The Effects of Climate Change on Bioretention Hydrology in Ohio

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Future Challenges in Urban Water Systems

- Population shifts/increases
- Development patterns
- Infrastructure degradation
- Exacerbated by Climate change
  - Associated impacts to flooding & conveyance capacity
Greenhouse Gas Emissions

Total Annual Anthropogenic GHG Emissions by Groups of Gases 1970-2010

Source: IPCC 2014
GHG Emissions Modeled Using Representative Concentration Pathways (RCPs)

Source: IPCC 2014
Revision of urban drainage design rules after assessment of climate change impacts on precipitation extremes at Uccle, Belgium

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Department of Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel, Belgium

Design parameters for urban drainage systems in Belgium have been revised. The revision involves extrapolation of the design rainfall statistics, taking into account the current knowledge on future climate change trends till 2100. Uncertainties in these trend projections have been assessed after statistically
Fig. 8. Change in the composite storm for a 2-year return period for the high and mean tailored climate scenarios.
Resiliency

• How can we design for or retrofit existing SCMs to ensure resilience?

Green Infrastructure for Climate Resiliency

Climate change is impacting urban areas in many ways, from exacerbating the urban heat island effect to elevating flood risk. Build green infrastructure to help improve community resilience.

1. Vegetation-based green infrastructure practices can mitigate carbon pollution.
2. Build green infrastructure like rain gardens and permeable pavement to manage flooding.
3. Reduce dependence on imported water and save money. Let water soak into the ground to recharge local groundwater supplies.
4. Keep water local. Capture runoff in cisterns and rain barrels to reduce municipal water use.
5. Plant trees and green roofs to mitigate the urban heat island effect.
6. Use living shorelines, buffers, dunes and marsh restoration to reduce the impact of storm surges.

Source: U.S. EPA
Bioretention Modeling

- Many models are single storm
  - Do not account of antecedent moisture
- Lack of long-term predictive tools
  - Droughts/Floods
- Lack of unsaturated flow equations
- Often poorly model underdrain flow
  - Elementary drain calculation or only have 1 drain
Modeling Bioretention in DRAINMOD

Brown et al. (2013)

- Concepts of water movement in bioretention are very similar to agricultural fields with drain tiles
- Most bioretention design specifications correspond directly to DRAINMOD inputs
Benefits of 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 Equations

3. Calibrated from actual bioretention cells with underdrains

4. Models IWS zone configuration
Benefits of DRAINMOD

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

- Other bioretention 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
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
  – We believe even/odd months better captures seasonal variations in performance
## Ursuline College (UC) Cell

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>UC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment area</td>
<td>0.89 acres</td>
</tr>
<tr>
<td>Imperviousness</td>
<td>77%</td>
</tr>
<tr>
<td>Bioretention surface area</td>
<td>1960 ft²</td>
</tr>
<tr>
<td>Media characteristics</td>
<td>87% sand, 4% silt, 9% clay</td>
</tr>
<tr>
<td>Vegetation</td>
<td>Forbs &amp; perennial grasses</td>
</tr>
</tbody>
</table>
# Holden Arboretumum (HA) cells

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>HA South</th>
<th>HA North</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment area</td>
<td>0.48 acres</td>
<td>0.67 acres</td>
</tr>
<tr>
<td>Imperviousness</td>
<td></td>
<td>58%</td>
</tr>
<tr>
<td>Bioretention surface area</td>
<td>610 ft²</td>
<td>850 ft²</td>
</tr>
<tr>
<td>Media characteristics</td>
<td>88% sand, 2% silt, 10% clay</td>
<td></td>
</tr>
<tr>
<td>Vegetation</td>
<td>Forbs and perennial grasses</td>
<td>Shrubs/trees</td>
</tr>
</tbody>
</table>

HA North

HA South
Future Climate Data

• Downscaled climate data (Gao et al. 2012)
  • Dynamically downscaled from regional climate model to 4 X 4 km grids
  • Weather Research and Forecasting (WRF) model
  • RCP 4.5 and RCP 8.5
  • Present climate (2001-2004) compared against future (2055 – 2059)
• Hourly rainfall and air temperature input into DRAINMOD
Extreme Precipitation

Gao et al. 2012
# Storm Event Summary

>0.1” depth

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Ursuline College*</th>
<th>Holden Arboretum*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base</td>
<td>RCP 4.5</td>
</tr>
<tr>
<td>Annual average rainfall (in)</td>
<td>37.8</td>
<td>33.2</td>
</tr>
<tr>
<td>Max (in)</td>
<td>3.14</td>
<td>3.57</td>
</tr>
<tr>
<td>Mean (in)</td>
<td>0.56</td>
<td>0.55</td>
</tr>
</tbody>
</table>

*Sites located 14 miles apart*
## Length of Dry Periods

<table>
<thead>
<tr>
<th>Statistic (days)</th>
<th>Ursuline College</th>
<th>Holden Arboretum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base</td>
<td>RCP 4.5</td>
</tr>
<tr>
<td>Maximum</td>
<td>35.7</td>
<td>43.3</td>
</tr>
<tr>
<td>90th percentile</td>
<td>9.5</td>
<td>11.3</td>
</tr>
<tr>
<td>Mean</td>
<td>4.4</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Future climate data generally suggest longer dry periods for northern Ohio.
## Air Temperature (°F)

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Ursuline College</th>
<th></th>
<th>Holden Arboretum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base</td>
<td>RCP 4.5</td>
<td>RCP 8.5</td>
</tr>
<tr>
<td>Mean</td>
<td>54.0</td>
<td>57.2</td>
<td>58.3</td>
</tr>
<tr>
<td>Median</td>
<td>55.8</td>
<td>59.2</td>
<td>60.8</td>
</tr>
<tr>
<td>Maximum daily average</td>
<td>91.2</td>
<td>93.4</td>
<td>97.9</td>
</tr>
</tbody>
</table>

Air temperature increases by 3-5°F by mid 21\textsuperscript{st} century
The diagram illustrates the comparison of base runoff between different models: RCP 4.5 and RCP 8.5. For each model, the data is categorized into four types: Drainage, Overflow, Exfiltration, and ET.

