Expectations vs. Outcomes: Considering Performance Metrics for Stormwater Green Infrastructure

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ASCE-NJ Educator of the Year, 2018

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1990s: NPDES Phase 1

Introduces stormwater quality treatment for large municipal separate storm sewer systems (MS4s)
The magic number: 80% TSS Removal

- Adopted from CZARA (1993)
- 1983 US EPA Nationwide Urban Runoff Program (NURP)
- Remove other pollutants by default
## Design Objectives: Hydrologic Mitigation

<table>
<thead>
<tr>
<th>Design Storm ARI</th>
<th>Impact Avoidance</th>
<th>Mitigation Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 100-yr, X-hr</td>
<td>Property damage &amp; loss of life</td>
<td>Post-development peak flow rate to pre-development conditions</td>
</tr>
<tr>
<td>10 to 50-yr, X-hr</td>
<td>Flooding, stream erosion</td>
<td>(or some fraction thereof)</td>
</tr>
<tr>
<td>2-yr, X-hr</td>
<td>Stream erosion</td>
<td></td>
</tr>
</tbody>
</table>
Design Objective: **Minimize Stream Erosion**

Leopold (1964) on natural streams:
2-yr return period flow $\rightarrow$ “bankfull” conditions $\rightarrow$ stream erosion
After ~38 years of “stormwater management”, why do performance metrics and permitting objectives largely remained unchanged?
What we’ve learned...

“One size fits all”, end-of-pipe approaches do not address the wide range of hydrologic and water quality impacts. (National Research Council 2008)
Stormwater Quality Performance

“Objectives”: 80% TSS Removal (& others by default)

Table 4-1: TSS Removal Rates for BMPs

<table>
<thead>
<tr>
<th>Best Management Practice (BMP)</th>
<th>Adopted TSS Removal Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioretention System</td>
<td>90</td>
</tr>
<tr>
<td>Constructed Stormwater Wetland</td>
<td>90</td>
</tr>
<tr>
<td>Dry Well</td>
<td>Volume Reduction Only^2</td>
</tr>
<tr>
<td>Extended Detention Basin</td>
<td>40 to 60^2</td>
</tr>
<tr>
<td>Infiltration Structure</td>
<td>80</td>
</tr>
<tr>
<td>Manufactured Treatment Device</td>
<td>See N.J.A.C. 7:8-5.7(d)^2</td>
</tr>
<tr>
<td>Pervious Paving System</td>
<td>Volume Reduction</td>
</tr>
<tr>
<td></td>
<td>0r</td>
</tr>
<tr>
<td></td>
<td>80^4</td>
</tr>
<tr>
<td>Sand Filter</td>
<td>80</td>
</tr>
<tr>
<td>Vegetative Filter</td>
<td>60-80</td>
</tr>
<tr>
<td>Wet Pond</td>
<td>50-90^3</td>
</tr>
</tbody>
</table>

Section 3.3 Standard Stormwater Management Practices for Treatment

1. Can capture and treat the full water quality volume (WQv)
2. Are capable of 80% TSS removal and 40% TP removal.
Stormwater Quality Performance
“Objectives”

Consider the “math”:

\[ \% \text{ reduction} = \frac{\text{In} - \text{Out}}{\text{In}} \times 100\% \]

80\% = \frac{200 - 40}{200} \times 100\%

60\% = \frac{50 - 20}{50} \times 100\%

Which is “better”?

What impacts the receiving environment?
Frequently Asked Questions:

Why does the International Stormwater BMP Database Project omit percent removal as a measure of BMP performance?

The BMP Database Project Team is frequently asked why percent removal is not used to assess best management practice (BMP) performance for the BMP database project. This paper summarizes some key shortcomings associated with percent removal as a tool to assess BMP performance. While we recognize that percent removal is an easy-to-understand concept that is attractive to many entities, we believe that the following shortcomings are significant and require an alternative measure (or measures) of BMP performance:

1. Percent removal is primarily a function of influent quality. In almost all cases, higher influent pollutant concentrations into functioning BMPs result in reporting of higher pollutant removals than those with cleaner influent. In other words, use of percent removal may be more reflective of how “dirty” the influent water is than how well the BMP is actually performing. Therefore (and ironically), to maximize percent removal, the catchment upstream should be “dirty” (which does not encourage use of good source controls or a “treatment train” design approach).

