Annual and Individual-Storm Green Roof Stormwater Response Models

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Green Roof Types

Extensive – large areas

Intensive – roof gardens
Typical Extensive Green Roof

- Vegetation
- Growth Medium
- Drainage Layer
- Waterproof Membrane and Root Barrier
Drainage Layer

- ½-inch plastic wire grid.
- Geotextile glued to grid.
- Porosity = 78%
- Field Capacity = 5%
Media

- 12.5% sphagnum peat moss
- 12.5% coir
- 15% perlite
- 60% hydrolite
  - 6.23 lb/in-ft²
  - Saturated
- Porosity = 55%
- Field Capacity = 34%
Green Roof Plants

- Crassulaceae Acid Metabolism (CAM) Plants
  - Arid Region (Desert) Plants
  - Stomates open at night (to reduce water loss).
  - Stomates close during day (to conserve water).
  - Plants get smaller as water becomes limiting.
Benefits

- Attenuate stormwater
  - Runoff volume reduction.
  - Peak runoff rate reduction.
  - Delay the runoff event.
  - Delay the peak runoff rate.
Impact of Development

The graph illustrates the comparison between pre-development and post-development runoff flow rates over time. The x-axis represents time in hours, ranging from 0 to 8, while the y-axis shows flow rate in Cfs (cubic feet per second), ranging from 0 to 200.

- **Post-Development Runoff**: The red curve shows an increased peak flow rate compared to the pre-development period.
- **Pre-Development Runoff**: The green curve indicates a lower peak flow rate, suggesting less runoff before development.

The graph highlights the impact of development on water runoff, with a noticeable increase post-development.
To understand how a Green Roof can help us manage stormwater, we must look at stormwater in three different ways:

- Individual storms (actual data collected).
- Annual rainfall basis.
- Extreme storm effects.
Individual Storm (Measured Data)

- Green roofs compared to non-green (traditional) roofs
  - Stormwater runoff volume and flow rates
October 25, 2002 Rain Event

Retained = 0.18 in

Rain
Green Roof Runoff
## October 2002

<table>
<thead>
<tr>
<th>Storm Date</th>
<th>Rain Date</th>
<th>Rainfall Depth (in)</th>
<th>Runoff Depth (in)</th>
<th>Retention (in)</th>
<th>Retention (%)</th>
<th>Delay to Start (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16-Oct</td>
<td>3</td>
<td>1.15</td>
<td>0.79</td>
<td>0.36</td>
<td>31.3</td>
<td>1.0</td>
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<tr>
<td>25-Oct</td>
<td>8</td>
<td>0.94</td>
<td>0.76</td>
<td>0.18</td>
<td>19.1</td>
<td>4.0</td>
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</table>

**Average =**

<table>
<thead>
<tr>
<th>Days</th>
<th>Green</th>
<th>Roof</th>
<th>Retention Depth (in)</th>
<th>Retention (%)</th>
<th>Runoff Delay (hr)</th>
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</thead>
<tbody>
<tr>
<td>1.045</td>
<td>0.78</td>
<td>0.27</td>
<td>25.23</td>
<td>2.50</td>
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### November 2002

<table>
<thead>
<tr>
<th>Date</th>
<th>Rain</th>
<th>Depth</th>
<th>Depth</th>
<th>Retention</th>
<th>Retention</th>
<th>Runoff</th>
<th>Delay to Start of Storm</th>
</tr>
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<tbody>
<tr>
<td>5-Nov</td>
<td>4</td>
<td>0.81</td>
<td>0.54</td>
<td>0.27</td>
<td>33.3</td>
<td>7.0</td>
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</tr>
<tr>
<td>10-Nov</td>
<td>5</td>
<td>0.42</td>
<td>0.13</td>
<td>0.29</td>
<td>69.0</td>
<td>18.0</td>
<td></td>
</tr>
<tr>
<td>12-Nov</td>
<td>1</td>
<td>0.45</td>
<td>0.30</td>
<td>0.15</td>
<td>33.3</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>16-Nov</td>
<td>4</td>
<td>1.56</td>
<td>1.02</td>
<td>0.54</td>
<td>34.6</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.81</td>
<td>0.50</td>
<td>0.31</td>
<td>42.58</td>
<td>7.75</td>
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## May 2003

<table>
<thead>
<tr>
<th>Storm Date</th>
<th>Rain Days</th>
<th>Rainfall (in)</th>
<th>Runoff Depth (in)</th>
<th>Retention Depth (in)</th>
<th>Retention (%)</th>
<th>Delay to Start of Runoff (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23-May</td>
<td>0.8</td>
<td>0.35</td>
<td>0.16</td>
<td>0.19</td>
<td>54.3</td>
<td>4.0</td>
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<tr>
<td>25-May</td>
<td>1.1</td>
<td>0.48</td>
<td>0.20</td>
<td>0.28</td>
<td>58.3</td>
<td>9.0</td>
</tr>
<tr>
<td>31-May</td>
<td>4.1</td>
<td>1.11</td>
<td>0.75</td>
<td>0.36</td>
<td>32.4</td>
<td>5.0</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td><strong>0.65</strong></td>
<td><strong>0.37</strong></td>
<td><strong>0.28</strong></td>
<td><strong>48.35</strong></td>
<td><strong>6.00</strong></td>
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## June 2003

