Effects of Design Characteristics on Bioretention Cell (Hydrologic) Performance

Ryan Winston, PhD, P.E.
Research Scientist
Department of Food, Agricultural, and Biological Engineering

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

- Inflow / Runoff
- Evapotranspiration
- Max. Surf. Storage ($S_m$)
- Depth to Drain ($B$)
- Depth to Impermeable Layer ($H$)
- Drain Spacing ($L$)
- Bowl
- Sandy Fill Media
- Internal Water Storage
- Underdrains
- Exfiltration
- Overflow
- Weir Depth
- Upturned Elbow
- In-situ Soil
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
- Invalid when water table is close to the surface
Soil-Water Characteristic

- Nashville
- Knightdale
- Rocky Mount

Soil Water Pressure Head (cm)

Volumetric Water Content (m³/m³)
Calculating Water Stored in Profile

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

![Graph showing volumetric water content and water table depth.](image)
DRAINMOD Water Balance

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

where

\(\Delta V_a\) = change in air volume (cm)

\(D\) = lateral drainage from section (cm)

\(ET\) = evapotranspiration (cm)

\(DS\) = deep seepage (cm)

\(F\) = infiltration entering the section in \(\Delta t\)

*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)
  – $K_{\text{sat}}$
    • 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. $I = \sum_{i=1}^{12} \left( \frac{T_i}{5} \right)^{1.514}$
      - Degrees Celsius
  - Daily PET values were estimated using the daily maximum and minimum temperatures and the calculated heat index.
## DRAINMOD Outputs: Water Balance

<table>
<thead>
<tr>
<th>YEAR</th>
<th>RAINFALL</th>
<th>INFILTRATION</th>
<th>ET</th>
<th>DRAINAGE</th>
<th>RUNOFF</th>
<th>VERTSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>1752.52</td>
<td>1484.75</td>
<td>95.57</td>
<td>861.64</td>
<td>267.77</td>
<td>532.19</td>
</tr>
<tr>
<td>AVG</td>
<td>1752.52</td>
<td>1484.75</td>
<td>95.57</td>
<td>861.64</td>
<td>267.77</td>
<td>532.19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DRAINMOD Outputs</th>
<th>Potential Meaning for Bioretention</th>
</tr>
</thead>
<tbody>
<tr>
<td>ET</td>
<td>Evapotranspiration <em>(volume eliminated)</em></td>
</tr>
<tr>
<td>Drainage</td>
<td>Underdrain flow volume <em>(treated volume)</em></td>
</tr>
<tr>
<td>Runoff</td>
<td>Overflow volume <em>(untreated volume)</em></td>
</tr>
<tr>
<td>Seepage</td>
<td>Exfiltration <em>(volume eliminated)</em></td>
</tr>
</tbody>
</table>
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

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

<table>
<thead>
<tr>
<th>Monitoring Period</th>
<th>Ursuline</th>
<th>Holden South</th>
<th>Holden North</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Validation</td>
<td>0.99</td>
<td>0.96</td>
<td>0.96</td>
</tr>
</tbody>
</table>

- 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

\[ y = 0.9986x + 0.2672 \]

\[ R^2 = 0.9819 \]
UC: Overall Water Balance
Measured vs. Modeled

Volume (in per BRC Area)

- Measured Runoff
- Modeled Runoff
- Measured Drainage
- Modeled Drainage
- Measured Overflow
- Modeled Overflow
- Measured Exfiltration+ET
- Modeled Exfiltration+ET

Date:
- 5/31/2014
- 6/30/2014
- 7/30/2014
- 8/29/2014
- 9/28/2014
- 10/28/2014
- 11/27/2014
HA South: Overall Water Balance
Measured vs. Modeled

Volume (in per BRC Area)

- Measured Runoff
- Modeled Runoff
- Measured Drainage
- Modeled Drainage
- Measured Overflow
- Modeled Overflow
- Measured Exfiltration+ET
- Modeled Exfiltration+ET

Dates:
10/3/2013
12/2/2013
1/31/2014
4/1/2014
5/31/2014
7/30/2014
9/28/2014
11/27/2014
HA North: Overall Water Balance
Measured vs. Modeled

