Bioretention: One Size Doesn’t Fit All

Bioretention Overview, Research & Common Design Elements

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Associate Professor & Extension Specialist
NC State University

www.bae.ncsu.edu/stormwater
Presentation Outline

• Summary of what BRC is & looks like
• Pollutant Removal & Hydrologic Mechanisms
• Hydrologic “Improvement” Mechanisms
• Designing BRC Components
  – What the State Mandates
  – What the Research Suggests
• Where do we go from here?

www.bae.ncsu.edu/stormwater
Where can you find Bioretention/ Rain Gardens?

www.bae.ncsu.edu/stormwater
Louisburg, NC - Joyner Park

www.bae.ncsu.edu/stormwater
Glencoe School Parking Lot retrofit - before
Glencoe Parking Lot Infiltration landscape
“Skinny” Street – Seattle, Wash.
Rain Gardens Integrated throughout - Seattle
In a Round-a-bout, Kapiti Coast, NZ
Huntersville, NC - Residential

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Integrating into “High $” Landscapes – Seattle, Washington
Rooftop Treatment... (Albany, NZ @ Mitre 10)

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Bioretention Schematic

Vegetation on Surface

Permeable Media Fill
Often Sandy

Underdrain System
Bioretention Water Table

Draw Water Table Down 2 ft below surface in maximum of 2 days

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Q: How do Rain Gardens work: Hydrologic (Flow) Control

- Temporary surface storage
- Slow flow through porous media (peak flow control).
- Media with good field capacity means volume control, whether or not exfiltration is possible.
- Especially effective for small(ish), frequently occurring storm events → typically little to no system discharge!
Q: How does Bioretention work: Pollutant Removal Mechanisms

• Sedimentation (temporary)
  – Trash, TSS, Phosphorus

• Microbial Processes
  – Nitrogen

• Chemical Processes & Media Filtration
  – Metals, Phosphorus

• Exposure to Sunlight & Dryness
  – Pathogens, Oil & Grease

• Infiltration

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Chapel Hill Cell, C1

STP/WS = 0.14

Conventional Drainage
Annual Loadings (2002-03)

Chapel Hill Cell C1 - Hunt et al., 2006

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## Mass Loads (kg/ha/yr)

<table>
<thead>
<tr>
<th></th>
<th>CP</th>
<th>SS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In</td>
<td>Out</td>
</tr>
<tr>
<td>TSS</td>
<td>1190</td>
<td>37</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.09</td>
<td>0.015</td>
</tr>
<tr>
<td>Copper</td>
<td>0.26</td>
<td>0.073</td>
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<tr>
<td>Lead</td>
<td>0.09</td>
<td>0.013</td>
</tr>
<tr>
<td>Zinc</td>
<td>1.0</td>
<td>0.063</td>
</tr>
<tr>
<td>Chloride</td>
<td>6800</td>
<td>458</td>
</tr>
<tr>
<td>TN</td>
<td>27</td>
<td>7.2</td>
</tr>
<tr>
<td>Nitrate</td>
<td>12</td>
<td>2.5</td>
</tr>
<tr>
<td>TKN</td>
<td>15</td>
<td>4.1</td>
</tr>
<tr>
<td>TP</td>
<td>3.6</td>
<td>0.72</td>
</tr>
<tr>
<td>TOC</td>
<td>44</td>
<td>154</td>
</tr>
</tbody>
</table>

*Li & Davis, J. Env. Eng. 2009*
Hal Marshal (Bioretention)
Cumulative Probability Plots – Bioretention

![Graph showing cumulative probability plots for E. Coli (MPN/100 ml) inflow and outflow. The x-axis represents E. Coli concentration in MPN/100 ml, ranging from 1 to 10,000, with specific points marked at 1, 10, 100, 1,000, and 10,000. The y-axis represents cumulative probability, ranging from 0.00 to 1.00. The data points for inflow and outflow are marked with distinct symbols: inflow with blue diamonds and outflow with red squares. The graph also includes a trend line at 126.]
## Mass Loads (kg/ha/yr)