<table>
<thead>
<tr>
<th>Storm Date</th>
<th>Rain Date</th>
<th>Rainfall Depth (in)</th>
<th>Runoff Depth (in)</th>
<th>Retention Depth (in)</th>
<th>Retention (%)</th>
<th>Delay to Start of Runoff (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-Jun</td>
<td>1.0</td>
<td>1.13</td>
<td>0.80</td>
<td>0.33</td>
<td>29.2</td>
<td>5.0</td>
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<tr>
<td>4-Jun</td>
<td>0.5</td>
<td>0.15</td>
<td>0.10</td>
<td>0.05</td>
<td>33.3</td>
<td>0.5</td>
</tr>
<tr>
<td>7-Jun</td>
<td>2.2</td>
<td>0.68</td>
<td>0.41</td>
<td>0.27</td>
<td>39.7</td>
<td>3.0</td>
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<tr>
<td>8-Jun</td>
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<td>0.23</td>
<td>0.09</td>
<td>0.14</td>
<td>60.9</td>
<td>0.5</td>
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<tr>
<td>12-Jun</td>
<td>3.4</td>
<td>0.14</td>
<td>0.02</td>
<td>0.12</td>
<td>85.7</td>
<td>1.0</td>
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<tr>
<td>14-Jun</td>
<td>2.0</td>
<td>0.19</td>
<td>0.00</td>
<td>0.19</td>
<td>100.0</td>
<td>---</td>
</tr>
<tr>
<td>17-Jun</td>
<td>3.0</td>
<td>1.00</td>
<td>0.51</td>
<td>0.49</td>
<td>49.0</td>
<td>12.0</td>
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<tr>
<td>19-Jun</td>
<td>1.4</td>
<td>0.26</td>
<td>0.08</td>
<td>0.18</td>
<td>69.2</td>
<td>0.5</td>
</tr>
<tr>
<td>21-Jun</td>
<td>1.4</td>
<td>0.18</td>
<td>0.16</td>
<td>0.02</td>
<td>11.1</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>Days</strong></td>
<td><strong>In</strong></td>
<td><strong>In</strong></td>
<td><strong>In</strong></td>
<td><strong>%</strong></td>
<td><strong>hr</strong></td>
</tr>
<tr>
<td></td>
<td><strong>2.88</strong></td>
<td><strong>0.44</strong></td>
<td><strong>0.24</strong></td>
<td><strong>0.20</strong></td>
<td><strong>53.13</strong></td>
<td><strong>2.88</strong></td>
</tr>
</tbody>
</table>
# July 2003

<table>
<thead>
<tr>
<th>Storm Date</th>
<th>Rainfall Depth (in)</th>
<th>Runoff Depth (in)</th>
<th>Retention (in)</th>
<th>Retention (%)</th>
<th>Delay to Start of Green Days</th>
<th>Runoff Duration (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-Jul</td>
<td>12.2</td>
<td>0.13</td>
<td>0.02</td>
<td>0.11</td>
<td>84.6</td>
<td>2.0</td>
</tr>
<tr>
<td>6-Jul</td>
<td>4.0</td>
<td>0.67</td>
<td>0.03</td>
<td>0.64</td>
<td>95.5</td>
<td>5.0</td>
</tr>
<tr>
<td>7-Jul</td>
<td>0.3</td>
<td>0.12</td>
<td>0.03</td>
<td>0.09</td>
<td>75.0</td>
<td>4.0</td>
</tr>
<tr>
<td>10-Jul</td>
<td>3.5</td>
<td>1.62</td>
<td>1.10</td>
<td>0.52</td>
<td>32.1</td>
<td>1.0</td>
</tr>
<tr>
<td>16-Jul</td>
<td>5.0</td>
<td>0.34</td>
<td>0.04</td>
<td>0.30</td>
<td>88.2</td>
<td>2.5</td>
</tr>
<tr>
<td>21-Jul</td>
<td>2.5</td>
<td>0.48</td>
<td>0.06</td>
<td>0.42</td>
<td>87.5</td>
<td>0.5</td>
</tr>
<tr>
<td>22-Jul</td>
<td>0.4</td>
<td>0.53</td>
<td>0.05</td>
<td>0.48</td>
<td>90.6</td>
<td>0.5</td>
</tr>
<tr>
<td>27-Jul</td>
<td>5.7</td>
<td>0.39</td>
<td>0.02</td>
<td>0.37</td>
<td>94.9</td>
<td>1.0</td>
</tr>
<tr>
<td>31-Jul</td>
<td>3.8</td>
<td>1.38</td>
<td>0.67</td>
<td>0.71</td>
<td>51.4</td>
<td>4.0</td>
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<tr>
<td><strong>Average =</strong></td>
<td><strong>0.63</strong></td>
<td><strong>0.22</strong></td>
<td><strong>0.40</strong></td>
<td><strong>77.76</strong></td>
<td><strong>2.28</strong></td>
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</tr>
</tbody>
</table>
Summary of Retention Results