Volume (in per BRC Area)

- Measured Runoff
- Modeled Runoff
- Measured Drainage
- Modeled Drainage
- Measured Overflow
- Modeled Overflow
- Measured Exfiltration+ET
- Modeled Exfiltration+ET

Dates: 10/3/2013 to 11/27/2014
Model Agreement
*Nash-Sutcliffe Coefficients during Validation Periods

<table>
<thead>
<tr>
<th>Hydrologic Fate</th>
<th>Ursuline</th>
<th>Holden North</th>
<th>Holden South</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runoff</td>
<td>0.99</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>Drainage</td>
<td>0.98</td>
<td>0.98</td>
<td>0.95</td>
</tr>
<tr>
<td>Overflow</td>
<td>0.73</td>
<td>0.74</td>
<td>0.71</td>
</tr>
<tr>
<td>Exfiltration/ET</td>
<td>0.95</td>
<td>0.76</td>
<td>0.75</td>
</tr>
</tbody>
</table>
## Modeled vs. Measured Water Balance

*Percent of Total Inflow*

<table>
<thead>
<tr>
<th>Type of Data</th>
<th>Hydrologic Fate</th>
<th>Ursuline</th>
<th>Holden North</th>
<th>Holden South</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitored</td>
<td>Drainage</td>
<td>33</td>
<td>51</td>
<td>57</td>
</tr>
<tr>
<td>Modeled</td>
<td></td>
<td>33</td>
<td>52</td>
<td>56</td>
</tr>
<tr>
<td>Monitored</td>
<td>Overflow</td>
<td>8</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Modeled</td>
<td></td>
<td>9</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Monitored</td>
<td>Exfiltration/ET</td>
<td>59</td>
<td>42</td>
<td>36</td>
</tr>
<tr>
<td>Modeled</td>
<td></td>
<td>58</td>
<td>40</td>
<td>35</td>
</tr>
</tbody>
</table>
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)
  – $K_{\text{sat}} = 0.5 \text{ in/hr}$
  – $K_{\text{sat}} = 0.2 \text{ in/hr}$
  – $K_{\text{sat}} = 0.05 \text{ in/hr}$
  – $K_{\text{sat}} = 0.02 \text{ in/hr}$
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
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)
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
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 \( K_{\text{sat}} \))
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

DRAINMOD: Drainage Inputs for PP

The diagram illustrates the drainage inputs for pervious pavements (PP) and includes the following key components:

- **Pavement Surface**
- **Restrictive Layer**
- **SOIL SURFACE**
- **WATER TABLE**
- **DEPRESSION STORAGE**
- **Restrictive Layer**

The diagram shows the depth (h), width (w), and length (L) of the elements involved. The restrictive layer is depicted with its depth (d_e) and the water table at (h). The diagram also illustrates the drainage inputs with the depth (h) and width (w) of the elements involved. The restrictive layer is depicted with its depth (d_e) and the water table at (h).
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

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
- Surface Infiltration (ASTM C1707M)
- Drainage Outflow
- Underlying Soil Characteristics
## Site Characteristics

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

Willoughby Hills Large

- Measured Effective Inflow
- Modeled Effective Inflow
- Measured Drainage
- Modeled Drainage
- Measured Ex/ET
- Modeled Ex/ET
- Estimated Surface Runoff

Willoughby Hills Small

- Measured Inflow
- Modeled Inflow
- Measured Drainage
- Modeled Drainage
- Measured Exf/ET
- Modeled Exf/ET
- Modeled Overflow
## Modeled vs. Measured Water Balance

*Percent of Total Inflow*

<table>
<thead>
<tr>
<th>Type of Data</th>
<th>Hydrologic Fate</th>
<th>Perkins Township</th>
<th>WH Small</th>
<th>WH Large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modeled</td>
<td>Evaporation</td>
<td>51</td>
<td>17</td>
<td>34</td>
</tr>
</tbody>
</table>

- 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 $K_{\text{sat}}$
– Aggregate depth
– Internal Water Storage Zone
– Run-on ratio
Baseline Models

