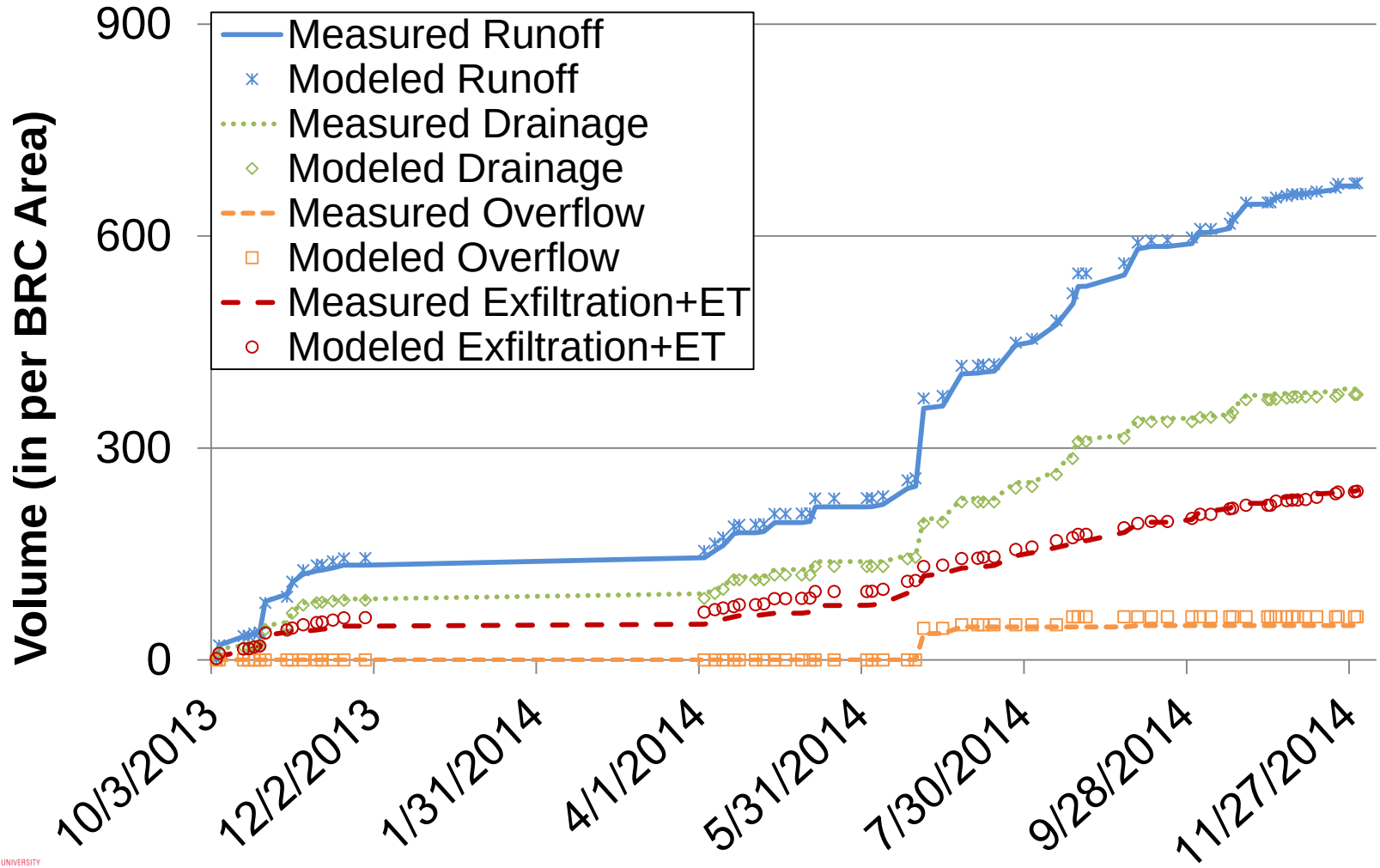
HA South: Overall Water Balance

Measured vs. Modeled



HA North: Overall Water Balance

Measured vs. Modeled



Model Agreement

*Nash-Sutcliffe Coefficients during Validation Periods

Hydrologic Fate	Ursuline	Holden North	Holden South
Runoff	0.99	0.96	0.96
Drainage	0.98	0.98	0.95
Overflow	0.73	0.74	0.71
Exfiltration/ET	0.95	0.76	0.75

Modeled vs. Measured Water Balance

*Percent of Total Inflow

Type of Data	Hydrologic Fate	Ursuline	Holden North	Holden South
Monitored	Drainage	33	51	57
Modeled		33	52	56
Monitored	Overflow	8	7	7
Modeled		9	8	9
Monitored	Exfiltration/ET	59	42	36
Modeled		58	40	35

Adjusting Design Parameters:
Analysis of Design Alternatives
(UC Data)

How is the long-term water balance affected by:

- **Underlying Soil K_{sat}**
- **Media depth**
- **Internal Water Storage Zone Depth**
- **Rooting Depth**
- **Bowl Storage Depth**
- **Hydraulic Loading**

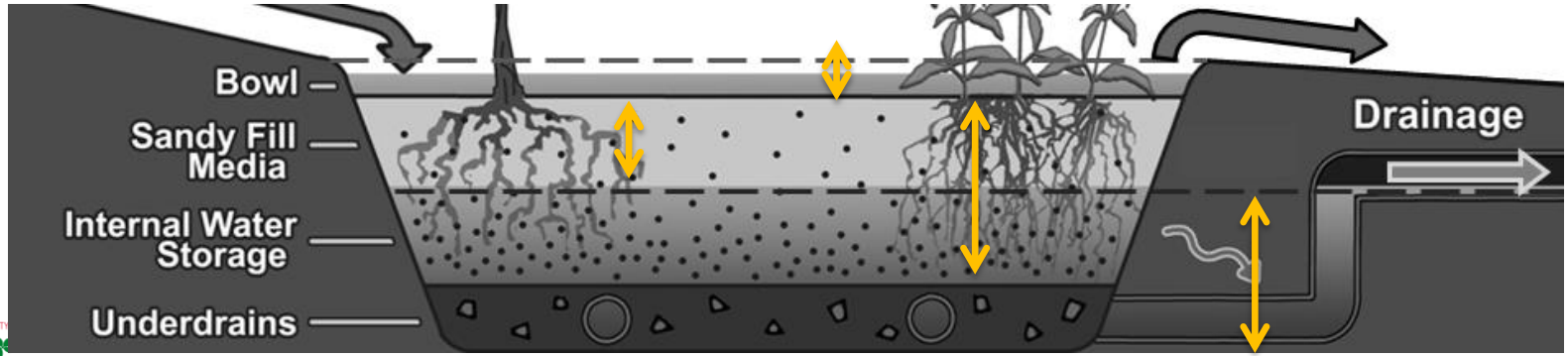
Weather Sources: Modeling

- **Long-term Weather Station**
  - Cleveland Hopkins International Airport (40 miles from Holden Arboretum)
    - *Primary weather source for simulations*
- **Long-term data range: 1983-2012**
- **(30 yr simulations)**
  - Daily Max. & Min. Temperature
    - *Source: NOAA - NCDC*
  - Hourly Rainfall
    - *Source: NOAA - NCDC*

Base Models for UC

- Media Depth: 2 ft
- IWS Zone: 2 ft
- Loading Ratio: 20:1
- Rooting Depth: 1 ft
- Bowl Depth: 1 ft

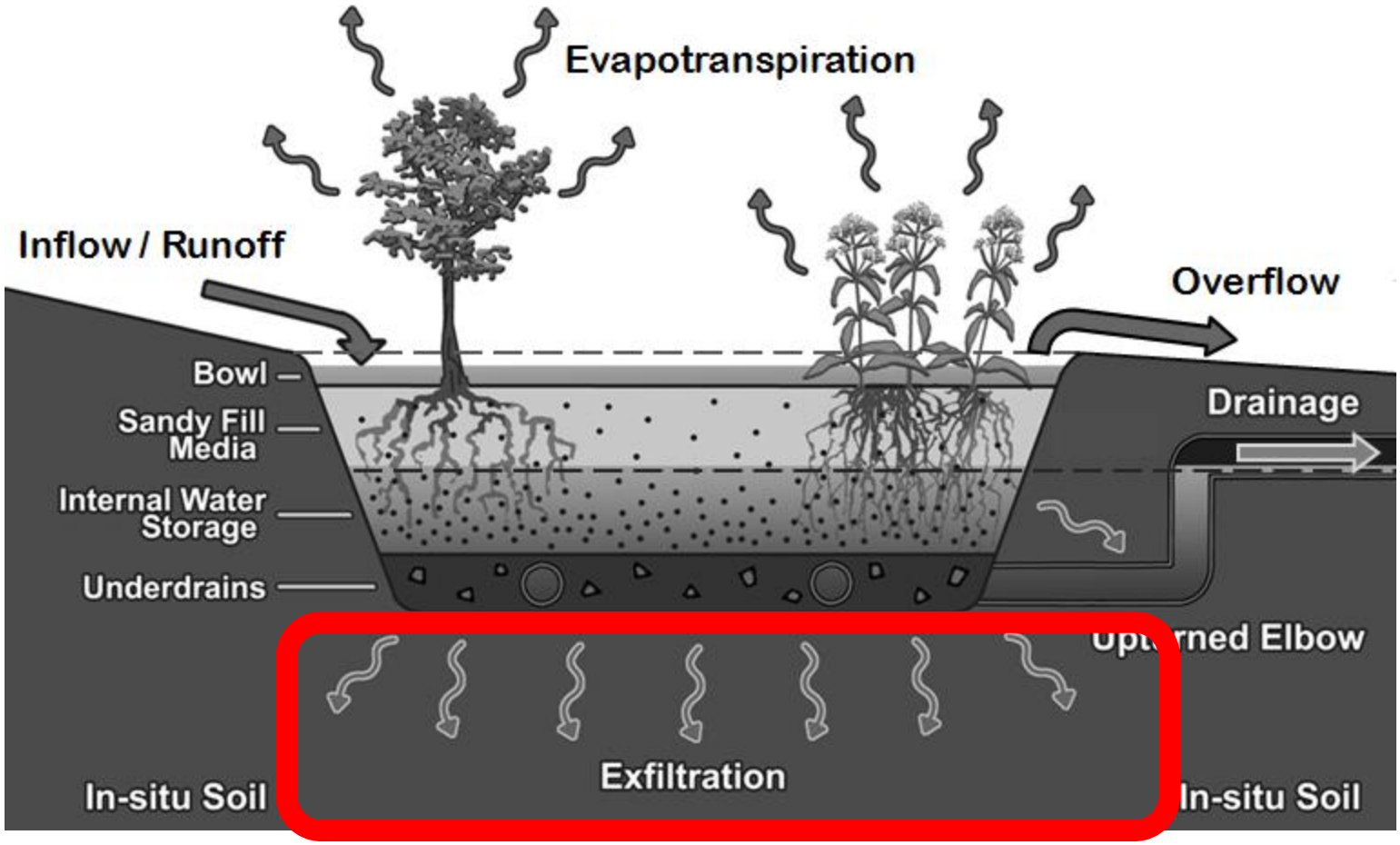
- All values matched as-built
- DRAINMOD output - long-term hydrology:
  - Inflow
  - Drainage
  - Overflow
  - Exfiltration/ET



Base Models

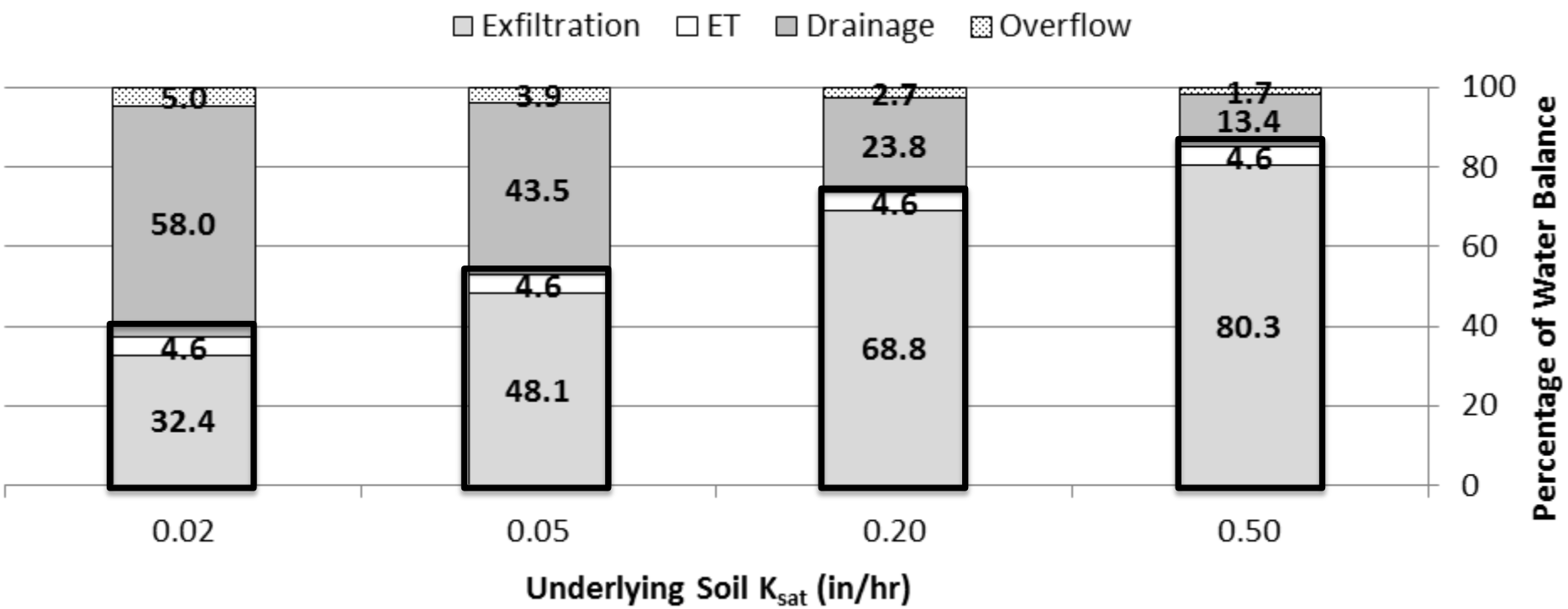
- Four baseline created based on conductivity of the underlying soil (vertical seepage tab in DRAINMOD)
  - K_{sat} = 0.5 in/hr
  - K_{sat} = 0.2 in/hr
  - K_{sat} = 0.05 in/hr
  - K_{sat} = 0.02 in/hr

Underlying Soil K_{sat}



Underlying Soil K_{sat}

Volume Reduction



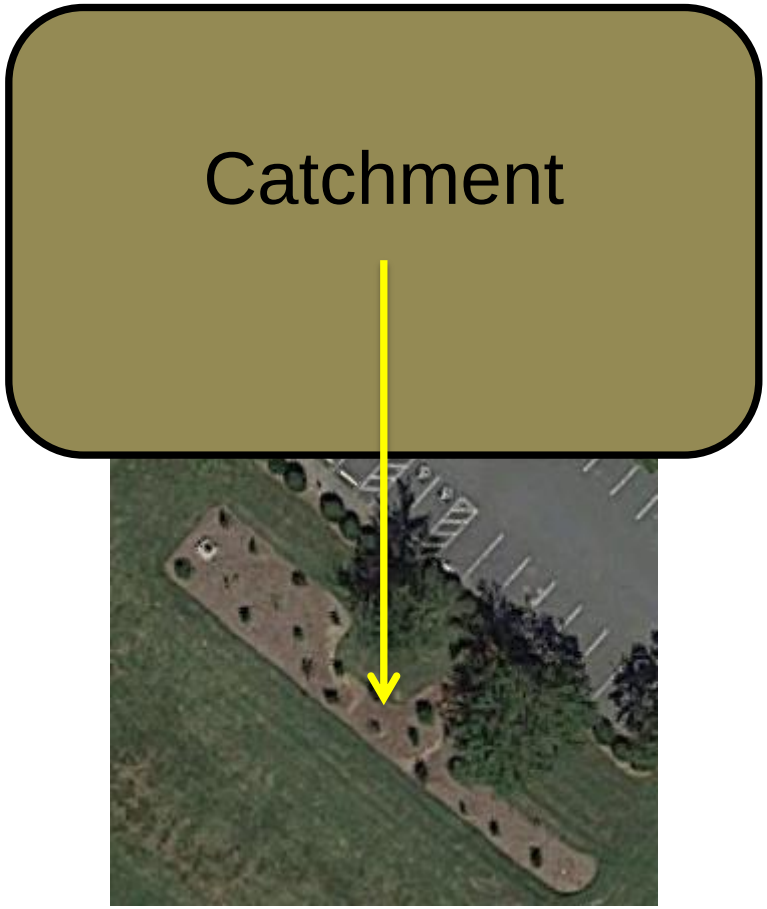
- Supports locating most permeable soils on a development site