<table>
<thead>
<tr>
<th></th>
<th>CP</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In</td>
<td>Out</td>
<td>In</td>
<td>Out</td>
</tr>
<tr>
<td>TSS</td>
<td>1190</td>
<td>37</td>
<td>570</td>
<td>38</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.09</td>
<td>0.015</td>
<td>0.02</td>
<td>~0.007</td>
</tr>
<tr>
<td>Copper</td>
<td>0.26</td>
<td>0.073</td>
<td>0.12</td>
<td>0.045</td>
</tr>
<tr>
<td>Lead</td>
<td>0.09</td>
<td>0.013</td>
<td>0.03</td>
<td>~0.005</td>
</tr>
<tr>
<td>Zinc</td>
<td>1.0</td>
<td>0.063</td>
<td>0.36</td>
<td>0.017</td>
</tr>
<tr>
<td>Chloride</td>
<td>6800</td>
<td>458</td>
<td>320</td>
<td>25</td>
</tr>
<tr>
<td>TN</td>
<td>27</td>
<td>7.2</td>
<td>9.6</td>
<td>3.6</td>
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<tr>
<td>Nitrate</td>
<td>12</td>
<td>2.5</td>
<td>3.7</td>
<td>~0.19</td>
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<td>6.0</td>
<td>3.6</td>
</tr>
<tr>
<td>TP</td>
<td>3.6</td>
<td>0.72</td>
<td>0.9</td>
<td>0.38</td>
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<tr>
<td>TOC</td>
<td>44</td>
<td>154</td>
<td>43</td>
<td>78</td>
</tr>
</tbody>
</table>

Li & Davis, J. Env. Eng. 2009
Where are pollutants removed?

- TSS
- TP
- Temp
- TN
- Pathogens
- Metals
- Oil & Grease

www.bae.ncsu.edu/stormwater
## Literature/Research Justification for Minimum Media Depths: WQ

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Depth (ft)</th>
<th>Studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSS</td>
<td>1</td>
<td>Diblasi et al. 2009, Li et al. 2008</td>
</tr>
<tr>
<td>Metals</td>
<td>1</td>
<td>Li and Davis 2008, Hatt et al. 2009</td>
</tr>
<tr>
<td>O&amp;G</td>
<td>1</td>
<td>Diblasi et al. 2009,</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>3</td>
<td>Passeport et al. 2009</td>
</tr>
<tr>
<td>Temperature</td>
<td>3 (min); 4 (optim)</td>
<td>Jones and Hunt 2009</td>
</tr>
</tbody>
</table>

DON’T FORGET HYDROLOGY… deeper cells = greater potential for volume control

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Things We Design For:

- Surface Area / Depth of Water
  - (In NC) per WQ Volume
- Vegetation Selection
- Media Type & Media Depth
- Underdrain Configuration
  - Internal Water Storage
- Underlying Soil Type (account for)
- Location of Seasonally High Water Table

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Seasonally High Water Table Depths & Bioretention

- Seasonally High Water Tables. A Problem?
- Depends on Depth of Bioretention area
- Recommend: No W.T. within 1-2 ft of bottom

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Question: Ponding Depths

What is this depth?
Bowl Depth Particularly Important. Determines S.A. of BRC

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Calculate Surface Area

- $S/A = \text{Surface Area Required}$
- $\text{Volume} = \text{Total Volume Captured}$
  
  (Water Quality Volume in NC)
- $\text{Depth} = \text{Average Depth of water over normal pool (Depth of Storage Volume)}$

$S/A = \text{Volume} \div \text{Depth}$
Ponding?
Maximum Ponding Depths

NC DOT rest stop
BR area, near Hickory

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Recommended Ponding Depths

– PG Co, Maryland specifies 0.15 m

– Dr. Hunt (NCDENR) suggests 0.3 m reasonable for most applications WITH maintenance

– 0.45 m only if VERY SANDY application (e.g. on coastal dunes?)

– TP10 - NZ (2003): average 0.22 m

– Waitakere City LID CoP - NZ (2010): 0.3 m

Though Deeper Depths are a not too distant possibility.

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Brink Storage Capacity Must Capture the WQ Volume (assuming no intra-event Infiltration)
Selecting Capture Volume

What’s the First Flush?
First Flush = Most Polluted Water

- Get Cleaner Quicker @ Beginning of Shower

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80% & 90% storms for NC cities

- Brevard: 1.55 (90%), 1.08 (80%)
- Asheville: 1.60 (90%), 1.28 (80%)
- Charlotte: 1.06 (90%), 0.83 (80%)
- Greensboro: 1.44 (90%), 1.02 (80%)
- Raleigh: 1.56 (90%), 0.97 (80%)
- Fayetteville: 1.55 (90%), 1.03 (80%)
- Greenville: 1.85 (90%), 1.15 (80%)
- Elizabeth City: 1.59 (90%), 1.0 (80%)
- Wilmington: 2.24 (90%), 1.40 (80%)

Visit www.bae.ncsu.edu/stormwater for more information.
Determining Volume: a pair of options (NC DENR)

• NRCS Curve Number Method (LID only)
  – Discrete
  – Composite
  – \[ Q = \frac{(P - 0.2 \, S)^2}{(P + 0.8 \, S)} \]
  – \[ V = Q \ast A \]

• Simple Method

\[ V = ((\text{Imp}\% \ast 0.9) + 0.05) \ast P \ast A \]
• Ability of bioretention to exfiltrate water leads to reductions in thermal load
• Effluent reductions were greatest for bioretention media volumes larger with respect to their watershed

<table>
<thead>
<tr>
<th>Location</th>
<th>Percentage of Watershed Area</th>
<th>Events with Outflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asheville</td>
<td>16%</td>
<td>12%</td>
</tr>
<tr>
<td>Lenoir</td>
<td>4%</td>
<td>79%</td>
</tr>
<tr>
<td>Brevard East</td>
<td>7%</td>
<td>76%</td>
</tr>
<tr>
<td>Brevard West</td>
<td>11%</td>
<td>27%</td>
</tr>
</tbody>
</table>
BRC Question: Does Turf covered bioretention function well?