- Four baseline models created based on conductivity of the underlying soil
  - $K_{sat} = 0.5 \text{ in/hr}$
  - $K_{sat} = 0.2 \text{ in/hr}$
  - $K_{sat} = 0.05 \text{ in/hr}$
  - $K_{sat} = 0.02 \text{ in/hr}$
- 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

<table>
<thead>
<tr>
<th>PERCENTAGE OF WATER BALANCE</th>
<th>UNDERLYING SOIL INFILTRATION RATE (IN/HR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>52.8</td>
<td>0.02</td>
</tr>
<tr>
<td>37.0</td>
<td>0.05</td>
</tr>
<tr>
<td>18.1</td>
<td>0.20</td>
</tr>
<tr>
<td>9.0</td>
<td>0.50</td>
</tr>
</tbody>
</table>

- Exfiltration
- Evaporation
- Surface Runoff
- Drainage
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

<table>
<thead>
<tr>
<th>Depth of Aggregate (IN)</th>
<th>Exfiltration</th>
<th>Evaporation</th>
<th>Surface Runoff</th>
<th>Drainage</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.0</td>
<td>11.7</td>
<td>12.0</td>
<td>12.3</td>
<td></td>
</tr>
<tr>
<td>12.0</td>
<td>4.3</td>
<td>11.9</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td>18.0</td>
<td>1.1</td>
<td>11.8</td>
<td>12.7</td>
<td></td>
</tr>
<tr>
<td>24.0</td>
<td>0.5</td>
<td>11.8</td>
<td>12.8</td>
<td></td>
</tr>
<tr>
<td>36.0</td>
<td>0.0</td>
<td>11.8</td>
<td>12.7</td>
<td></td>
</tr>
</tbody>
</table>

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%

### Depth of Internal Water Storage (IN)

<table>
<thead>
<tr>
<th>PERCENTAGE OF WATER BALANCE</th>
<th>DEPTH OF INTERNAL WATER STORAGE (IN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exfiltration</td>
<td>0.0</td>
</tr>
<tr>
<td>Evaporation</td>
<td>6.0</td>
</tr>
<tr>
<td>Surface Runoff</td>
<td>12.0</td>
</tr>
<tr>
<td>Drainage</td>
<td></td>
</tr>
</tbody>
</table>

- 23.3
- 0.4
- 11.8
- 64.5
- 78.8
- 84.7

### PERCENTAGE OF WATER BALANCE

- 3.1
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
### WATER BALANCE (%) 0.50 IN/HR

- Exfiltration: 23.3
- Evaporation: 0.4
- Overflow: 11.8
- Drainage: 0.4
- Internal Water Storage: 64.5

### WATER BALANCE (%) 0.20 IN/HR

- Exfiltration: 39.4
- Evaporation: 0.4
- Overflow: 11.8
- Drainage: 0.4
- Internal Water Storage: 81.2

### WATER BALANCE (%) 0.05 IN/HR

- Exfiltration: 60.9
- Evaporation: 0.5
- Overflow: 11.8
- Drainage: 0.5
- Internal Water Storage: 26.8

### WATER BALANCE (%) 0.02 IN/HR

- Exfiltration: 74.9
- Evaporation: 0.6
- Overflow: 11.8
- Drainage: 0.6
- Internal Water Storage: 12.8

VR: 75%  
VR: 70%
Ohio Standard Design (2:1 Run-on Ratio)

- 0.02 in/hr
  - Depth of Internal Water Storage:
    - 0 in: 68%
    - 6 in: 156%
    - 12 in: 64%

- 0.05 in/hr
  - Depth of Internal Water Storage:
    - 0 in: 99%
    - 6 in: 38%
    - 12 in: 65%

- 0.20 in/hr
  - Depth of Internal Water Storage:
    - 0 in: 38%
    - 6 in: 65%
    - 12 in: 20%

- 0.50 in/hr
  - Depth of Internal Water Storage:
    - 0 in: 20%
    - 6 in: 31%
    - 12 in: 31%
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?