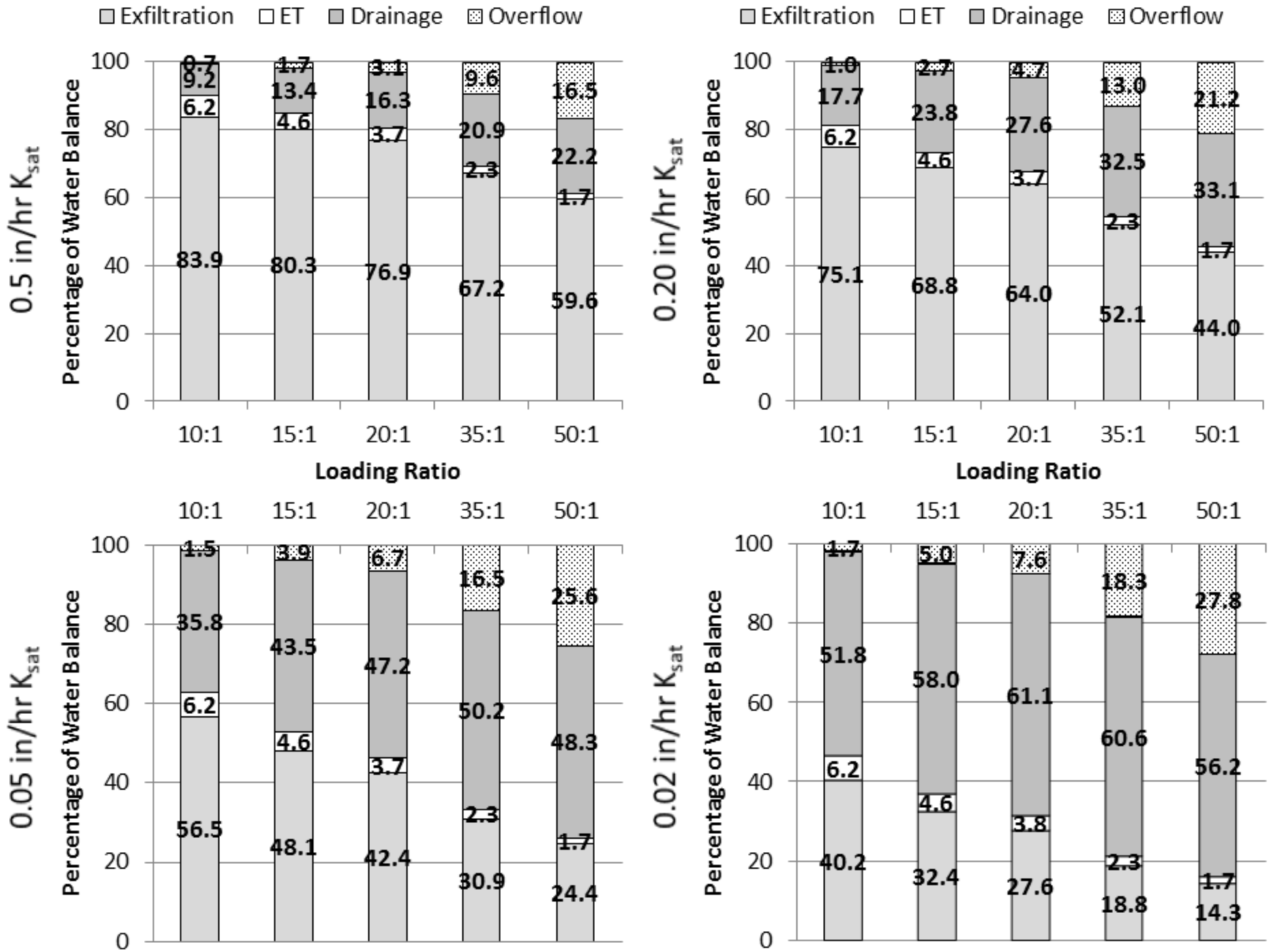
Underlying Soil K_{sat}

- Prioritize SCMs over soils with higher hydraulic conductivities
  - 41% volume reduction for K_{sat} = 0.02 in/hr (heavy clay) – includes IWS zone
  - Bioretention SCMs still provide a volume mitigation benefit in even the poorest soils
  - Percentage of overflow and drainage increases as K_{sat} decreases

Over/Under-Sized Bioretention

- Ohio design event =0.75 inches
- Catchment Area : Bioretention Area Ratio
  - **10:1**
  - **15:1**
  - **20:1 (base model)**
  - **35:1**
  - **50:1**
- Changed field ratio in DRAINMOD




Exfiltration
ET
Drainage
Overflow
0.5 in/hr K_{sat}
0.20 in/hr K_{sat}
0.05 in/hr K_{sat}
0.02 in/hr K_{sat}
Percentage of Water Balance
Loading Ratio
10:1
15:1
20:1
35:1
50:1
0
20
40
60
80
100
0.7
9.2
6.2
83.9
1.7
13.4
4.6
80.3
3.1
16.3
3.7
76.9
9.6
20.9
2.3
67.2
16.5
22.2
1.7
59.6
1.0
17.7
6.2
75.1
2.7
23.8
4.6
68.8
4.7
27.6
3.7
64.0
13.0
32.5
2.3
52.1
21.2
33.1
1.7
44.0
1.5
35.8
6.2
56.5
3.9
43.5
4.6
48.1
6.7
47.2
3.7
42.4
16.5
50.2
2.3
30.9
25.6
48.3
1.7
24.4
1.7
51.8
6.2
40.2
5.0
58.0
4.6
32.4
7.6
61.1
3.8
27.6
18.3
60.6
2.3
18.8
27.8
56.2
1.7
14.3

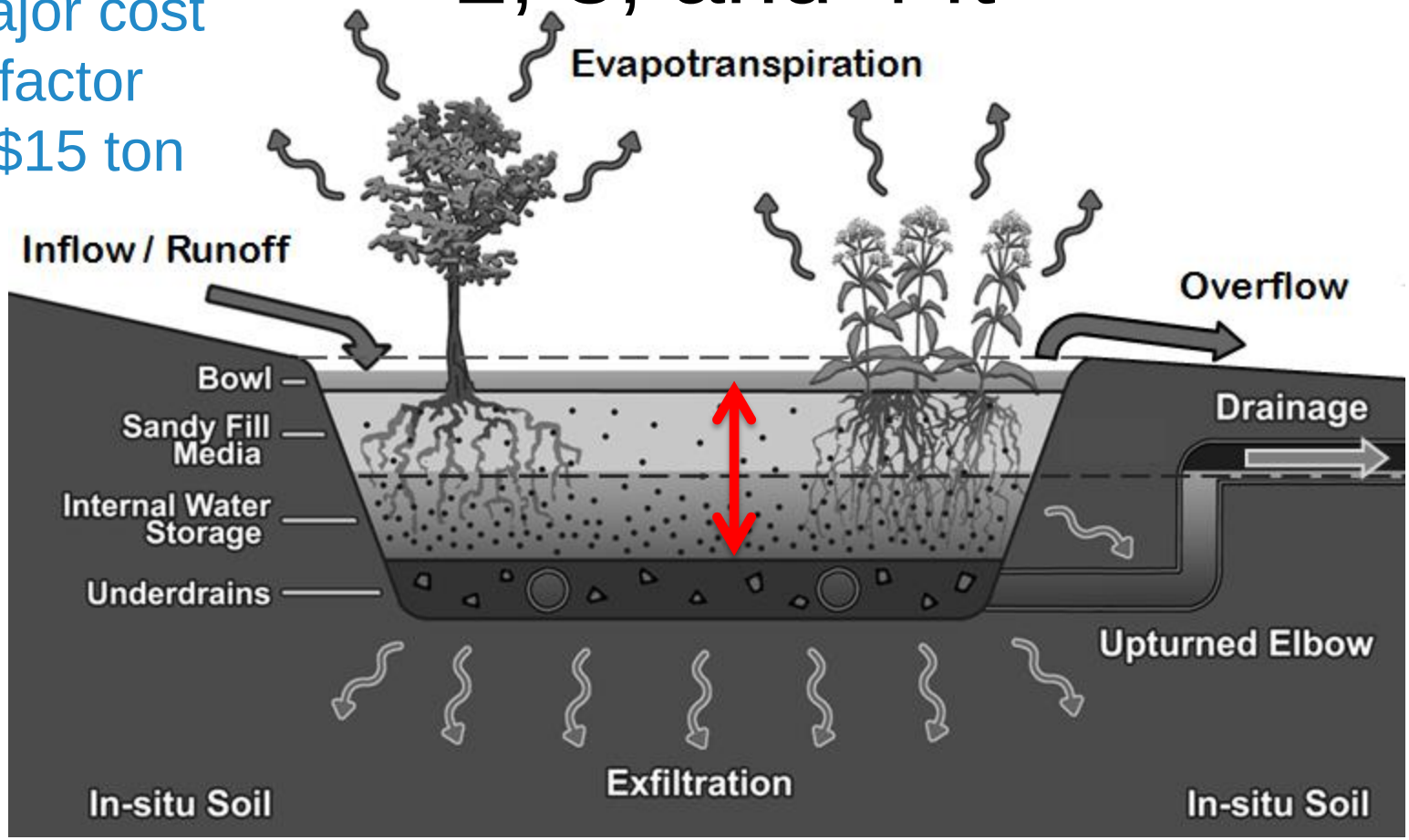
Over/Under-Sized Bioretention

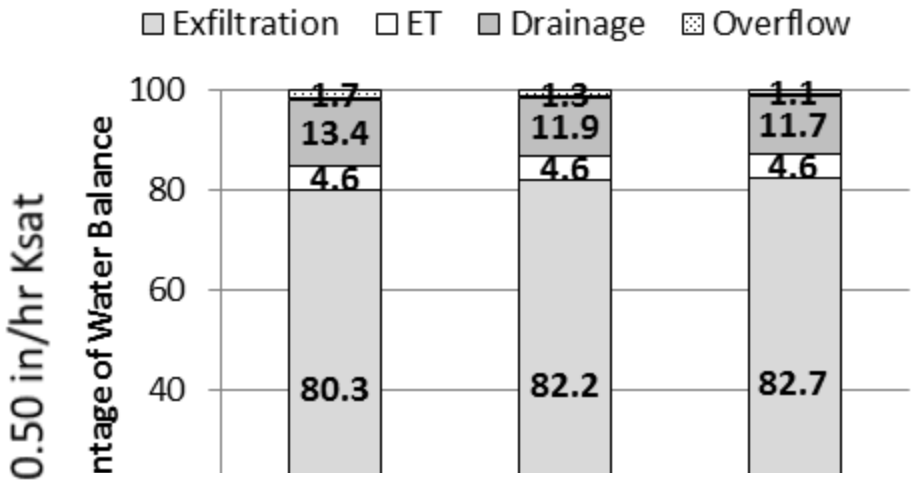
- Only factor that substantially changes ET (more/less plants in BRC)
- As HLR increases, we observe:
  - More overflow
  - More drainage
  - Less exfiltration
  - Less ET
- Differences exacerbated as underlying soil K_{sat} approaches zero

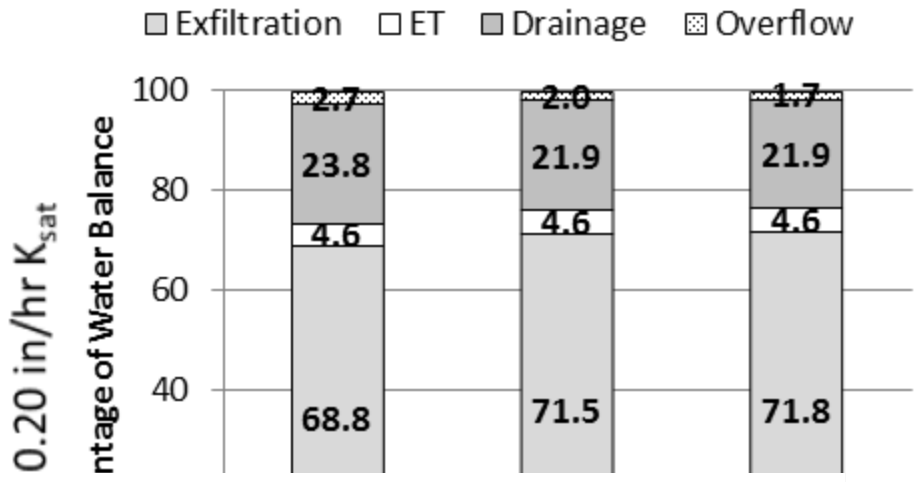
Variable credit for volume reduction as a function of sizing?

Media Depth 2, 3, and 4 ft

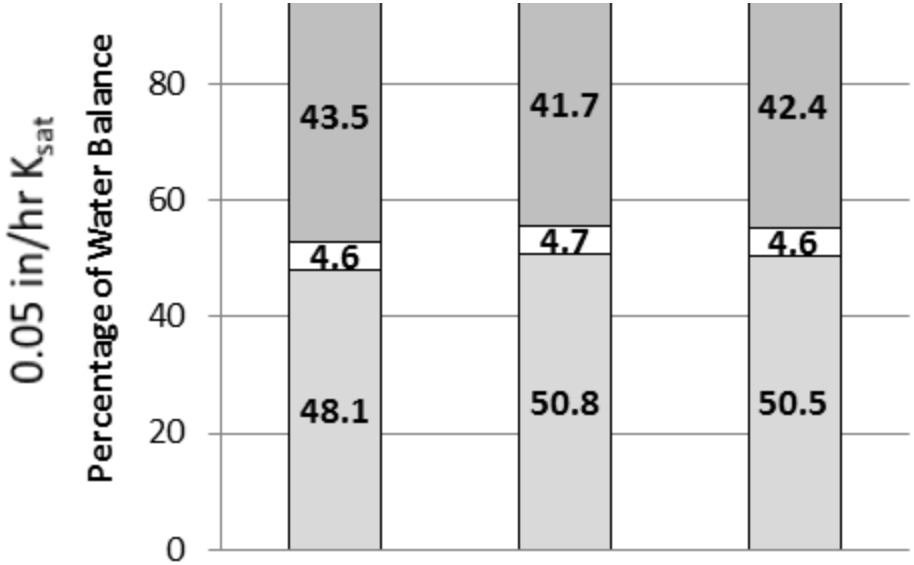
Major cost factor ~$15 ton

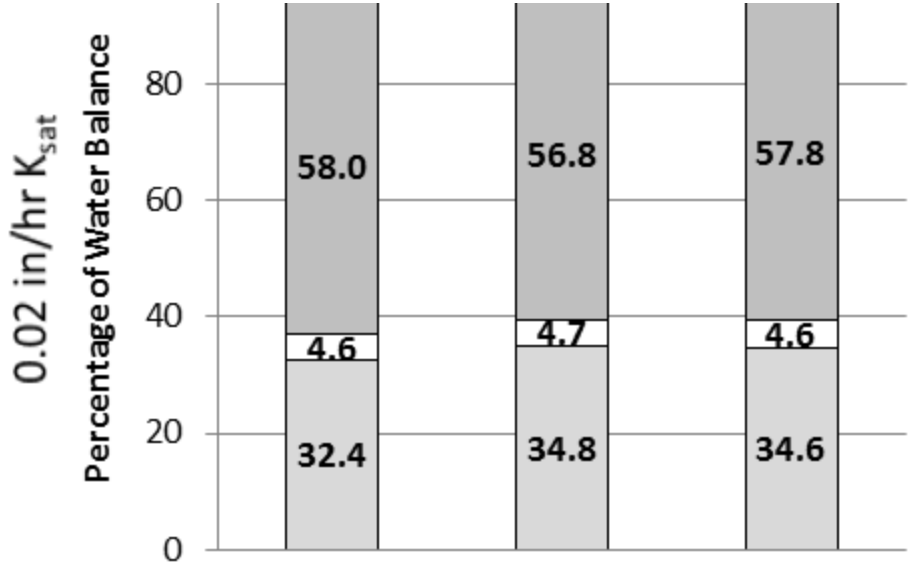






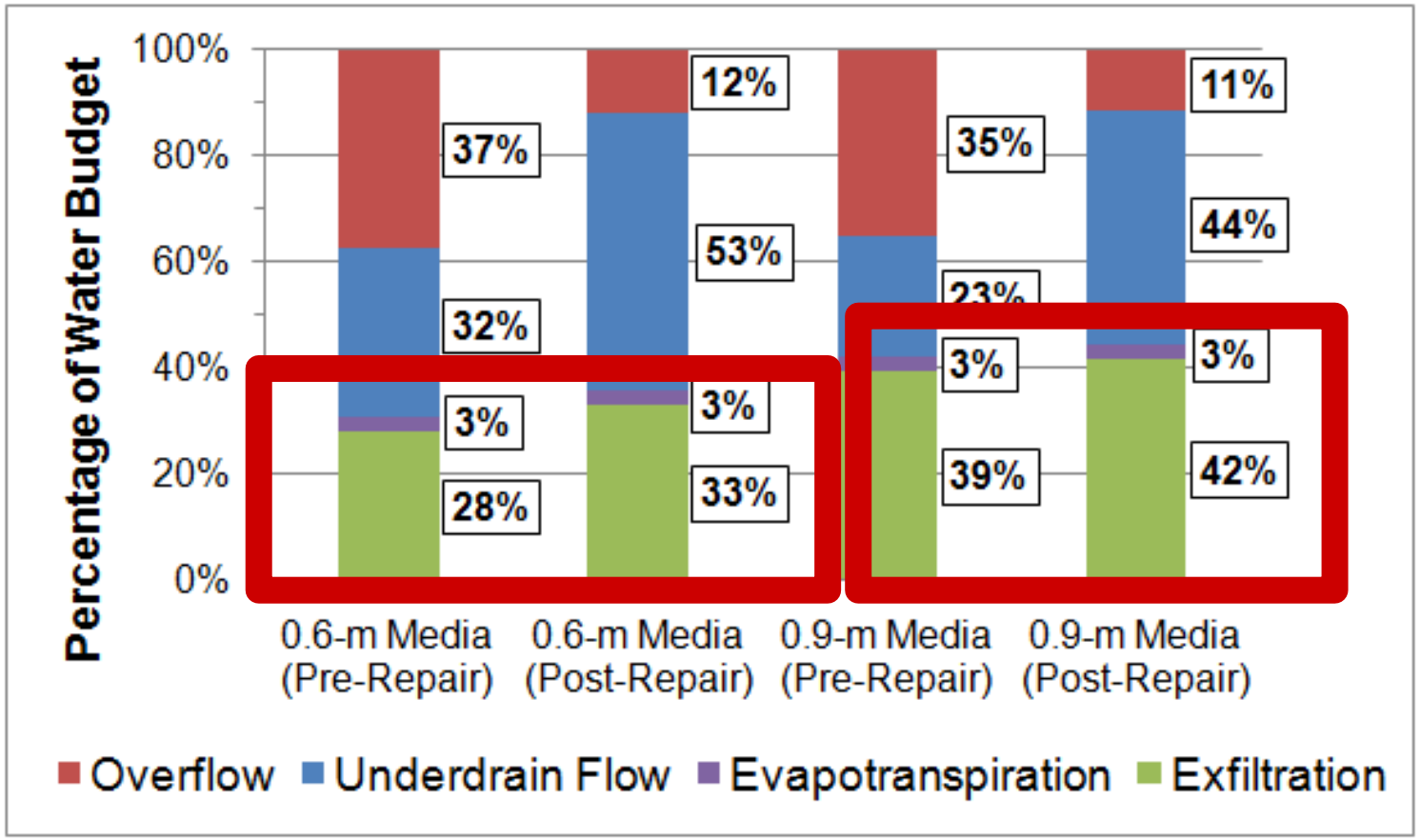
- Media depth only a critical factor when there are concomitant increases in IWS zone depth
- Deeper media depth important for treatment of pollutants (temperature, nitrogen)