- October: 25.2%
- November: 42.6%
- May: 48.4%
- June: 53.1%
- July: 77.8%
Modeling Annual Green Roof Impact

- Assumed
  - Simple ET curve; \( f(\text{month}) = \text{daily ET} \)
  - Drainage layer, roof media, and plants had maximum of 1.582 inches of retention storage.
- For each daily rain amount
  - Estimated water lost to atmosphere.
  - Estimated water remaining in green roof.
- Added rain to green roof.
Schematic of Green Roof

Max. Retention = 1.582 in

Rain

Evaporation

Transpiration

(3.5 in)
1986, GR Max Retention = 1.582 in

![Graph showing rainfall and runoff data from 1986, with peak retention at 1.582 inches.](image-url)
1993, GR Max Retention = 1.582 in
Modeling Results

Based on 28 years (1976-2003) of rain data from State College, PA
- Roof maximum retention = 1.582 inches
- Average annual rain = 40.3 inches.
- 22.9 inches if average annual rain was retained on Green Roof
- Average annual rain retained = 65%.
  - This captured water is returned to the atmosphere by
    - Evaporation
    - Transpiration
If we assume the roof in question has maximum retention capacities different from our green roof,
  – Retention values from
    • 0.125 inches to
    • 3.0 inches were evaluated.
Stormwater; Extreme Storm Response

- Stormwater Management is based on extreme hydrologic events.
  - 2-year rainfall/runoff.
  - 25-year rainfall/runoff.
  - 100-year rainfall/runoff.

- How well can a Green Roof be expected to attenuate these large design storms?
Extreme Storm Response

- Modified Puls Routing Model
- Accounts for capillary & hygroscopic water stored in:
  - drainage layer
  - 3.5-in media
  - CAM plants
- Accounts for 0.05 in interception.
- Blaney-Criddle ET Model applied on a daily basis to remove water from roof.
- Rain must fill all layers to field capacity before runoff starts.
Extreme Storm Response

Model Validation.
- Inputted rainfall hyetographs for 16 storms measured at Rock Springs.
  - 24-hour rains varied from:
    - 0.14 in to
    - 1.62 in
    - Averaged 0.84 in
- Computed runoff from roof.
- Compared to measured runoff.
Observed (in/hr) vs. Predicted (in/hr) for Peak Runoff Rate, ver 5

$R^2 = 0.907$
$R^2 = 0.938$
Extreme Storm Response

- Applied synthetic rainfall to Green Roof.
  - Type II Rainfall Distributions.
  - Assumed State College, PA
  - Assumed Green Roof had same characteristics as our research roofs.
  - Simulated the Roof’s runoff hydrographs for a 270- by 70-foot Roof:
    - 1 day since last storm in February and July.
    - 5 days since last storm in February and July.
    - 2-Year Synthetic Rain.
    - 100-Year Synthetic Rain.
2-Year Rain After 5 Dry July Days

Flow Rate (cfs) vs Time, t (hrs)

- Rain
- Roof Runoff

2-yr Pre-Dev, CN = 79
Cumulative Green Roof 2-Y After 5 Dry July Days

- **Rain**
- **Roof Runoff**

**Cumulative In & Out Flow (In)** vs **Time (Hrs)**

- Vertical axis: Cumulative In & Out Flow (In)
- Horizontal axis: Time (Hrs)
100-Year Rain After 5 Dry July Days

100-yr Pre-Dev, CN = 79
Cumulative Green Roof 100-Y After 5 Dry July Days
100-Year Rain After 5 Dry Feb. Days

100-yr Pre-Dev, CN = 79
Cumulative Green Roof 100-Y After 5 Dry Feb. Days

Cumulative In & Out Flow (In)

Time (Hrs)

Rain
Roof Runoff

[Graph showing cumulative green roof performance over time]
Summary of Extreme Storms

- 2-Year (2.6 inches in 24 hours)
  - July w/ 5 Dry Days = 85% reduction in peak.
  - July w/ 5 Dry Days = 61% reduction in volume.
- 100-Year (5.3 inches in 24 hours)
  - July w/ 5 Dry Days = 60% reduction in peak.
  - July w/ 5 Dry Days = 30% reduction in volume.
  - Rain water retained and detained
- Detained water released after storm
Thank You

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...Questions?