- Could save money on construction and maintenance

www.bae.ncsu.edu/stormwat
Graham High School (2006-2007)

- Watershed area = 0.69 ha
- Bioretention Cells Area = 204m²
- Fill Media/ Soil
  - 90% Expanded Slate Byproduct
  - 10% Top Soil
  - P-Index: Low
  - 0.6 m & 0.9 m depth
- Both Cells Covered in Turf (Hybrid Bermuda)

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TN concentrations: Grassed Graham HS Bioretention (2006)
# Inflow & Outflow Pollutant Concentrations: Grassed Cell

**Passeport et al. (2009)**

All Units in mg/L

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Inflow</th>
<th>Outflow – S</th>
<th>Outflow - N</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP</td>
<td>0.14</td>
<td>0.051</td>
<td>0.058</td>
</tr>
<tr>
<td>Ortho-P</td>
<td>0.057</td>
<td>0.013</td>
<td>0.015</td>
</tr>
<tr>
<td>TN</td>
<td>1.66</td>
<td>0.76</td>
<td>0.76</td>
</tr>
<tr>
<td>TKN</td>
<td>1.11</td>
<td>0.45</td>
<td>0.57</td>
</tr>
<tr>
<td>NO$_2$-3</td>
<td>0.42</td>
<td>0.38</td>
<td>0.28</td>
</tr>
</tbody>
</table>
Grassed Bioretention in Eastern Wake County

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Grassed Bioretention Cell
EMC Reductions

Average influent and effluent nutrient concentrations

![Graph showing nutrient concentrations]

- **TKN**
- **NO₂,3-N**
- **TN**
- **NH₄-N**
- **TP**

**Bioretention Inlet**  
**Small Cell Outlet**  
**Large Cell Outlet**  
**Target TN Conc.**  
**Target TP Conc.**

[For more information, visit: www.bae.nccsu.edu/stormwater]
I’m not saying shrubs & trees aren’t a better option (than grass)...

- Australian Research
  - Griffith
  - Monash
- Improve infiltration rates
- Prevent compaction
- Increased uptake
- Shading...

...But both are acceptable
Fill Media ("Soil")
Q: How much Fill Soil Media Needed?

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Media Depth

• Major Cost Consideration

What is this depth?

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Fill Media Depth predicated upon 3 factors

- Vegetation Health
- Hydrologic Goals
- Water quality needs
- Perhaps the most restrictive goal dictates design

www.bae.ncsu.edu/stormwater
Bioretention Soil Depth: Vegetation Health

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grass</td>
<td>0.3-0.45</td>
</tr>
<tr>
<td>Shrubs</td>
<td>0.45-0.75</td>
</tr>
<tr>
<td>Shrubs/Trees</td>
<td>0.75-1.0</td>
</tr>
</tbody>
</table>

Some thoughts...
1. Deeper cells may provide moisture reserves for extended dry periods.
2. Deeper cells provide runoff VOLUME reduction, regardless of in-situ soil condition or lining.

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Hydro & WQ Design Goals

1. Exceedance Probability
2. Volume Discharge Ratio, \( f_v \) or \( f_{v24} \)

- CP
- SS
- G1
- G2
- LB1
- LB2

Proportionally Larger Cells

Proportionally Smaller Cells

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Media Selection

[Image of media selection process]

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Initial NCSU Research

- Relationship between P-Index (Soil Test P) and TP outflow load.

<table>
<thead>
<tr>
<th></th>
<th>Greensboro</th>
<th>Chapel Hill</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP</td>
<td>+240%</td>
<td>- 65%</td>
</tr>
<tr>
<td>P-Index</td>
<td>85-100</td>
<td>4-12</td>
</tr>
</tbody>
</table>

P-Index 50-100: High P-Index 0-25: Low

(Hunt 2003)

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Blame it on the Media...

Phosphorus Index (P-Index) is a measure of how much phosphorus is already in the soil media.