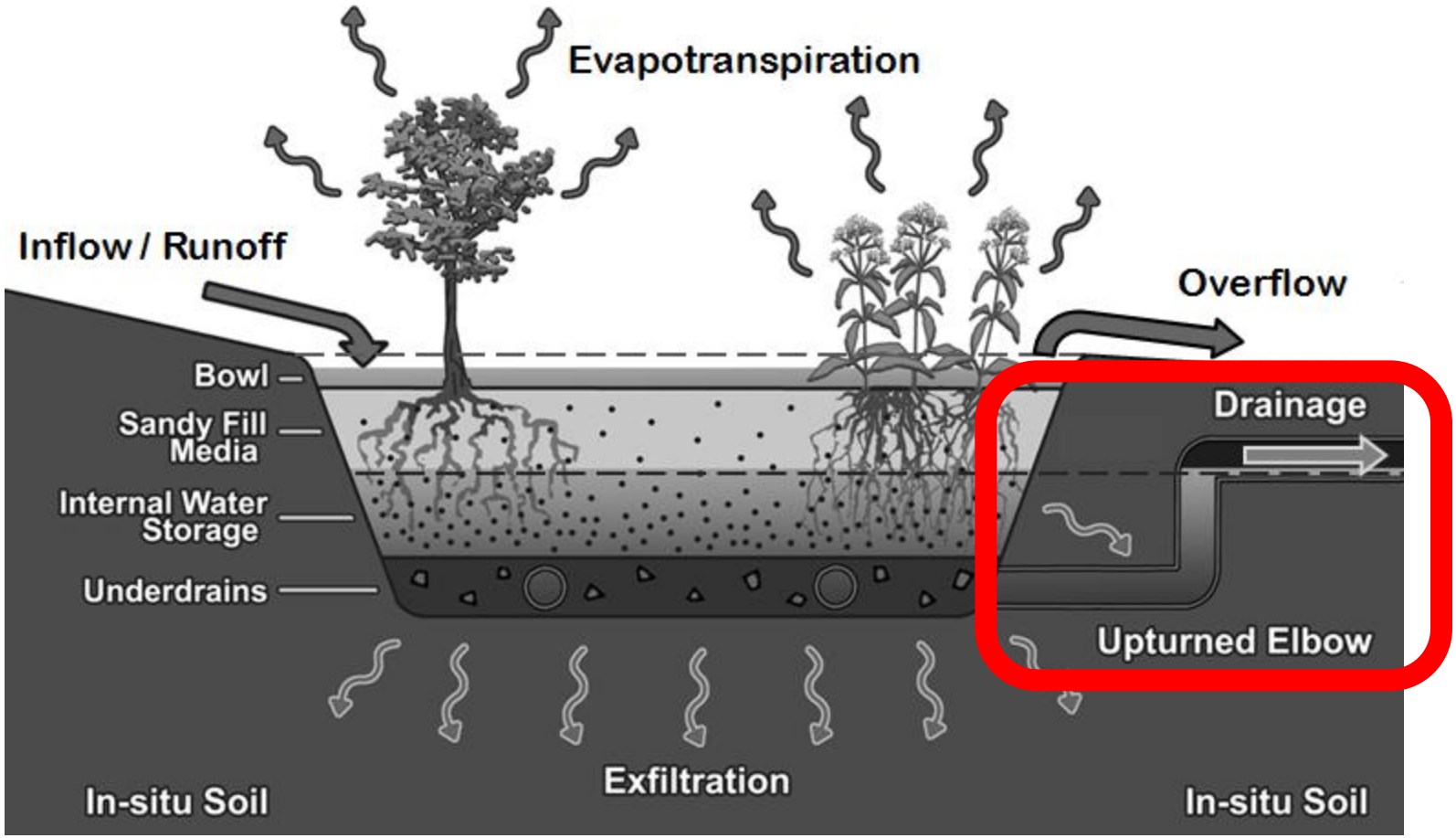
Media Depth

Nashville, NC Modeling



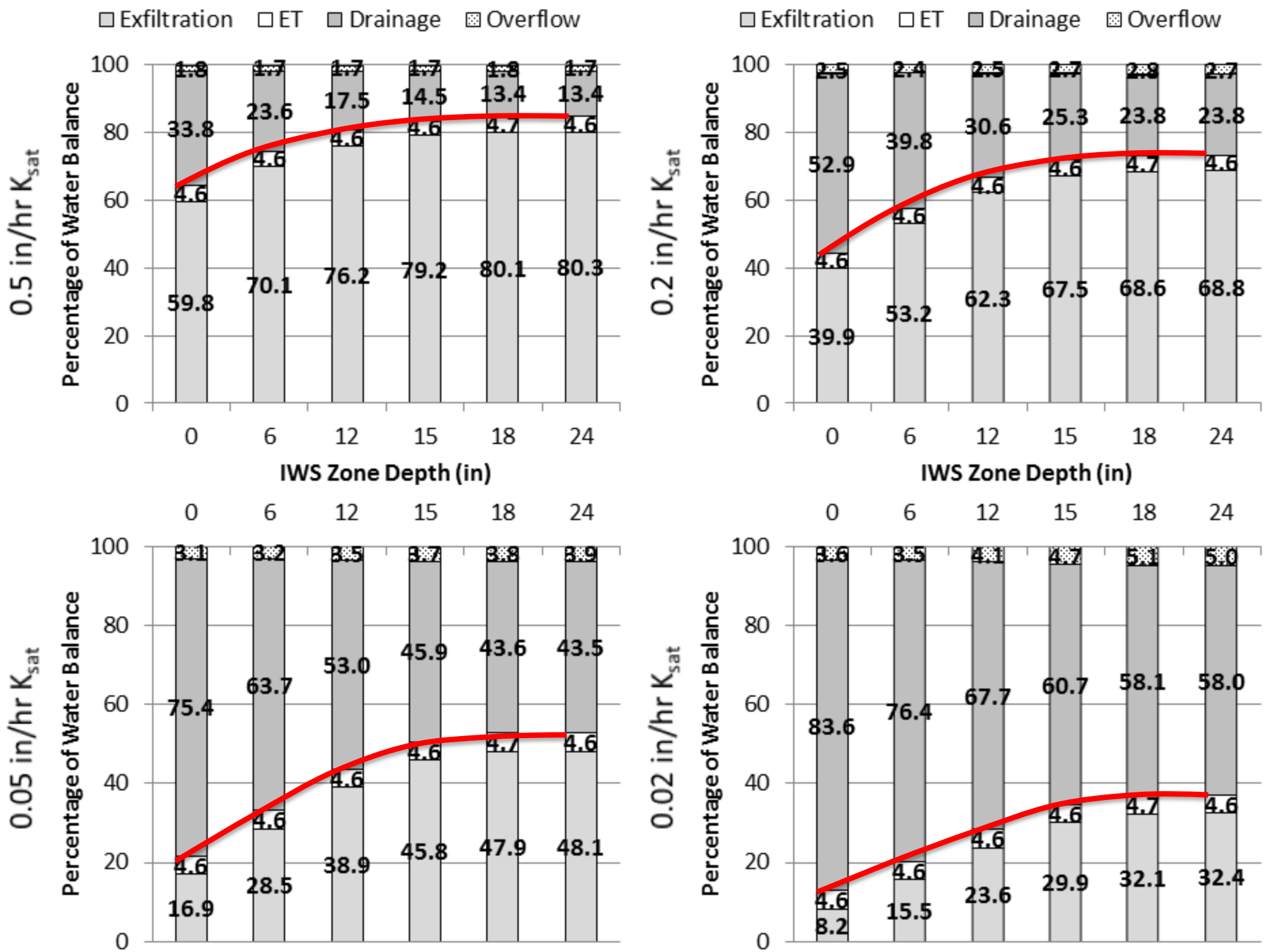
Small changes in long-term hydrology compared to past studies. Perhaps because model calibrated to poor soils?

Internal Water Storage



Internal Water Storage

- Modeled IWS zone depths of:
  - 0 inches (flat underdrain)
  - 6 inches
  - 12 inches
  - 15 inches (baseline model)
  - 18 inches
  - 24 inches


Exfiltration
ET
Drainage
Overflow
0.5 in/hr K_{sat}
0.2 in/hr K_{sat}
0.05 in/hr K_{sat}
0.02 in/hr K_{sat}
Percentage of Water Balance
IWS Zone Depth (in)
0
6
12
15
18
24
100
80
60
40
20
0
1.8
1.7
1.7
1.7
1.8
1.7
33.8
23.6
17.5
14.5
13.4
13.4
4.6
4.6
4.6
4.6
4.7
4.6
59.8
70.1
76.2
79.2
80.1
80.3
2.5
2.4
2.5
2.7
2.8
2.7
52.9
39.8
30.6
25.3
23.8
23.8
4.6
4.6
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39.9
53.2
62.3
67.5
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68.8
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3.8
3.9
75.4
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4.6
4.6
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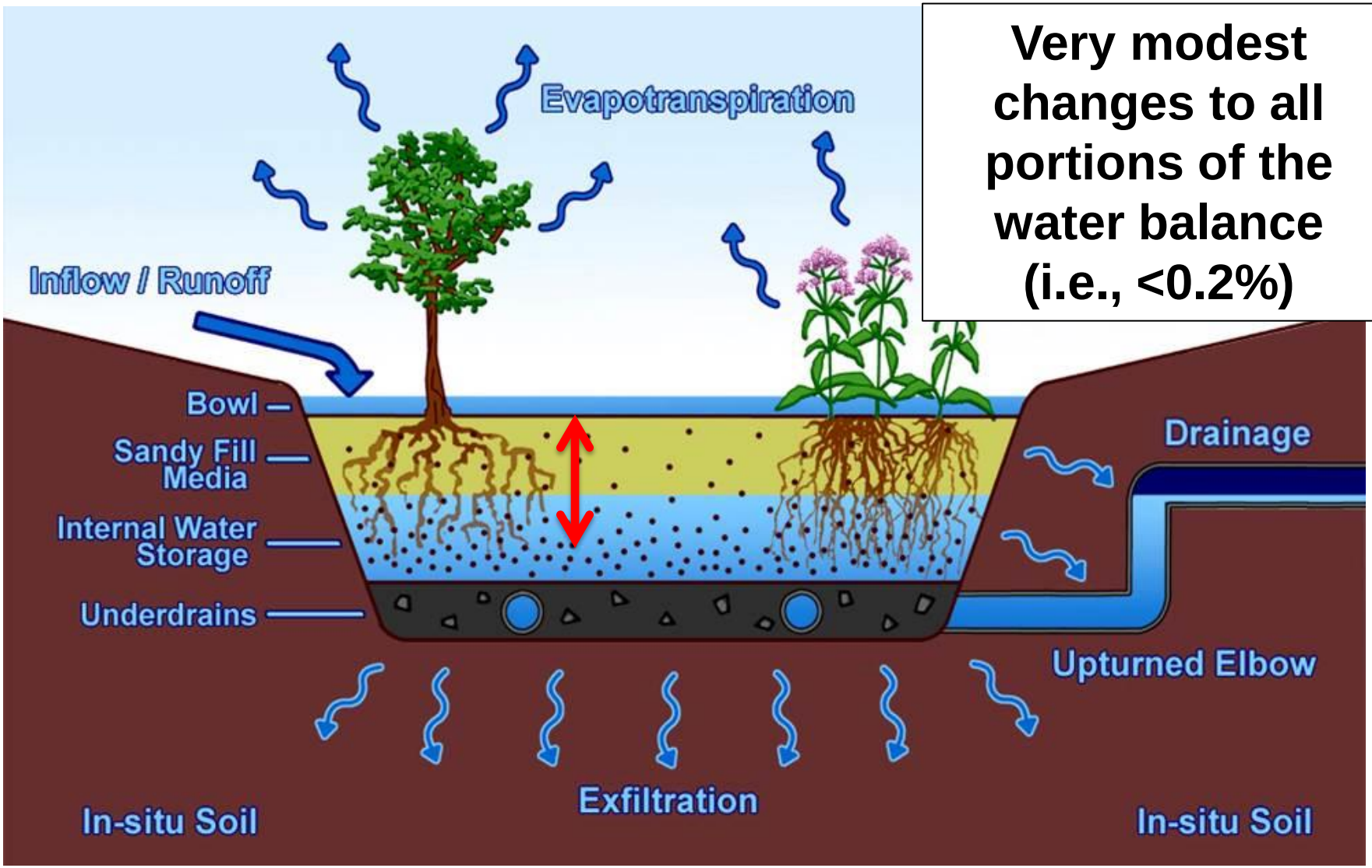
4.7
4.6
16.9
28.5
38.9
45.8
47.9
48.1
3.6
3.5
4.1
4.7
5.1
5.0
83.6
76.4
67.7
60.7
58.1
58.0
4.6
4.6
4.6
4.6
4.7
4.6
8.2
15.5
23.6
29.9
32.1
32.4

Internal Water Storage

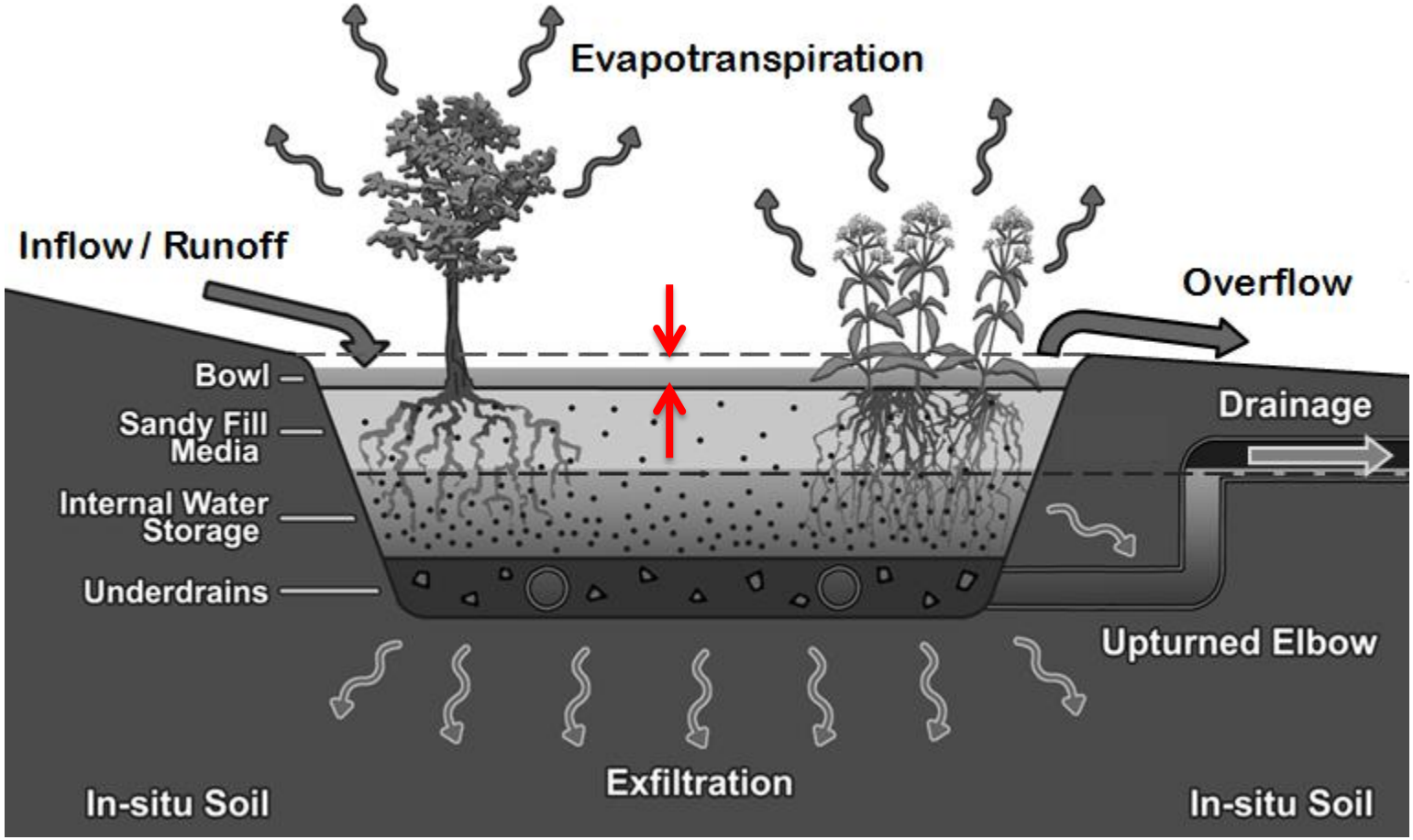
- By incorporating optimal 15-18 inch IWS zone in sandy soil:
  - Reduce drainage and increase exfiltration by 20%
  - No change in overflow
- By incorporating optimal 15-18 inch IWS zone in heavy clay soil:
  - Decrease drainage by ~25-30% and increase exfiltration ~3-fold
  - Modestly increase overflow (~1-2%)
- No modeled change to ET due to IWS zone