- **Base**: 67% Drainage, 23% Overflow, 4% Exfiltration, 6% ET.
- **RCP 4.5**: 61% Drainage, 26% Overflow, 5% Exfiltration, 7% ET.
- **RCP 8.5**: 57% Drainage, 30% Overflow, 6% Exfiltration, 7% ET.

Comparative analysis:
- Mean, Max RF: The diagrams show a comparison between HA North and HA South. For HA North, the percentages remain consistent across models, indicating no significant change. For HA South, a slight increase is observed, with a volume reduction of 5-8% less compared to the Base model.
- Mean, Max RF: The diagrams show a comparison between UC and HA South. For UC, the percentages also remain consistent across models, indicating no significant change. For HA South, a slight decrease is observed, with a volume reduction of 4-6% greater compared to the Base model.
Overflow Occurrences

- OR -

Similar volume but greater number of occurrences

Fewer overflow events, but much greater overflow volume
What is Resilience in Context of SCMs?

- Overflow and runoff reduction (exfiltration + ET) can be evaluated using volume or percentage of the water balance metrics
  - **Volume**: 30 inches of exfiltration in base model -> match 30 inches in future climate model (Groundwater recharge)
  - **Percentage**: overflow represents 7% of the water balance in base model -> match 7% in future climate model (TMDLs)
Resilience in the Water Balance

• An example:

<table>
<thead>
<tr>
<th>Site</th>
<th>Climate Scenario</th>
<th>Overflow % of Inflow</th>
<th>% Diff. Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holden</td>
<td>Base</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>RCP 4.5</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>RCP 8.5</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>South</td>
<td>Base</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>RCP 4.5</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>RCP 8.5</td>
<td>7</td>
<td>0</td>
</tr>
</tbody>
</table>

To ensure resilience, make bioretention cell larger or not?

• Options for retrofit & new design: Increase bowl storage or media depth, decrease loading ratio
Resilience through Increased Bowl Storage Depth

- For no net increase in overflow volume:

<table>
<thead>
<tr>
<th>Site</th>
<th>Existing Depth (in)</th>
<th>Climate Projection</th>
<th>Depth Increase (in)</th>
<th>Depth Increase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UC</td>
<td>11</td>
<td>RCP 4.5</td>
<td>2.0</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RCP 8.5</td>
<td>5.4</td>
<td>51</td>
</tr>
<tr>
<td>HA South</td>
<td>15</td>
<td>RCP 4.5</td>
<td>6.5</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RCP 8.5</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>HA North</td>
<td>16</td>
<td>RCP 4.5</td>
<td>4.2</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RCP 8.5</td>
<td>0.0</td>
<td>0</td>
</tr>
</tbody>
</table>

0-51% increase in bowl storage depth to ensure resilience
Or...Resilience through Increased Bowl Storage Depth

- For no net increase in overflow percentage:

<table>
<thead>
<tr>
<th>Site</th>
<th>Existing Depth (in)</th>
<th>Climate Projection</th>
<th>Depth Increase (in)</th>
<th>Depth Increase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UC</td>
<td>11</td>
<td>RCP 4.5</td>
<td>4.3</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RCP 8.5</td>
<td>6.1</td>
<td>57</td>
</tr>
<tr>
<td>HA South</td>
<td>15</td>
<td>RCP 4.5</td>
<td>17.8</td>
<td>116</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RCP 8.5</td>
<td>3.4</td>
<td>22</td>
</tr>
<tr>
<td>HA North</td>
<td>16</td>
<td>RCP 4.5</td>
<td>14.6</td>
<td>92</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RCP 8.5</td>
<td>4.6</td>
<td>36</td>
</tr>
</tbody>
</table>

- 22-116% increase in bowl storage depth to ensure resilience
Comparing the Metrics:

• Resilience by percentage of the water balance is more challenging/conservative metric in this case
  – Since annual rainfall is reduced in the future climate scenarios

• Practical questions: Is a 30 inch bowl depth practical?
  – Concurrent reduction in media depth
Other Thoughts…

• Changing design parameters sometimes produces contradictory effects on runoff reduction and overflow:
  • IWS zone depth
  • Drain spacing
  • Loading ratio

• **Much** more difficult to meet both overflow and runoff reduction goals
Conclusions

• High level of special variability in future climate data
  – Appropriate temporal scale for hydrologic modeling

• Volume reduction related to rainfall depth

• Overflow greater portion of the water balance

• Volume and percentage metrics may result in vastly different designs
  – Already resilient (volume)
  – Double bowl storage (percentage)
I ❤️ Stormwater Modeling

Any Questions?

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