2. Significant variations in percent removal may occur for BMPs providing consistently good effluent quality. Stated differently, the variability in percent removal is almost always much broader than the uncertainty of effluent pollutant concentrations. These variations in percent removal have little relationship to the effective hydraulic capacity.
Average %-EMC Removal in Detention and Retention Basins

Size matters

- Coarse particles caught in gutters & catchpits
- Sediment > 20 µm settles rapidly
- Sediment < 10 µm poorly removed by sedimentation (without chemical pre-treatment)

<table>
<thead>
<tr>
<th>Particle-size fraction (mm)</th>
<th>Total Metal Concentration (mg/kg of sediment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-32</td>
<td>Cu 181, Zn 2080, Pb 316</td>
</tr>
<tr>
<td></td>
<td>32-63 197, 1695, 322</td>
</tr>
<tr>
<td></td>
<td>63-125 212, 1628, 334</td>
</tr>
<tr>
<td></td>
<td>125-250 184, 1073, 251</td>
</tr>
<tr>
<td></td>
<td>250-500 85, 507, 193</td>
</tr>
<tr>
<td></td>
<td>500-1000 26, 268, 323</td>
</tr>
<tr>
<td></td>
<td>1000-2000 21, 226, 36</td>
</tr>
</tbody>
</table>

Dissolved vs. Particulate?

Example: 4 Living (Green) Roofs

![Box plot comparing dissolved and particulate phosphorus in green roofs.](chart.png)
A spectrum of potential impacts
Rainfall vs. Impacts

(Source: CRC, 1996)
“New” concerns: Combined Sewer Overflow Mitigation

• 2000’s Wet Weather Quality Act: drives focus on CSO mitigation, quantity control for quality improvement

Stormwater Green Infrastructure is natural and engineered systems which integrate with the built environment to promote natural hydrologic processes, improve water quality, and maximize stormwater as a resource, to provide a wide range of ecological, community, and infrastructure services.
Bioretention/ Rain Gardens

- Water quality treatment: sedimentation, filtration, sorption
- Hydrologic control: evapotranspiration, infiltration (maybe), flow through porous media
Swales & Bioswales
Where runoff needs to be conveyed from one location to another.

- Flow rate & some volume mitigation
- Some water quality benefit
- Reduce or eliminate buried pipes
- Aesthetic enhancement

Hoboken

Seattle
Green (Living) Roofs

Objective: Prevent runoff generation from rooftops

NYC US Postal Service

- Excellent flow & volume control
  - High field capacity; Evapotranspiration; Flow through porous media
- Reduce or eliminate stormwater ponds
- Recreational space, habitat (?)
- LEED credit
Permeable Pavement

- Water quality control
- Hydrologic mitigation
  Flow through porous media; storage; infiltration (maybe)
- Drive, park, load, walk

NC Arboratum, Raleigh, NC
Permeable Interlocking Pavers

Seattle High Point Neighborhood
Porous Concrete Street

US EPA, Edison, NJ
Test Facility
Porous Asphalt
Roof Runoff SCMs

- Confined space
- Flow control (?)
- CSO mitigation

Rainwater Harvesting & Reuse

Bioretention Planters
Spoiled for Choice?

• Many GI technologies
• Flow control mechanisms differ
• Water quality treatment mechanisms differ

Where we are (broadly):
Use green infrastructure
to the maximum extent practicable

Where we should be:
Match form to function.
Treatment trains.
Embrace new knowledge with “new” metrics

<table>
<thead>
<tr>
<th>Hydrologic Mitigation</th>
<th>Water Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Flow frequency analysis</td>
<td>• Probability plots / frequency analysis</td>
</tr>
<tr>
<td>• Flow duration curves</td>
<td>• Receiving water capacity</td>
</tr>
</tbody>
</table>

Design storms → continuous simulation

% Removals → effluent quality
Permeable Pavement Hydrology

Asphalt Catchment
850 m² asphalt road, footpath, grass

Permeable Pavement Catchment
200 m² permeable pavement
195 m² sidewalk, driveway, grass