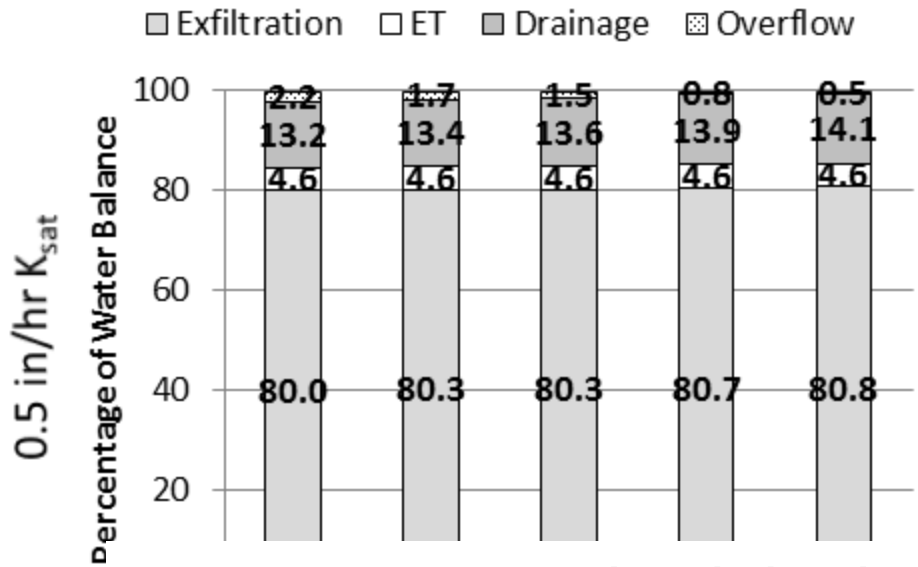
Rooting Depth

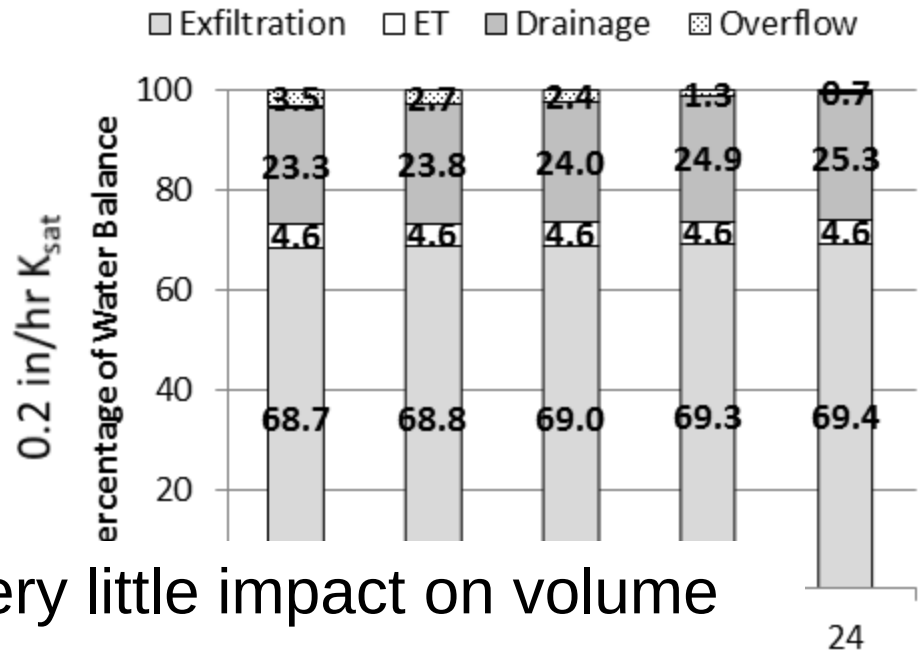


Very modest changes to all portions of the water balance (i.e., <0.2%)

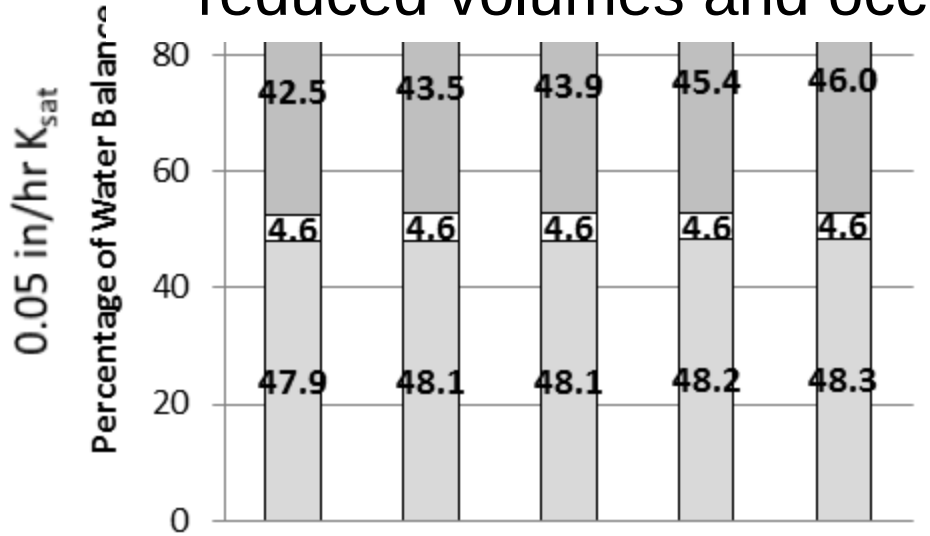
Bowl Storage Depth
9, 12, 15, 18, and 24 inches

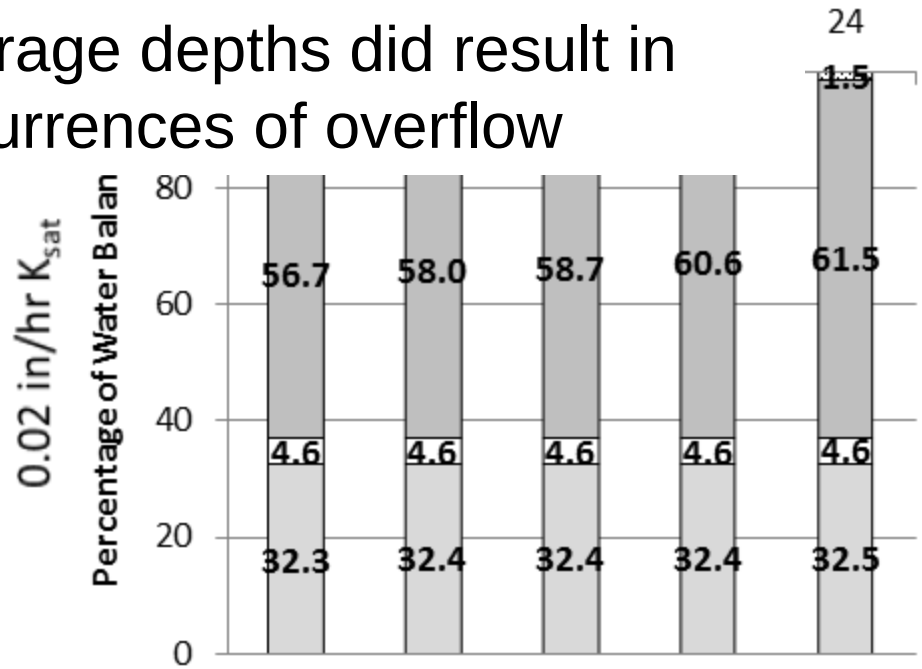




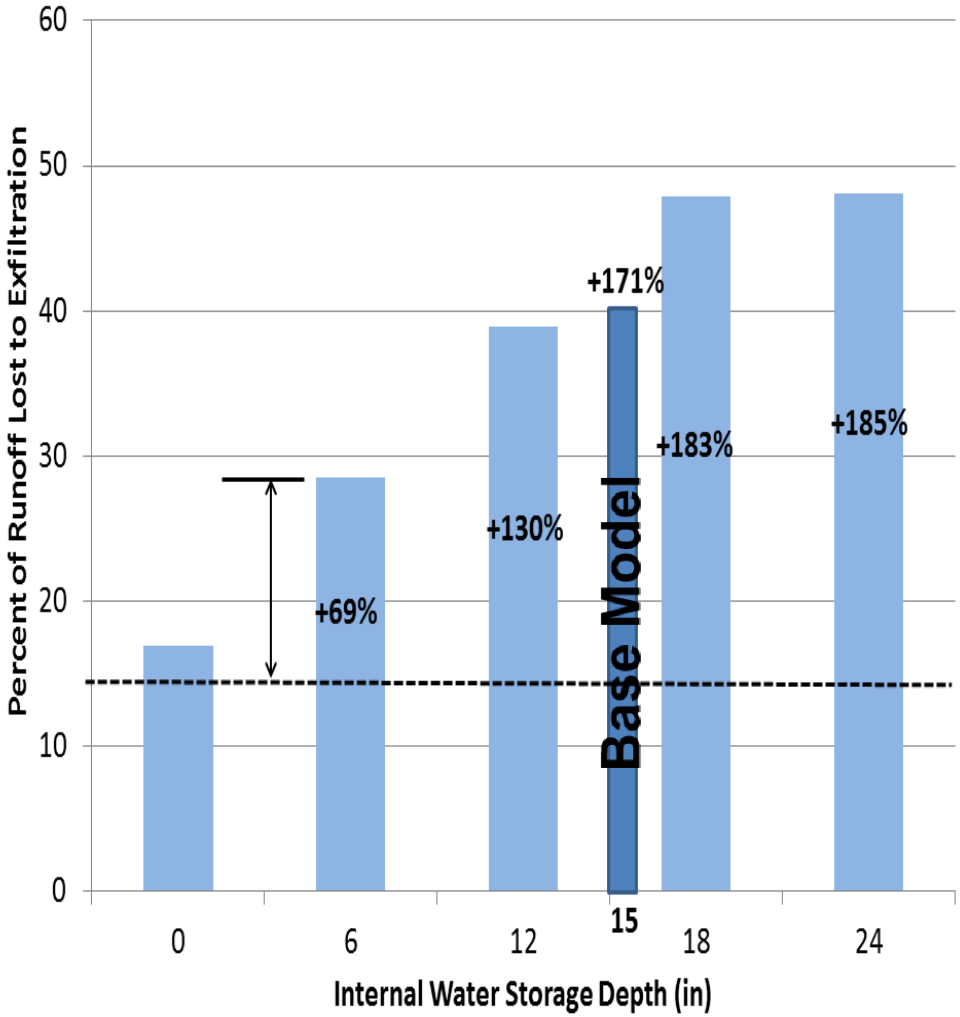


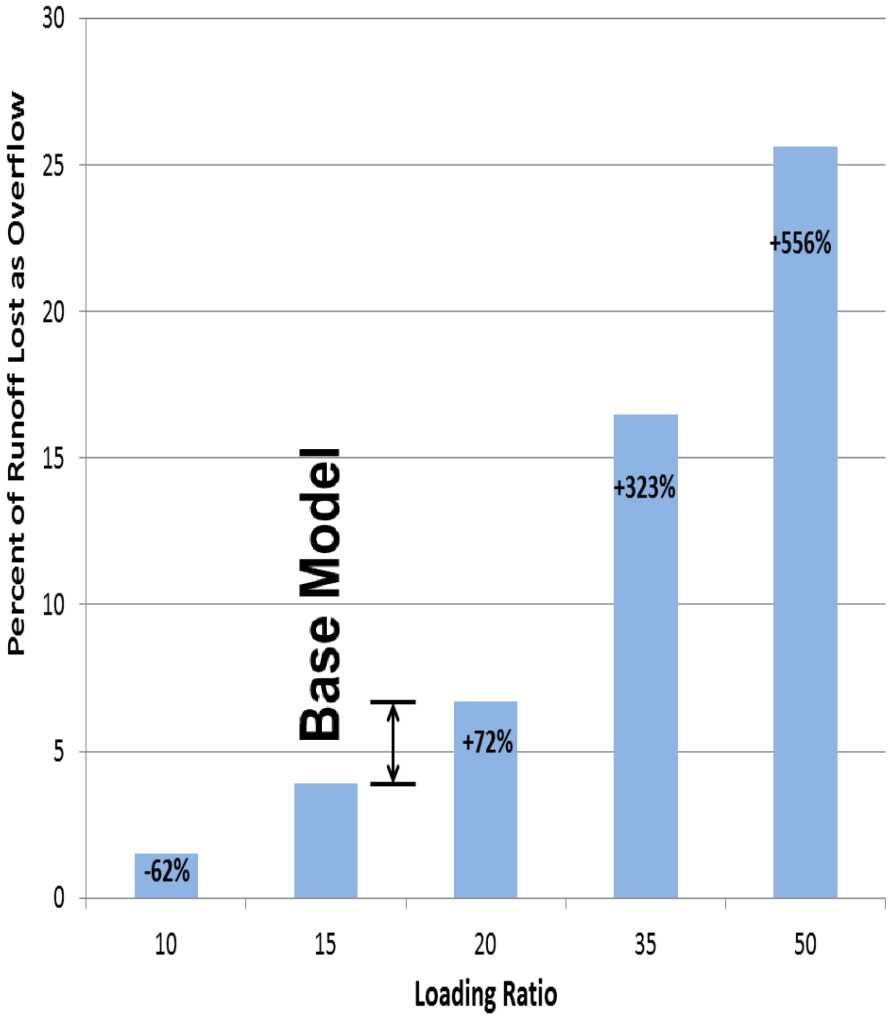
- Bowl storage depth had very little impact on volume reduction
- However, deeper bowl storage depths did result in reduced volumes and occurrences of overflow





Percent Change in Performance (0.05 in/hr underlying soil K_{sat})





Lessons Learned

- 3 biggest factors: underlying soil conductivity, loading ratio, presence of IWS
- Sensitivity of Model:
  - Moderate: Bowl storage, media depth* – mainly affect overflow
  - Least: Rooting Depth

*important when IWS depth also increases

Lessons Learned

- Incorporation of an IWS zone (15-18” optimal) has greater impact as soil K_{sat} decreases
- Bowl storage has little impact on volume reduction but does reduce overflow
- Loading ratio is critical
  - Undersized systems will have large amounts of overflow and increased maintenance burden

Questions?

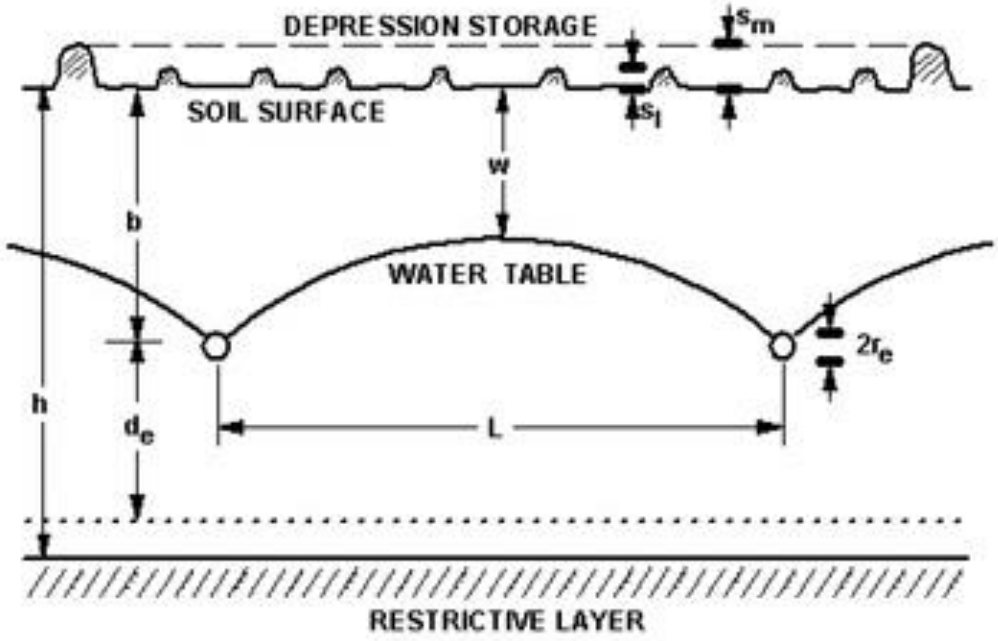
Designing and Developing Stormwater Practices in NW Ohio
Toledo, OH

Influence of Design Alternatives on Permeable Pavement Hydrology in NE Ohio

Alessandra Smolek, Ph.D.
North Carolina State University
April 14, 2016

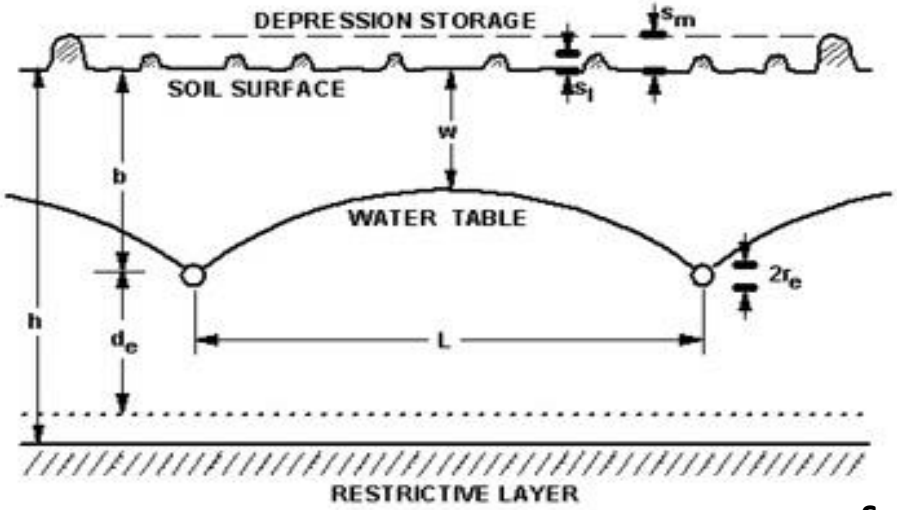
DRAINMOD: A new application

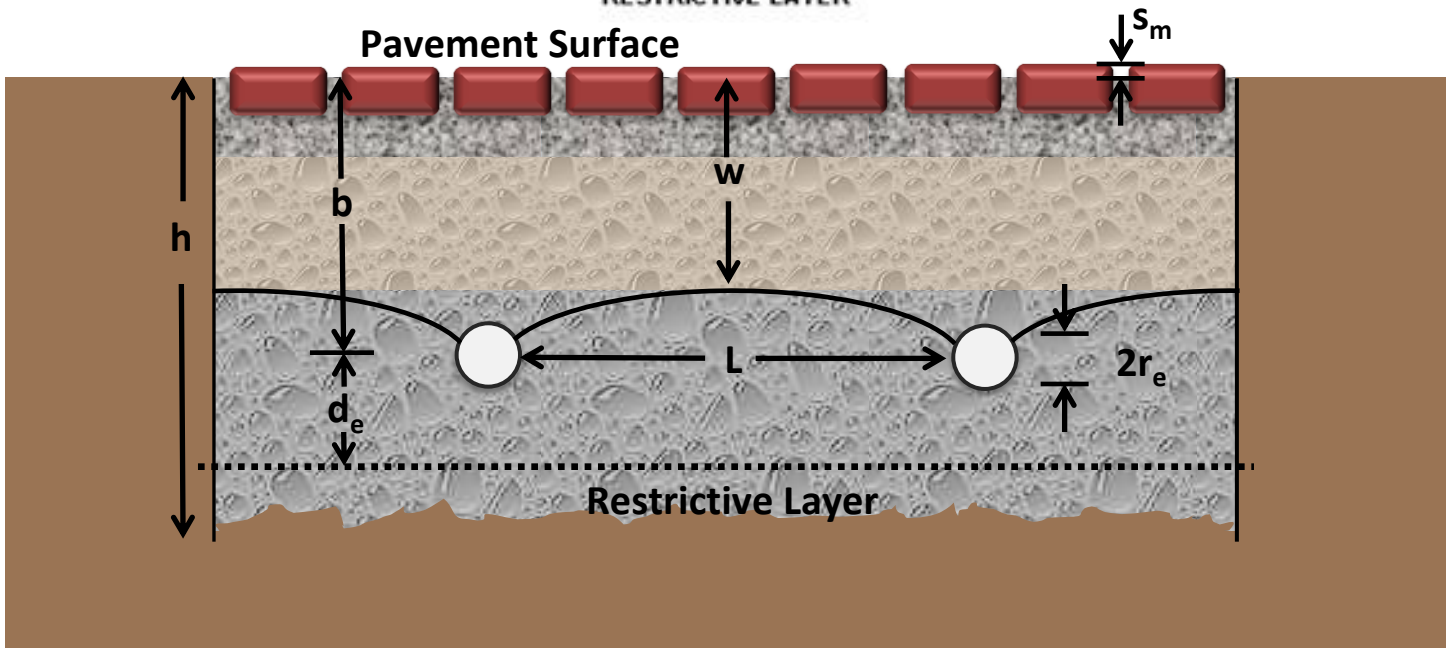
- DRAINMOD
  - Agricultural drainage model
- Other applications
  - Wetland Hydrology
  - Nitrogen transport
  - Bioretention (Brown et al. 2013, Winston et al. 2016)
- Potential use for modeling permeable pavement
  - Primary hydrologic mechanisms
    - Exfiltration
    - Drainage



Brown, R.A., R.W. Skaggs, and W.F. Hunt. (2013). "Calibration and validation of DRAINMOD to model bioretention hydrology." *Journal of Hydrology*. 486, 430-442.