Low P-Index: Can capture more phosphorus

High P-Index: Soil is “saturated” with phosphorus

<table>
<thead>
<tr>
<th>Classification</th>
<th>Range</th>
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</thead>
<tbody>
<tr>
<td>Very High</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>High</td>
<td>50-100</td>
</tr>
<tr>
<td>Medium</td>
<td>25-50</td>
</tr>
<tr>
<td>Low</td>
<td>0-25</td>
</tr>
</tbody>
</table>

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Where does the P go in BR?

- Is it plant uptake?
- Leaching?
- On the clay fraction?
  - P strongly held by Al & Fe in acid soils
  - History of ‘liming’ with excessive P in NC

Why the “red” in red clay is good!

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Mecklenburg Co. Hal Marshall
Bioretention Cell (2004-2006)

Fill Soil/ Media

- 80% Mason Sand
- 20% Fines + Compost
- P-Index = 6
- 4 ft (1.2 m) Depth

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Concentration Reduction = 31%
Load Reduction ≈ 50%

Hunt et al. 2008
Why Can’t We Just Use Sand?

Can Fill Media Perc Rate be too fast?

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What happens if High Fill K meets TN removal?

Effluent Concentrations in mg/L

<table>
<thead>
<tr>
<th>Fill Media Type</th>
<th>TKN</th>
<th>NO2-3-N</th>
<th>TN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.82</td>
<td>0.49</td>
<td>1.31</td>
</tr>
<tr>
<td>Sandy Loam</td>
<td>0.19</td>
<td>0.21</td>
<td>0.40</td>
</tr>
</tbody>
</table>

2 (nearly) side-by-side cells in Rocky Mount, NC

Brown and Hunt, 2011b

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In NC, N & P are typical design considerations

• So, err on side of lower Infiltration rates
• 1 -2 inches per hour optimal
• 8-12% fines recommended
• 8% fines = 2 inch per hour rate
• 12% fines = 1 inch per hour
• Remember, infiltration rates may slow over time

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Summary: The “ideal” bioretention soil

- 85% coarse sand, ~10% fines, 2-5% OM
- Low Phosphorus index (10-30)
- Low but measurable organic matter (denitrification)
- Low cost
- Locally available
- Easily spec’ed

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Underdrain Configuration – Including an Upturn

www.bae.ncsu.edu/stormwater
New Design Guidance: Discussed Later
While you can’t “design” it...
Underlying Type Counts
State of North Carolina Does Differentiate Nutrient Removal Among Underlying Soil Type

- Use IWS Layer in Coastal Plain & Sandhills with A/B HSG soil
  - 60% TN and 60% TP Removal
- Use IWS Layer in Piedmont & Mountains with B/C soil
  - 40% TN and 45% TP Removal

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Excavation Technique to Enhance Infiltration – Read Bulletin

- Scoop vs. Rake
  - For final 0.25m of excavation, depth most affected by compaction
# Average Infiltration Sand Site

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>Wet</td>
<td>Rake</td>
<td>24.4</td>
<td>10.4</td>
</tr>
<tr>
<td>Sand</td>
<td>Wet</td>
<td>Scoop</td>
<td>17.2</td>
<td>6.6</td>
</tr>
<tr>
<td>Typical Sand</td>
<td></td>
<td></td>
<td>8</td>
<td>--</td>
</tr>
<tr>
<td>Loamy Sand</td>
<td>Dry</td>
<td>Rake</td>
<td>2.6</td>
<td>2.0</td>
</tr>
<tr>
<td>Loamy Sand</td>
<td>Dry</td>
<td>Scoop</td>
<td>1.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Typical Loamy Sand</td>
<td></td>
<td></td>
<td>2.5</td>
<td>--</td>
</tr>
</tbody>
</table>

[www.bae.ncsu.edu/stormwater](http://www.bae.ncsu.edu/stormwater)
### Average Infiltration Clay Site

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>Wet</td>
<td>Rake</td>
<td>0.47</td>
<td>0.11</td>
</tr>
<tr>
<td>Clay</td>
<td>Wet</td>
<td>Scoop</td>
<td>0.09</td>
<td>0.02</td>
</tr>
<tr>
<td>Clay</td>
<td>Dry</td>
<td>Scoop</td>
<td>0.17</td>
<td>0.20</td>
</tr>
<tr>
<td>Typical Clay</td>
<td></td>
<td></td>
<td>0.20</td>
<td>--</td>
</tr>
</tbody>
</table>
Excavation Summary

• Use Rake method of excavation to promote higher exfiltration rates

• In (loamy sand \(\rightarrow\) clay) soils:
  – Excavate in dry soil moisture conditions
  – **Avoid:**
    • Excavation immediately after a storm
    • Water ponded in bottom of cut
    • Excavation if a storm will hit before the cell can be refilled
So we’re done, right?

• Are our Designs on Paper being Realized in the Field?
• Can we adjust our base design & still get “good” performance?
• How can we credit that?
  – What Factor of Safety is needed?

Some Remaining Workshop Items

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