Flow Frequency Analysis vs. Event-Based Assessment

81 storms

<table>
<thead>
<tr>
<th>No. of Storms</th>
<th>Storm Depth (mm)</th>
<th>Average Peak Flow (mm/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre*</td>
<td>Asph</td>
</tr>
<tr>
<td>36</td>
<td>2 – 7**</td>
<td>0.0</td>
</tr>
<tr>
<td>10</td>
<td>7 - 10</td>
<td>0.1</td>
</tr>
<tr>
<td>24</td>
<td>10 - 20</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>20 - 30</td>
<td>3.3</td>
</tr>
<tr>
<td>3</td>
<td>30 - 50</td>
<td>6.6</td>
</tr>
<tr>
<td>3</td>
<td>50 - 150</td>
<td>12.4</td>
</tr>
</tbody>
</table>

* Modelled using regulatory approach.
** Best estimate. Storms < 7 mm not accurately measured.

Discharge Volume Frequency Analysis vs. Event-Based Runoff Coefficient

Field-Measured Runoff

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Asphalt Catchment “C”</th>
<th>Permeable Pavement Underdrain “C”</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>0.48</td>
<td>0.29</td>
</tr>
<tr>
<td>0.25</td>
<td>0.60</td>
<td>0.43</td>
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<tr>
<td>0.50</td>
<td>0.85</td>
<td>0.49</td>
</tr>
<tr>
<td>0.75</td>
<td>0.94</td>
<td>0.57</td>
</tr>
<tr>
<td>0.90</td>
<td>0.98</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Flow Duration Analysis
Green Roofs

• Demonstrate compliance (or exceedance) with allowable discharge rates under all conditions

• Duration and magnitude of exceedance of combined sewer capacity

Data and analysis courtesy of Birgitte Gisvold Johannessen, Ph.D. Candidate, Norwegian University of Science and Technology
2015 USEPA Campus RainWorks Challenge: Stevens 2nd Pl. Master Plan

25-yr Continuous Simulation using SWMM

Existing Conditions
With GI

# of runoff events vs. Runoff Depth (in)
Challenges of stormwater quality
Alternatives to the 80% “Rule”

Flow (ft³/s)

Time (h)

Runoff Samples from Residential Subdivision in Denver, c.2003
Welcome! The International Stormwater Best Management Practices (BMP) Database project website features a database of over 600 BMP studies, performance analysis results, tools for use in BMP performance studies, monitoring guidance and other study-related publications. New to the site? Start Here

News
- 2016 BMP Performance Summaries
- 2016 Studies Now Available
- Stream Restoration Database
- Agricultural BMP Database Version 2.0 Now Available
- 2014 BMP Database Release
- 2014 BMP Performance Summaries
- 2013 Advanced Analysis
- National Stormwater Quality Database Has A New Home

Related Databases & Research
- Stream Restoration Database
- National Stormwater Quality Database
- Agricultural BMP Database
- Chesapeake Bay Research Portal

Urban Stormwater Research Reports
- 2016 BMP Performance Summaries
- 2014 Statistical Appendices
- 2012 Manufactured Device Performance Analysis Summary
- 2012 Volume Reduction in Bioretention
- 2012 Database Overview
- 2012 Chesapeake Bay BMP Performance Summary

Retrieve Urban Stormwater BMP Performance
- BMP Study Retrieval Tool
- BMP Map Tool
- BMP Category Reports
- Online Statistical Analysis Tool
- Download Access Database
Accounting for variability?