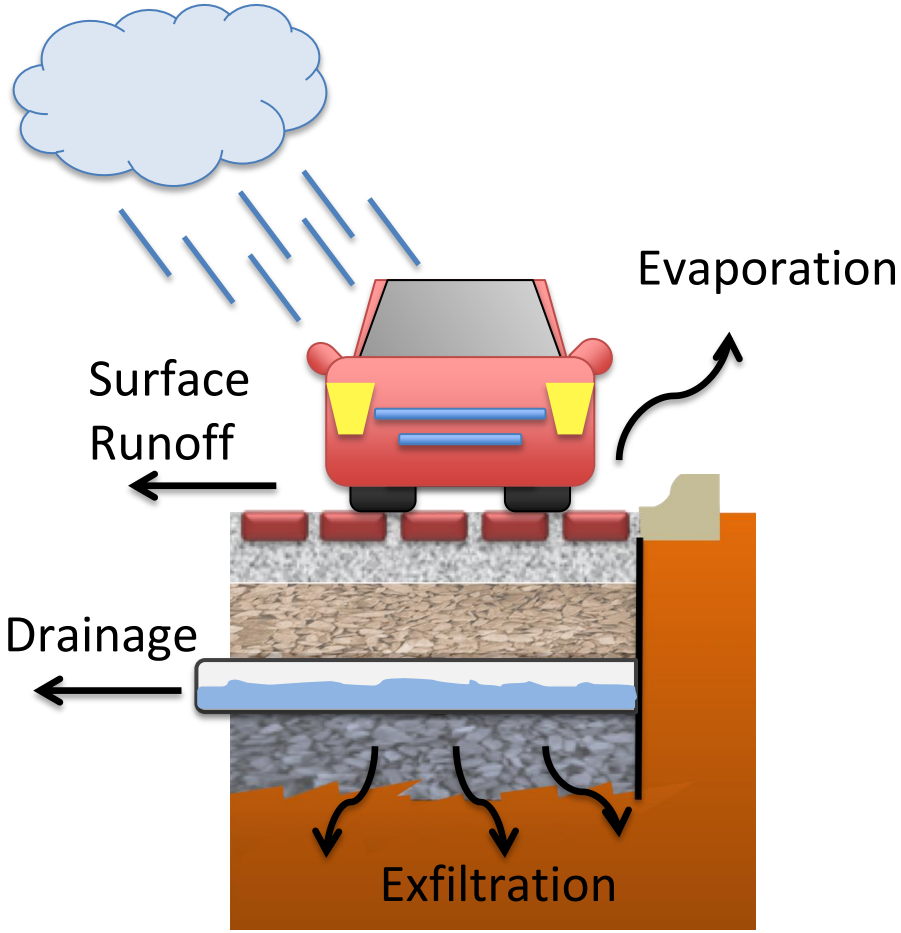
DRAINMOD: Drainage Inputs for PP





Modeling PP with DRAINMOD

- Model parking lot runoff, input PP design characteristics
- Calibration methods similar to bioretention (Brown et al. 2013, Winston et al. 2016)
- Calibrate on even months, validate on odd months
  - Captures seasonality of full year

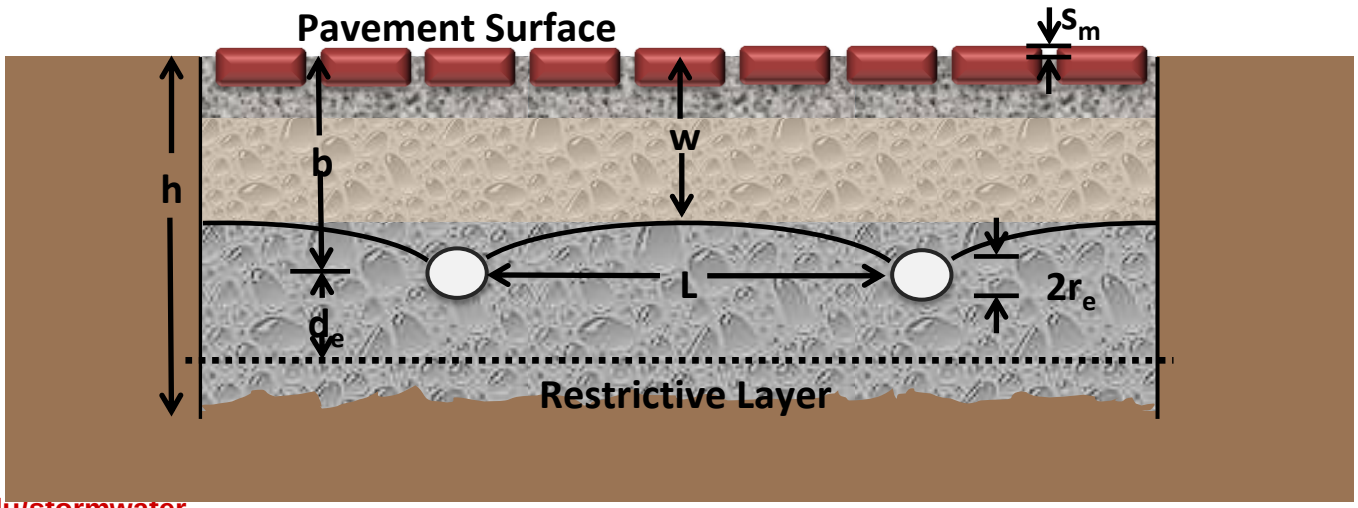


Brown, R.A., R.W. Skaggs, and W.F. Hunt. (2013). "Calibration and validation of DRAINMOD to model bioretention hydrology." *Journal of Hydrology*. 486, 430-442.

Calibration Methods

1. Site specific inputs

- Contributing run-on area
- Infiltrative surface area of permeable pavement
- Aggregate depth + water retention curve of aggregate
- Drain pipe depth, spacing, and radius
- Internal water storage zone depth



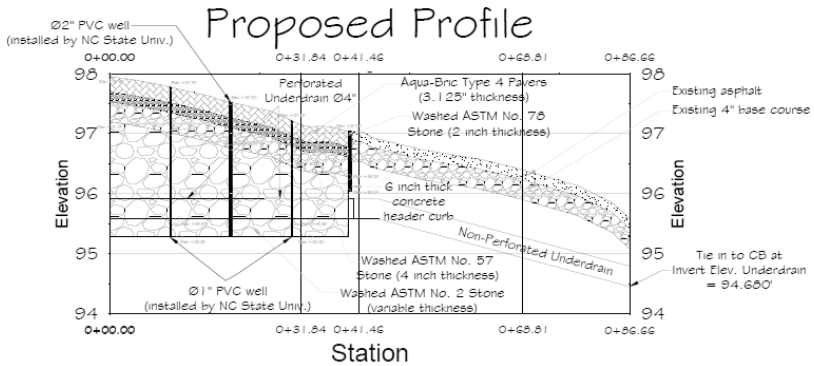
Calibration Methods

2. Measured water level

- Compare to daily output in DRAINMOD
- Measures exfiltration/evaporation rate for deep seepage

3. Measured / estimated flow volumes

- Drainage (measured)
- Surface Runoff (measured/negligible)
- Inflow (estimated by Curve Number Method)
- Exfiltration/evaporation (measured cumulatively)



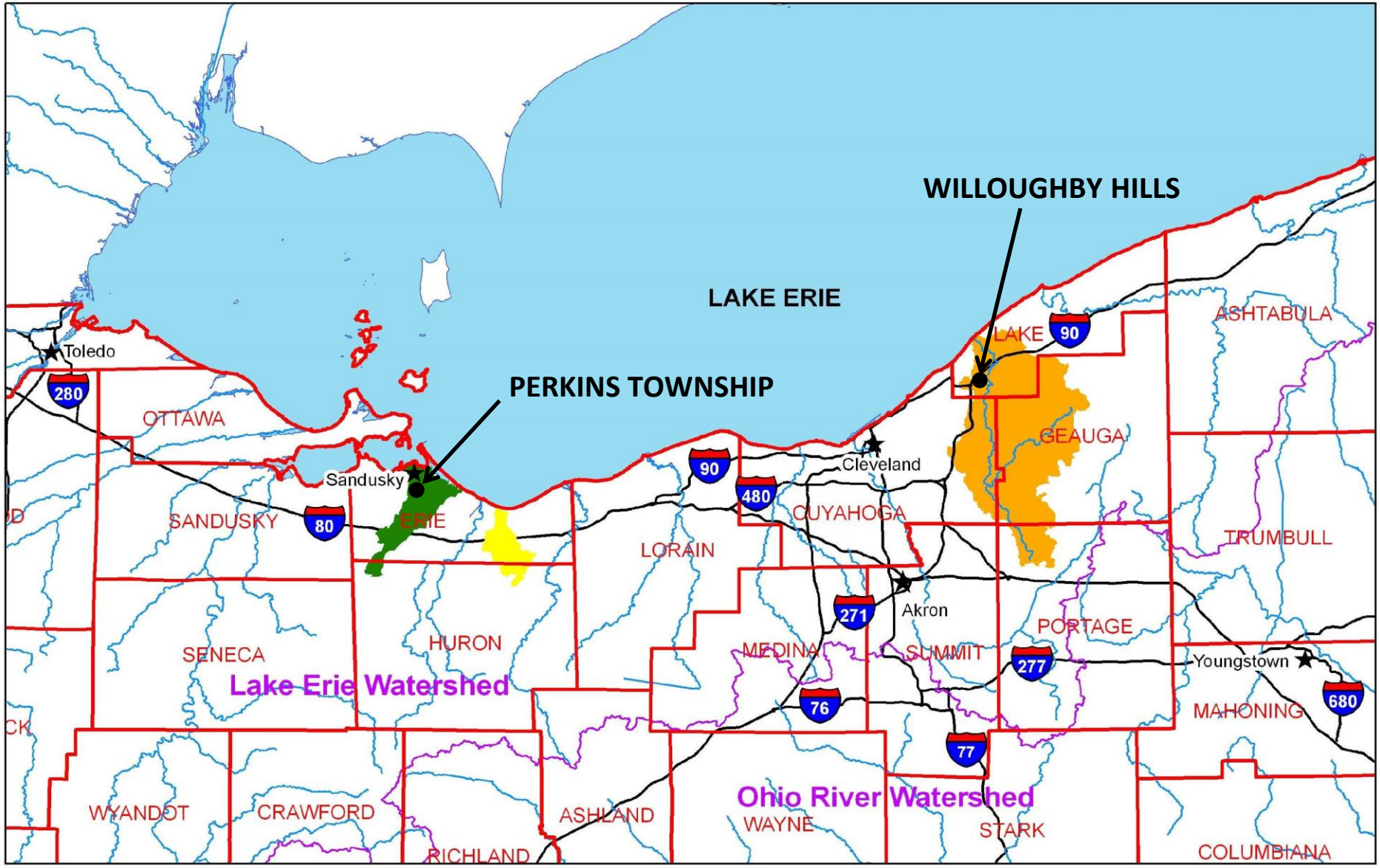
Monitoring Methods

Internal Water Level

Drainage Outflow

Surface Infiltration (ASTM C1707M)

Underlying Soil Characteristics



Watersheds:

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

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

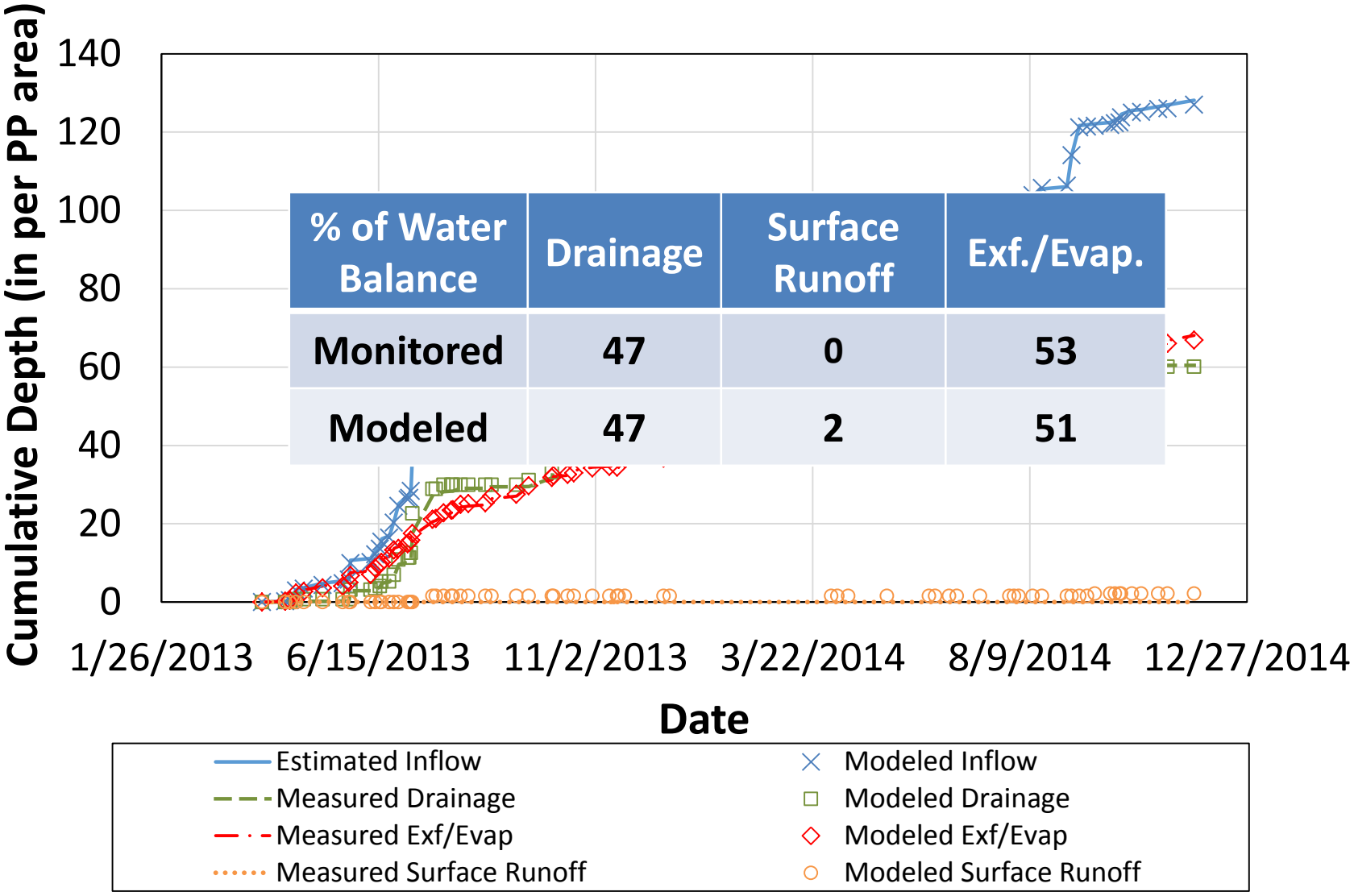
0 10 20 40 Miles

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

Site Characteristics

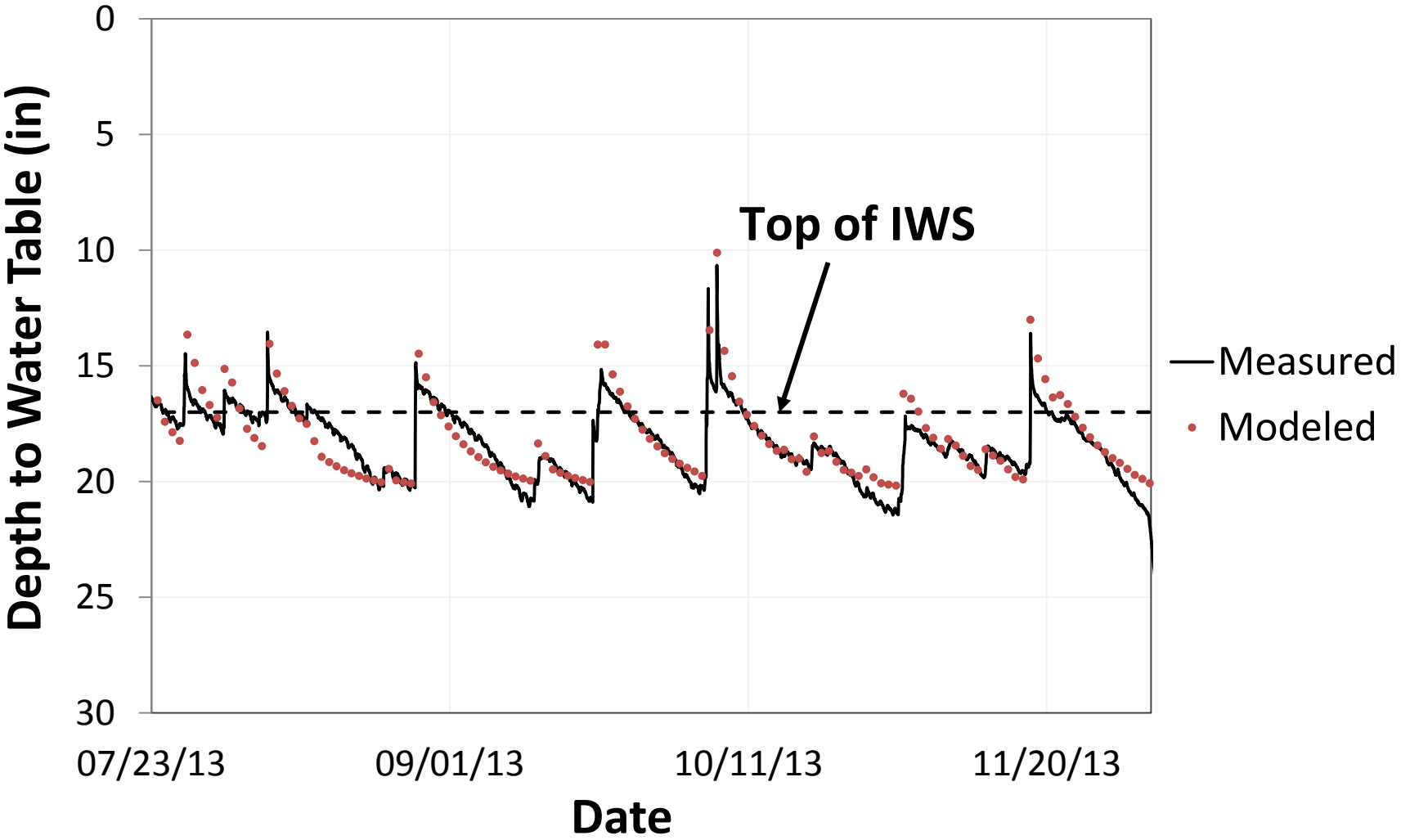
Site	Soil Type	Pavement Type (Drainage Configuration)	Impervious Run-on Ratio	Average Measured Drawdown Rate	Data Collection Period
Perkins Township, OH	Silty Clay Loam	Permeable Concrete (IWS)	4.8 : 1	0.02 in/hr	Apr. 2013-Nov. 2014
Willoughby Hills, OH (Large)	Fill	PICP (IWS)	2.2 : 1	0.01 in/hr	Oct. 2013-Nov. 2014
Willoughby Hills, OH (Small)	Fill	PICP (IWS)	7.2 : 1	0.01 in/hr	Oct. 2013-Nov. 2014

Perkins: Cumulative Volume



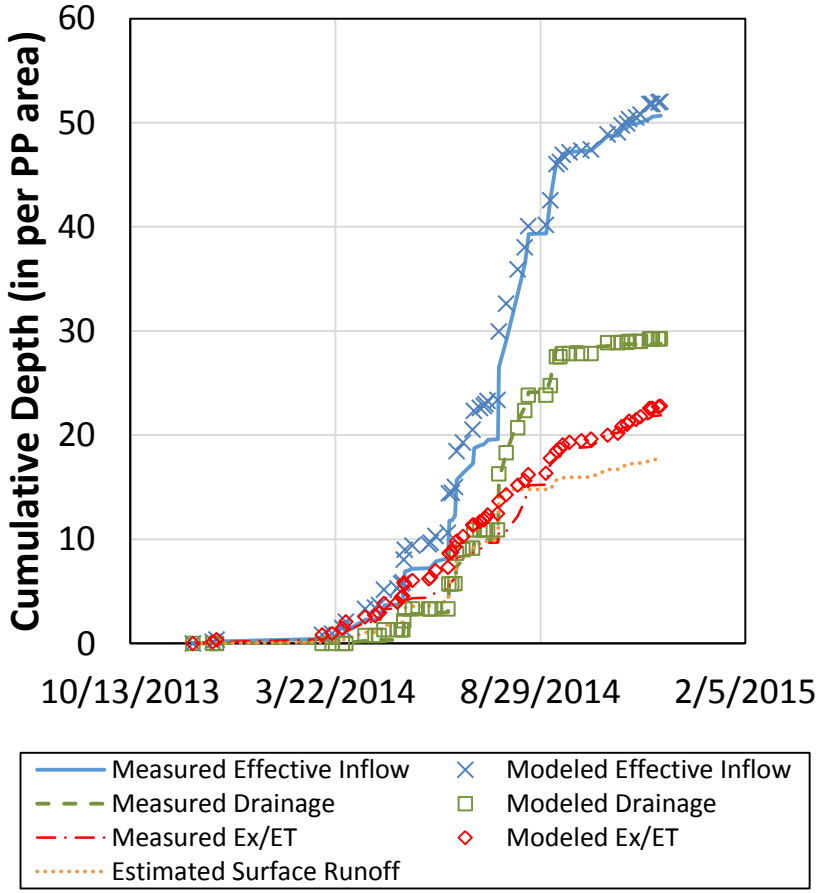
% of Water Balance	Drainage	Surface Runoff	Exf./Evap.
Monitored	47	0	53
Modeled	47	2	51

Perkins: Water Table Depth

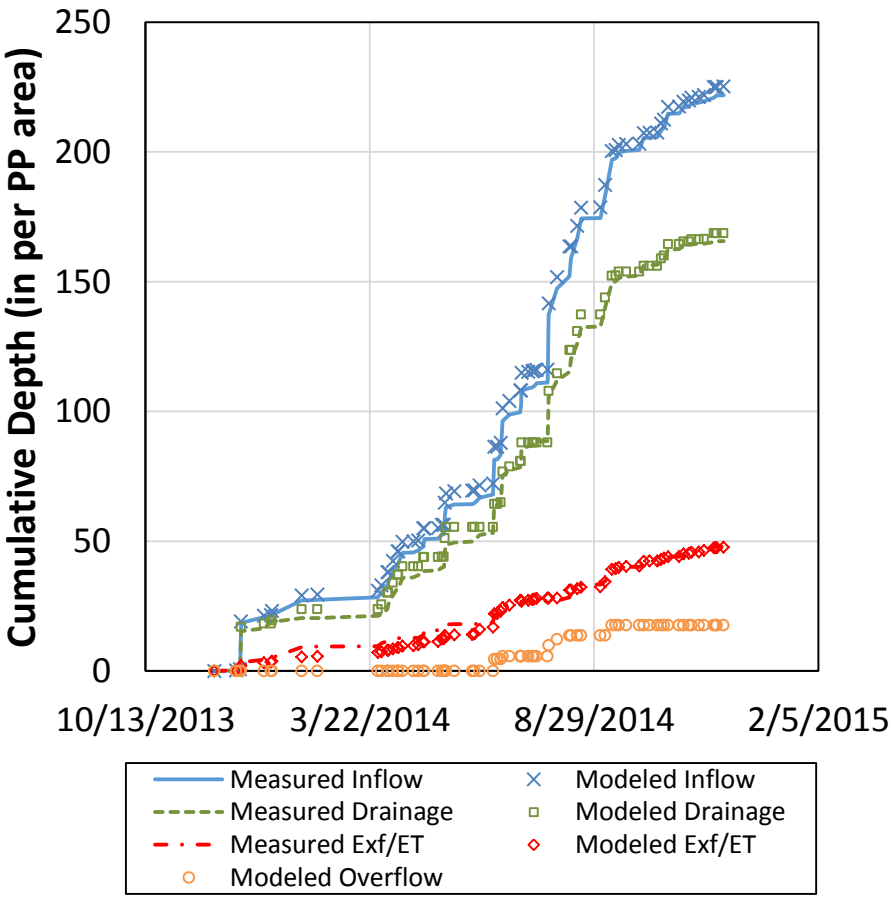


Cumulative Volume Results

Willoughby Hills Large



Willoughby Hills Small



Modeled vs. Measured Water Balance

*Percent of Total Inflow

Type of Data	Hydrologic Fate	Perkins Township	WH Small	WH Large
M				
M				
M				
M				
M				
Modeled	Evaporation	51	17	34

→ **Nash-Sutcliffe exceeded 0.75 for inflow and drainage**

→ **Cumulative volumes predicted to within 8% for all sites**

→ **Components of water balance predicted to within 2% for all sites**

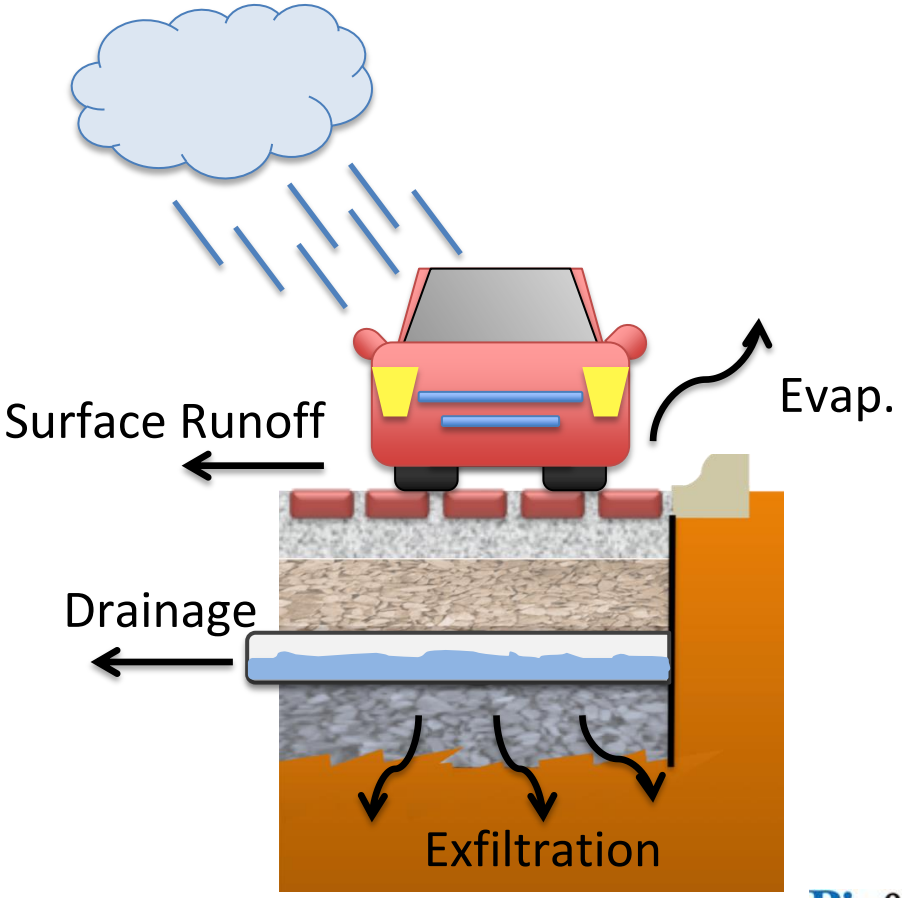
Design Alternative Analysis

How is the long-term hydrologic fate affected by:

- Underlying Soil K_{sat}
- Aggregate depth
- Internal Water Storage Zone
- Run-on ratio

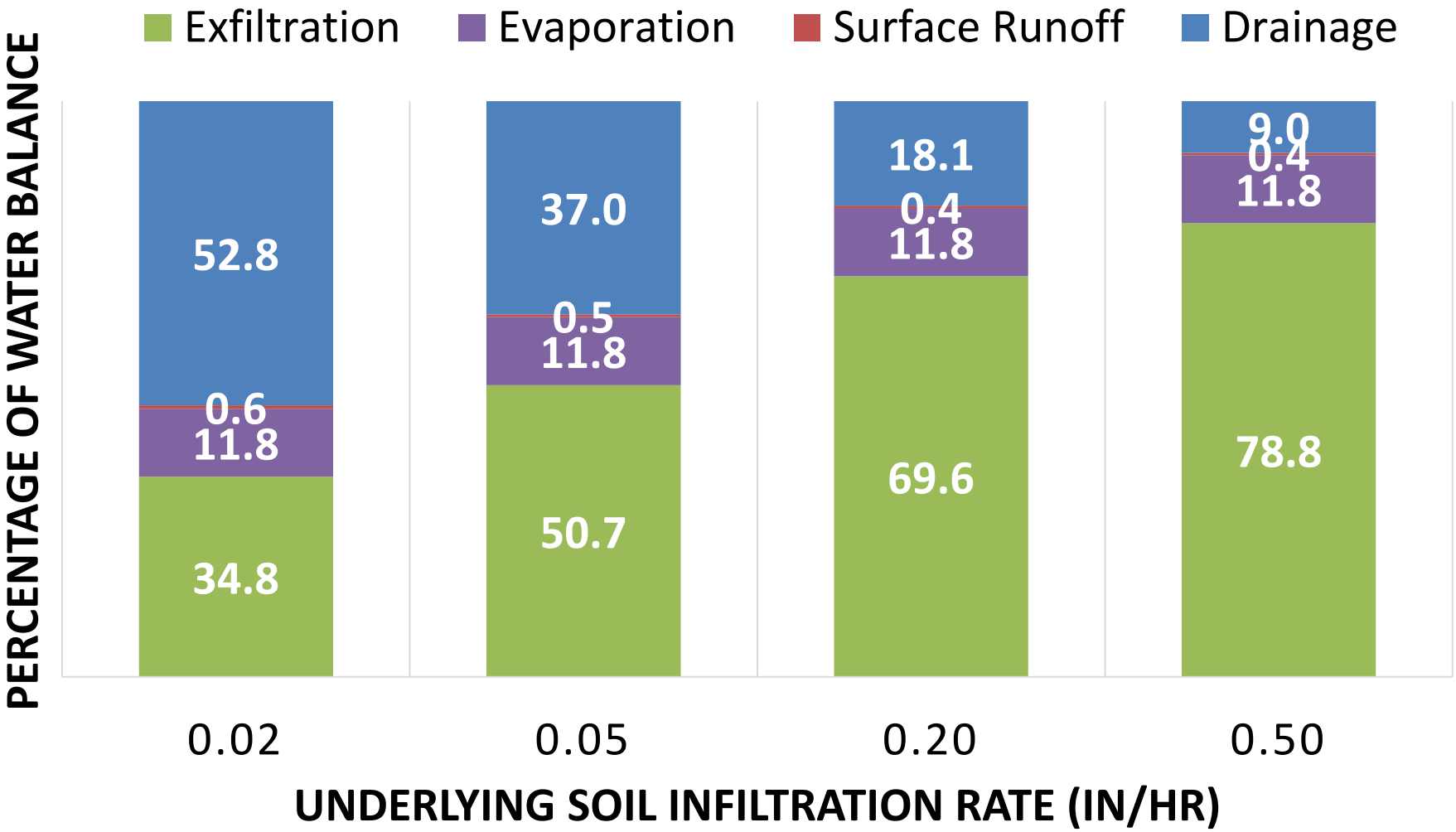
Baseline Models

- Four baseline models created based on conductivity of the underlying soil
  - K_{sat} = 0.5 in/hr
  - K_{sat} = 0.2 in/hr
  - K_{sat} = 0.05 in/hr
  - K_{sat} = 0.02 in/hr
- 30-years of rainfall and temperature
- Completed for each site and typical design in OH (2:1 run-on ratio)



Underlying Soil K_{sat}

- **WH Large, 2.2:1 run-on ratio, 24 inch agg. depth, 6 in. of IWS**

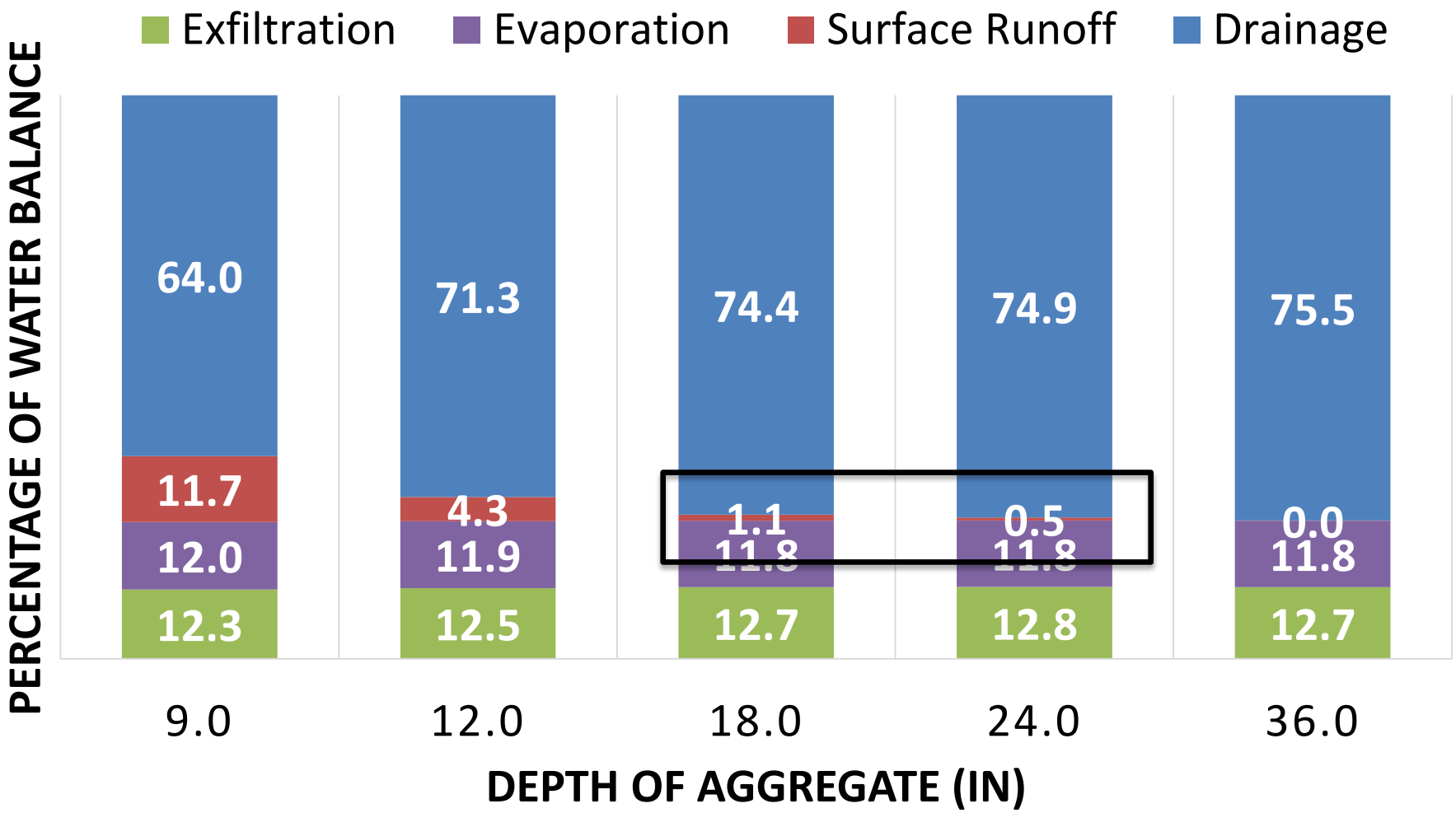


Design Alternative Analysis

- Pavement + aggregate depth
  - 9 in, 12 in, 18 in, 24 in, 36 in
- Internal Water Storage zone depth
  - 0 in, 6 in, 12 in
- Contributing Drainage Area : PP Area
  - None, 1:1, 2:1, 3:1

Effect of Pavement + Aggregate Depth

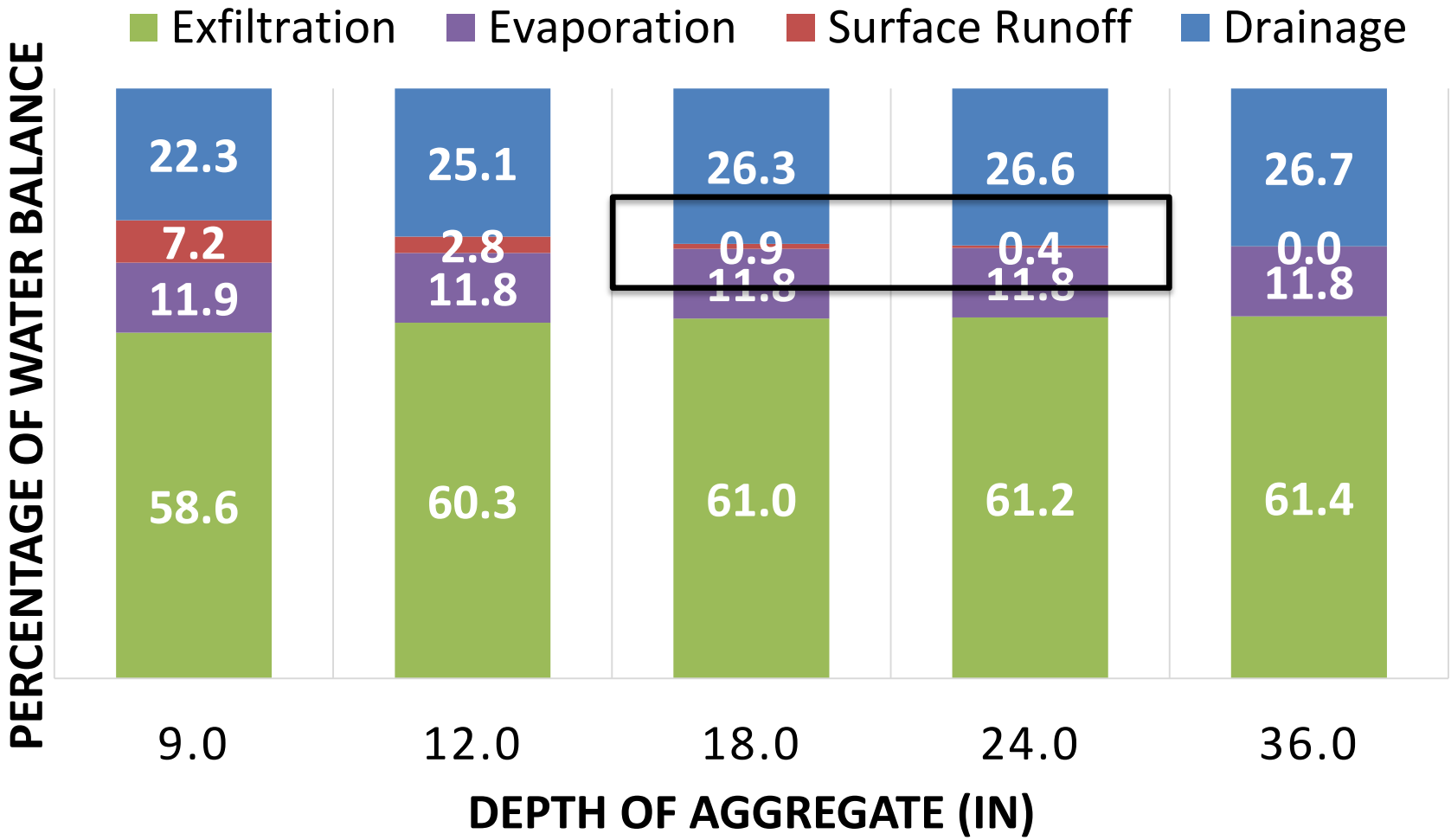
- **WH Large, No IWS, 0.02 in/hr infiltration rate**



For HSG D soil: 18 inches – appx. 1% surface runoff

Effect of Pavement + Aggregate Depth

- **WH Large, No IWS, 0.50 in/hr infiltration rate**



For HSG B soil: 18 inches < 1% surface runoff

Effect of Pavement + Aggregate Depth

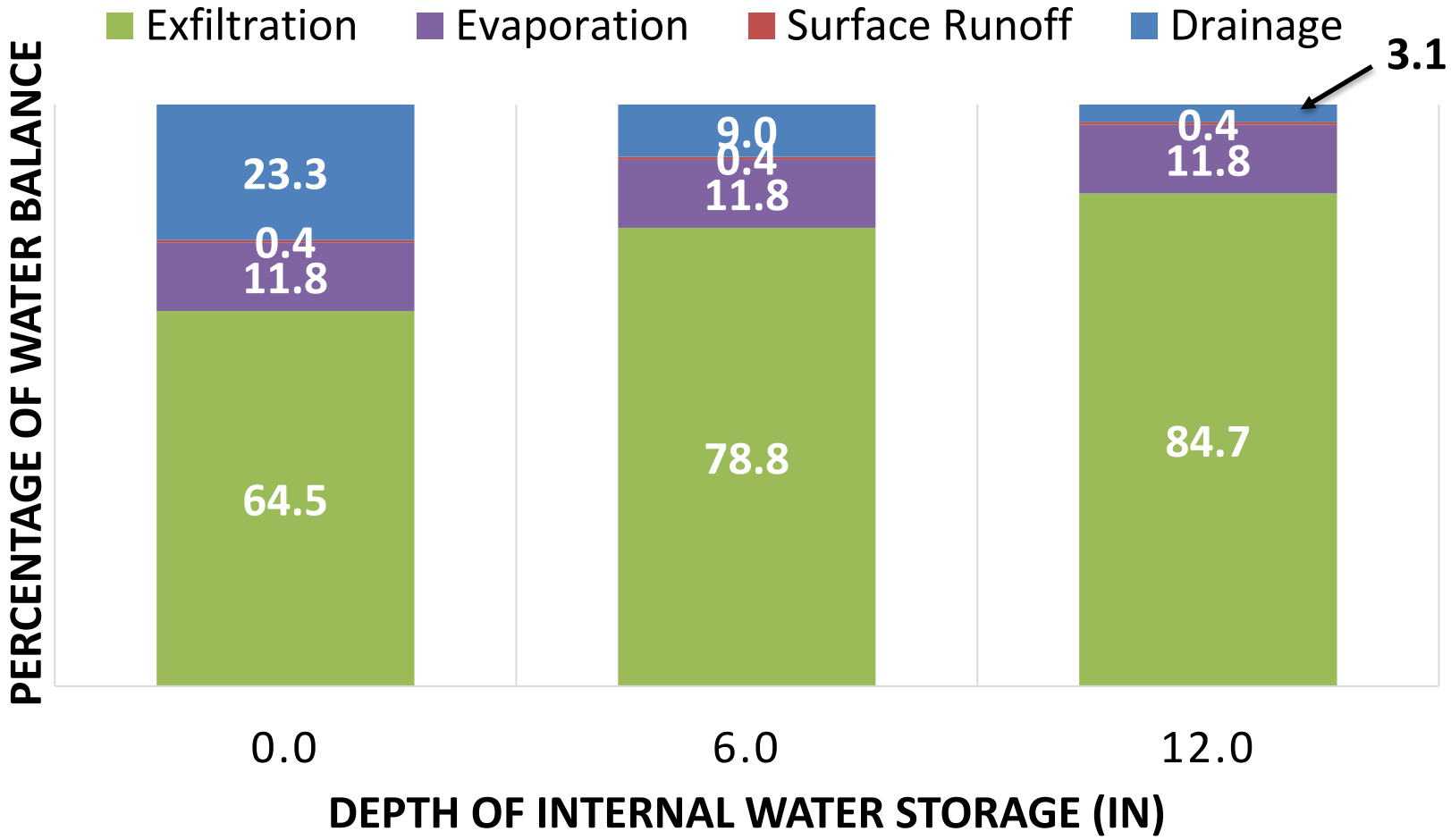
- Most sensitive output: **Surface Runoff**
- Less pronounced as infiltration rate, IWS increases
- **12 - 18 inches** probably adequate for meeting most structural and hydrologic needs

Design Alternative Analysis

- Pavement + aggregate depth
  - 9 in, 12 in, 18 in, 24 in, 36 in
- Internal Water Storage zone depth
  - 0 in, 6 in, 12 in
- Contributing Drainage Area : PP Area
  - None, 1:1, 2:1, 3:1

Effect of Internal Water Storage

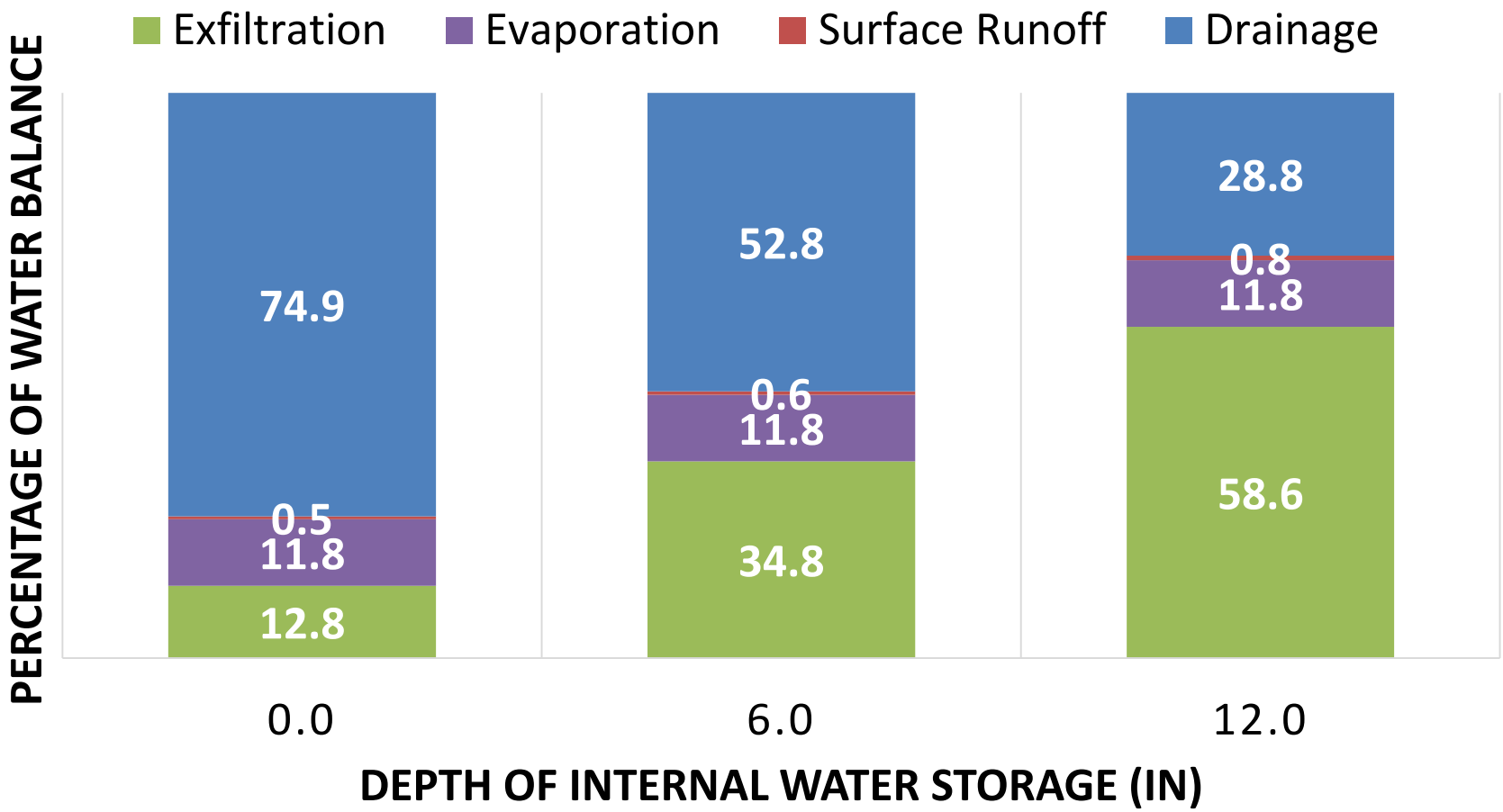
- **0.50 in/hr infiltration rate**



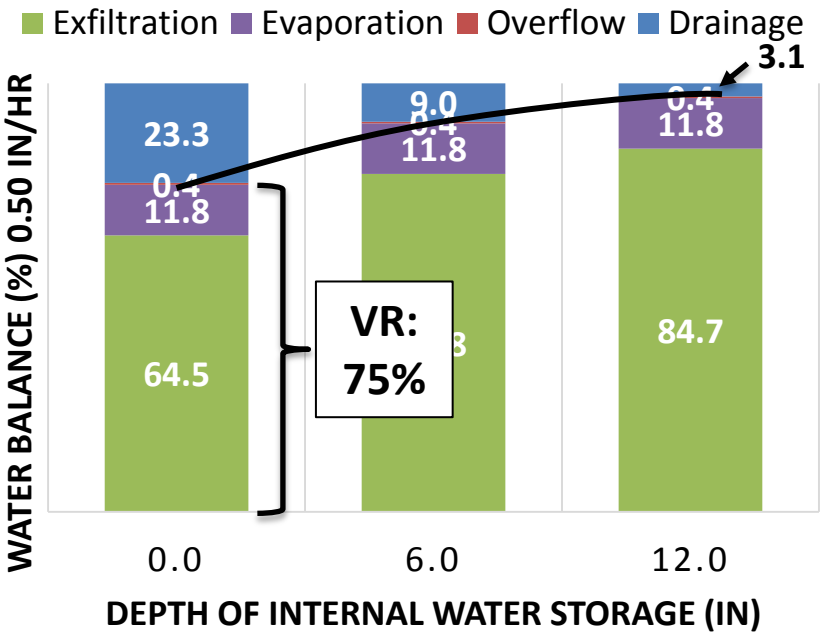
Adding 6 inches of IWS increases volume reduction by 15%

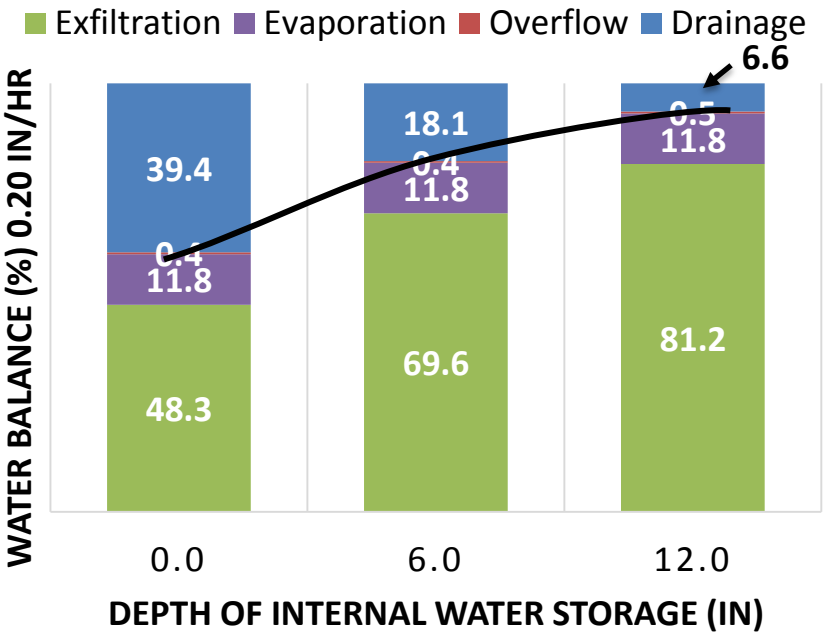
Effect of Internal Water Storage

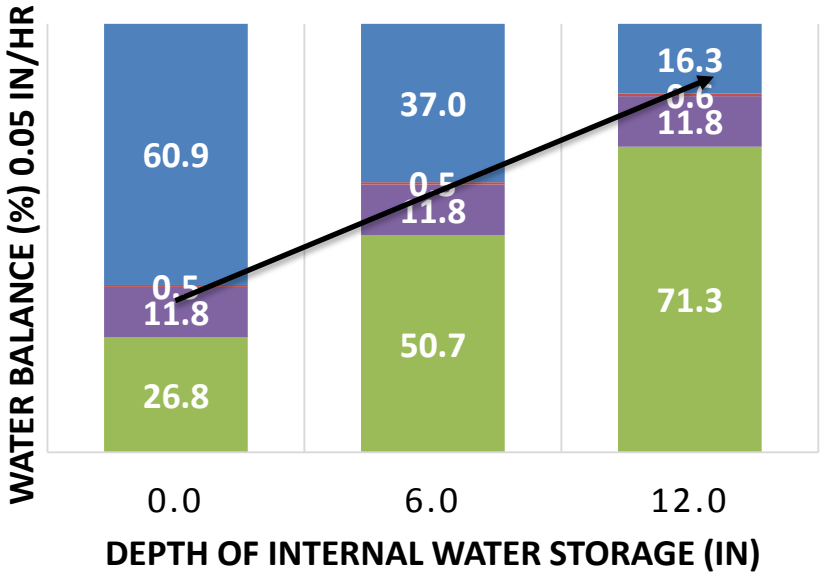
- **0.02 in/hr infiltration rate**

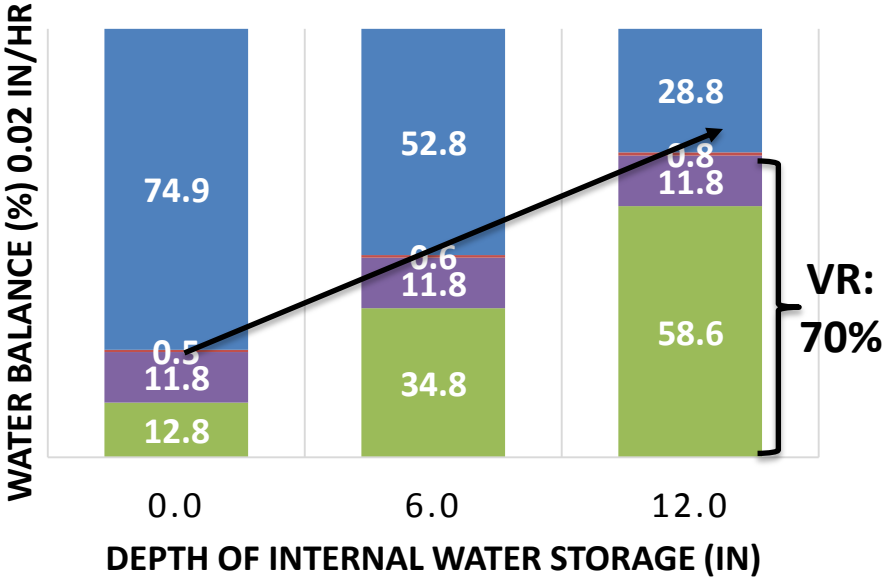


12 inches of IWS required to mimic volume reduction from 0.50 in/hr without IWS

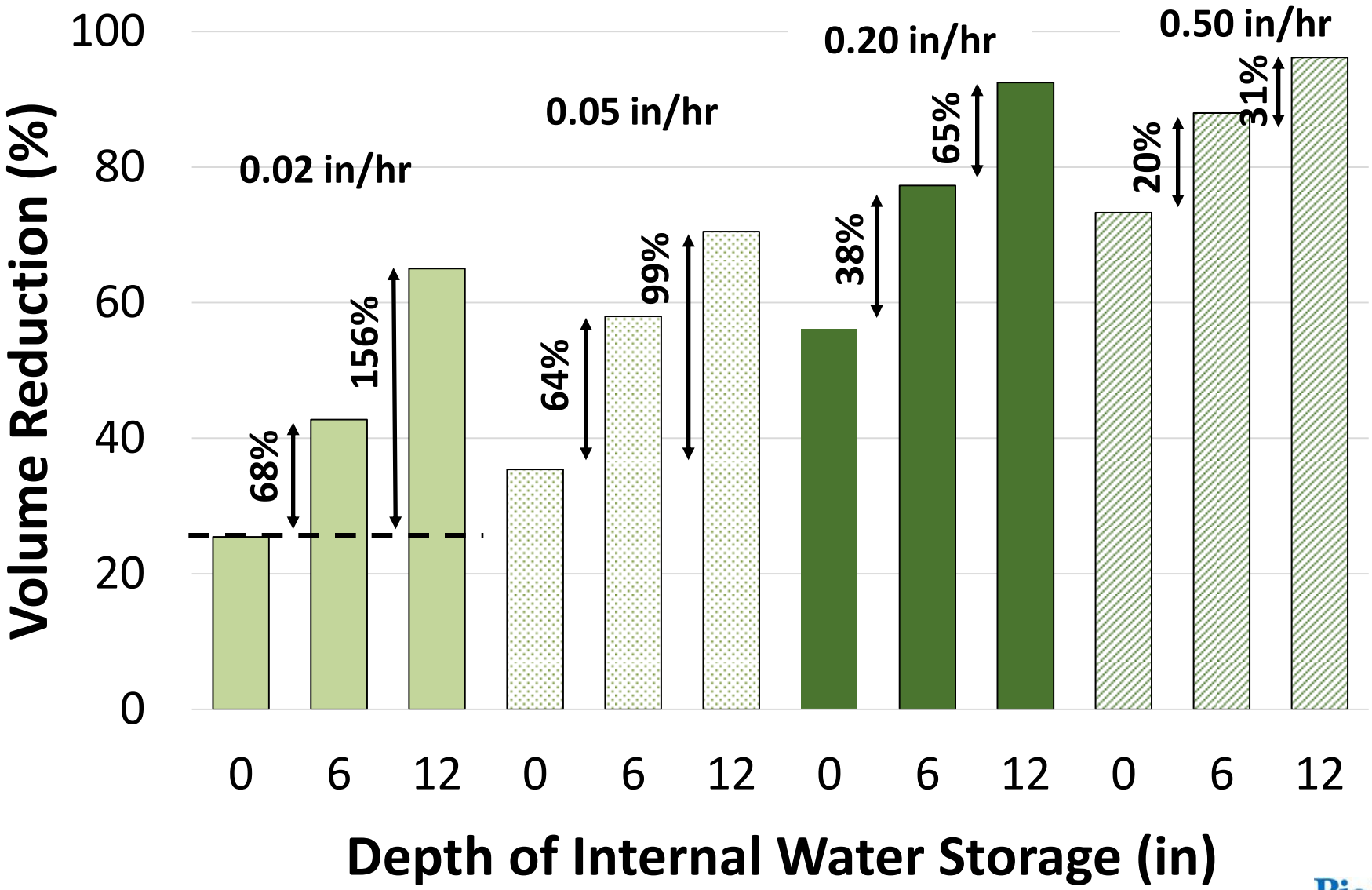

Exfiltration
Evaporation
Overflow
Drainage
3.1
23.3
0.4
11.8
64.5
9.0
0.4
11.8
84.7
VR:
75%
WATER BALANCE (%) 0.50 IN/HR
0.0
6.0
12.0
DEPTH OF INTERNAL WATER STORAGE (IN)


Exfiltration
Evaporation
Overflow
Drainage
6.6
39.4
0.4
11.8
48.3
18.1
0.4
11.8
69.6
0.5
11.8
81.2
WATER BALANCE (%) 0.20 IN/HR
0.0
6.0
12.0
DEPTH OF INTERNAL WATER STORAGE (IN)


60.9
0.5
11.8
26.8
37.0
0.5
11.8
50.7
16.3
0.6
11.8
71.3
WATER BALANCE (%) 0.05 IN/HR
0.0
6.0
12.0
DEPTH OF INTERNAL WATER STORAGE (IN)


74.9
0.5
11.8
12.8
52.8
0.6
11.8
34.8
28.8
0.8
11.8
58.6
VR:
70%
WATER BALANCE (%) 0.02 IN/HR
0.0
6.0
12.0
DEPTH OF INTERNAL WATER STORAGE (IN)

Ohio Standard Design (2:1 Run-on Ratio)

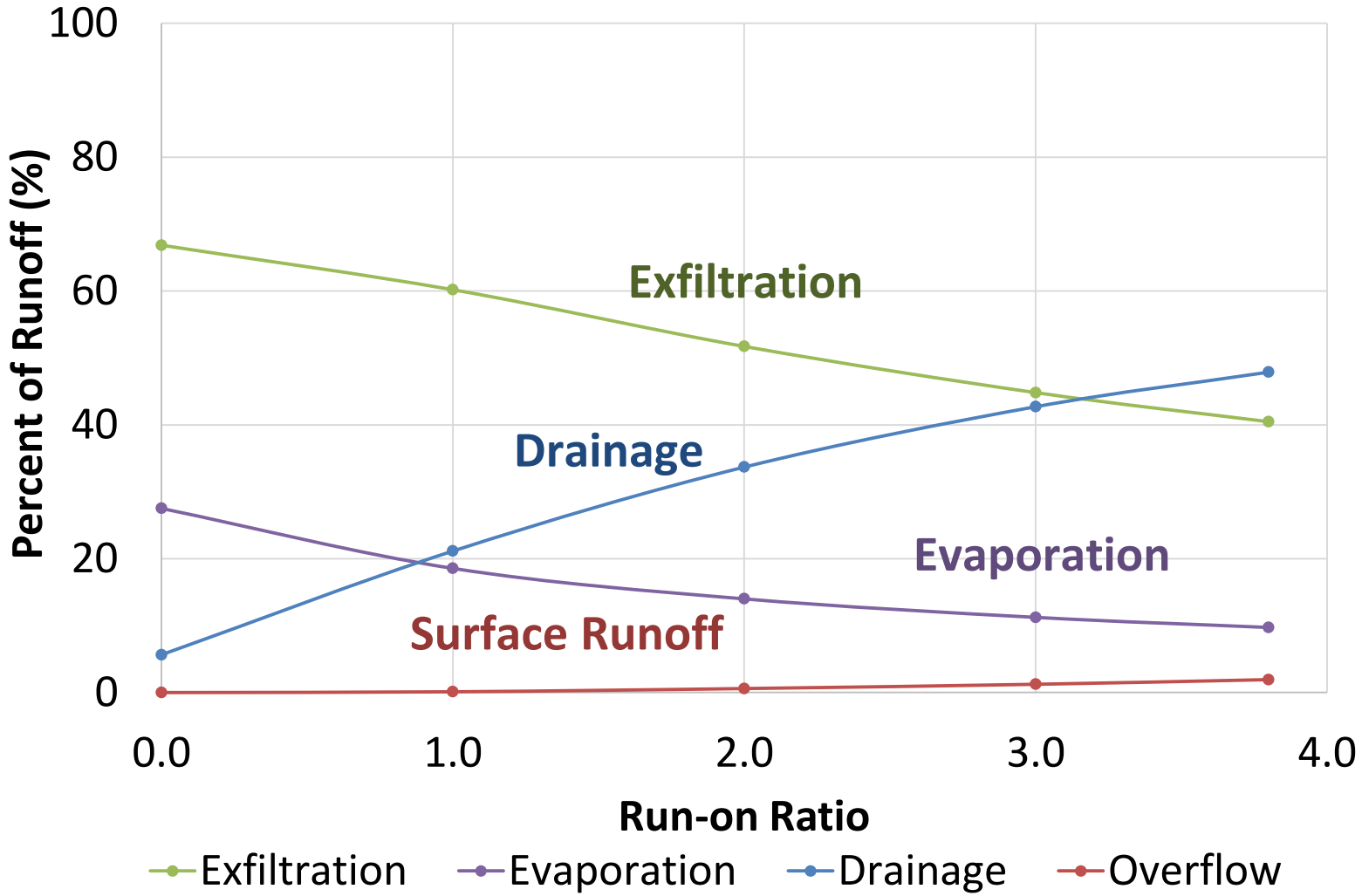


Effect of Internal Water Storage

- Most sensitive output: **Drainage and Exfiltration**
- Little effect on overflow and evaporation
- Marginal returns as infiltration rate increases
- **12 inches** of IWS maximizes exfiltration/evaporation, minimizes outflow (drainage + overflow)
- Greatest impact from increasing IWS observed for lowest infiltration rates (0.02 in/hr, 0.05 in/hr)

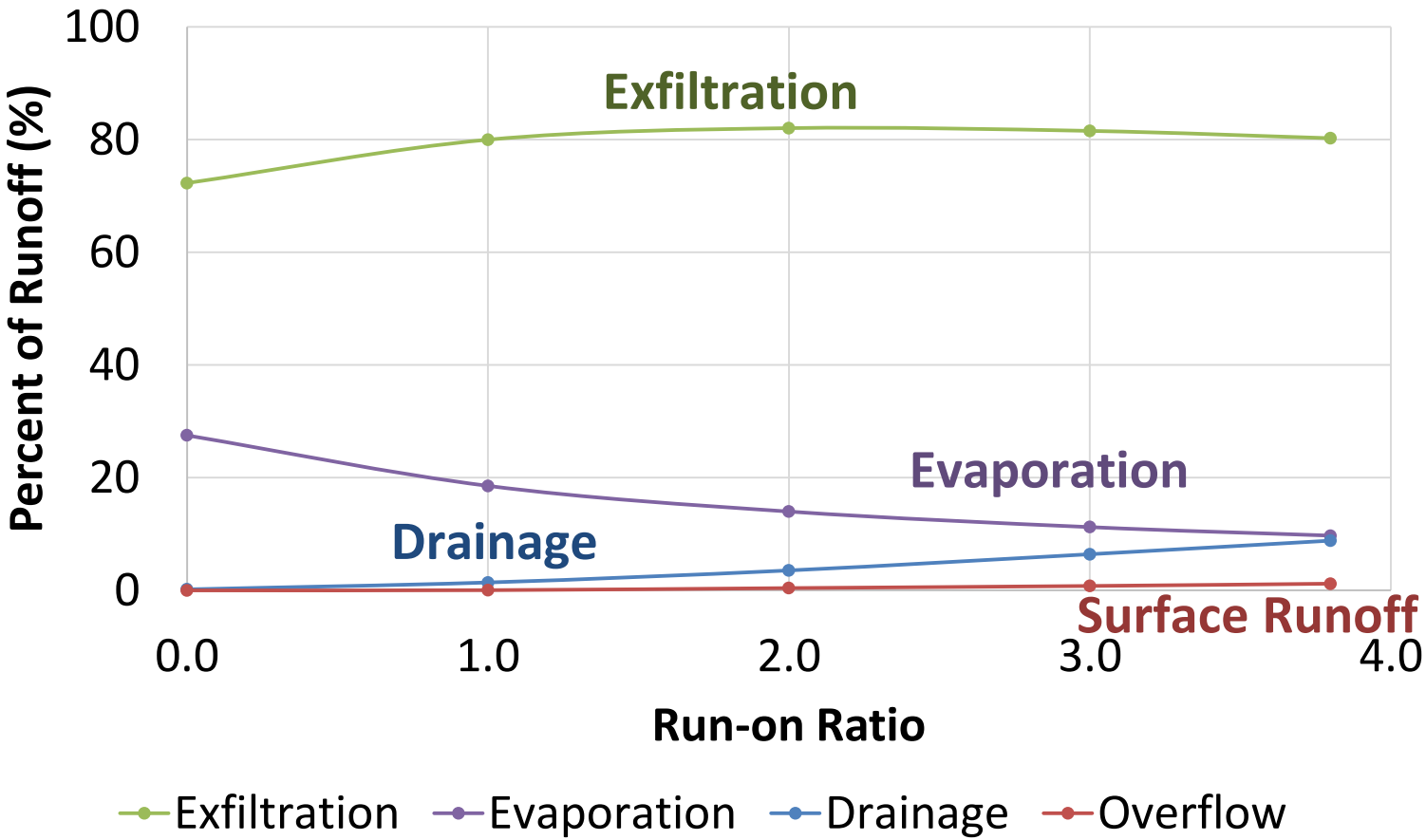
Effect of Run-on Ratio

- 6” IWS zone, 24” agg. depth, and 0.02 in/hr



Effect of Run-on Ratio

- 6” IWS zone, 24” agg depth, and 0.50 in/hr

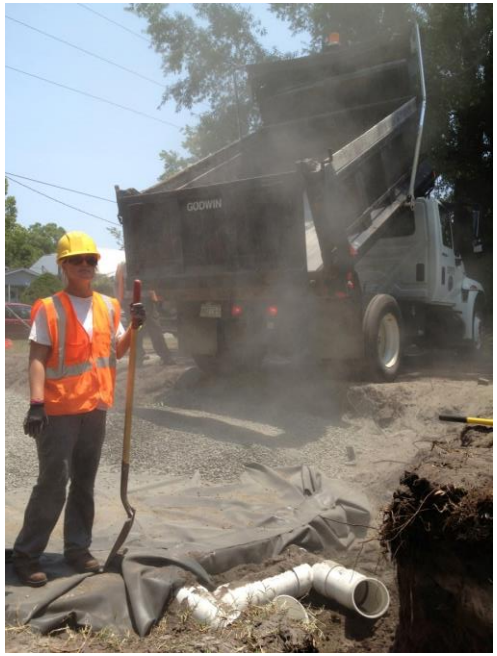


Increasing CA has less effect on high inf. rate soils
…but increases susceptibility to clogging

Effect of Run-on Ratio

- As contributing area increases, clogging susceptibility increases, increased need for maintenance
- Balance between maximizing performance and cost-effectively treating watershed area
- Best option? Route roof runoff directly into aggregate subbase

Design Alternative Analysis Summary

1) Flexible design options for “better” underlying soils
2) **IWS** increases “bang for your buck”
3) Targeted design improves volume reduction for PP over low infiltration soils

Questions?