Figure 2.1: Box and Probability Plots of Total Suspended Solids at Bioretention BMPs

Int’l BMP Database
Geosyntec Consultants & Wright Water Engineers, May 2011
Swale TSS Performance

NJ DEP awards “credit” for 50% TSS removal if design complies with minimum guidelines in stormwater manual (Sect 9.12)
Total Phosphorus

Detention Basin

Retention Basin
Example Data Analysis: TSS Box & Whisker Plots

# Statistical Performance Summary: TSS

<table>
<thead>
<tr>
<th>BMP Category</th>
<th>BMPs</th>
<th>EMCs</th>
<th>25th</th>
<th>Median</th>
<th>75th</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In</td>
<td>Out</td>
<td>In</td>
<td>Out</td>
<td>In</td>
</tr>
<tr>
<td>Bioretention</td>
<td>25</td>
<td>25</td>
<td>520</td>
<td>463</td>
<td>18.0</td>
</tr>
<tr>
<td>Composite</td>
<td>10</td>
<td>10</td>
<td>202</td>
<td>174</td>
<td>42.4</td>
</tr>
<tr>
<td>Detention Basin</td>
<td>32</td>
<td>33</td>
<td>411</td>
<td>436</td>
<td>24.1</td>
</tr>
<tr>
<td>Grass Strip</td>
<td>19</td>
<td>19</td>
<td>361</td>
<td>282</td>
<td>20.0</td>
</tr>
<tr>
<td>Grass Swale</td>
<td>24</td>
<td>24</td>
<td>442</td>
<td>418</td>
<td>9.2</td>
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<tr>
<td>LID</td>
<td>3</td>
<td>3</td>
<td>131</td>
<td>62</td>
<td>25.5</td>
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<tr>
<td>Media Filter</td>
<td>25</td>
<td>25</td>
<td>400</td>
<td>377</td>
<td>22.0</td>
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<tr>
<td>Porous Pavement</td>
<td>9</td>
<td>9</td>
<td>404</td>
<td>248</td>
<td>36.8</td>
</tr>
<tr>
<td>Retention Pond</td>
<td>56</td>
<td>56</td>
<td>923</td>
<td>933</td>
<td>15.0</td>
</tr>
<tr>
<td>Wetland Basin</td>
<td>22</td>
<td>22</td>
<td>492</td>
<td>486</td>
<td>13.1</td>
</tr>
<tr>
<td>Wetland Basin/Retention Pond</td>
<td>78</td>
<td>78</td>
<td>1415</td>
<td>1419</td>
<td>14.0</td>
</tr>
<tr>
<td>Wetland Channel</td>
<td>12</td>
<td>12</td>
<td>199</td>
<td>178</td>
<td>13.0</td>
</tr>
</tbody>
</table>

## Inflow-Outflow Concentration Differences

<table>
<thead>
<tr>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>◆◆◆◆</td>
</tr>
<tr>
<td>95% confidence intervals around influent/effluent medians do not overlap.</td>
</tr>
<tr>
<td>◆◆◆</td>
</tr>
<tr>
<td>P-value of the Mann-Whitney test is less than 0.05.</td>
</tr>
<tr>
<td>◆◆◆◆</td>
</tr>
<tr>
<td>P-value of the Wilcoxon test is less than 0.05.</td>
</tr>
</tbody>
</table>

### Promising developments?

The Water Quality requirement stipulates infiltration of the first 1.5 inches of runoff from all directly connected impervious area (DCIA) within the limits of earth disturbance. This volume of stormwater runoff is referred to as the Water Quality Volume (WQv). If infiltration is feasible on the project site, the Water Quality requirement must be met by infiltrating 100% of the WQv through stormwater management practices (SMPs).

### Requirement

In the past, 85% TSS removal has been used as a standard. DEQ is no longer using that standard because it is not reflective of the actual field performance of SCMs. Most SCMs do not remove 85% of TSS, especially at lower concentrations of TSS in the influent.

### A-2. SCM Credit Table

<table>
<thead>
<tr>
<th>SCM</th>
<th>Role</th>
<th>% Annual Runoff Treated if 100% Sized</th>
<th>% Treated Runoff to Fates</th>
<th>EMC Cement (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>HSG</td>
<td>ET&amp;I</td>
</tr>
<tr>
<td>Bioretention per MDC</td>
<td>Primary</td>
<td>94</td>
<td>A</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>D</td>
<td>14</td>
</tr>
<tr>
<td>Bioretention per MDC but without MWS (retrofits and special cases only)</td>
<td>Primary</td>
<td>94</td>
<td>A</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>D</td>
<td>9</td>
</tr>
<tr>
<td>Bioretention with design variants per Hyper Tool</td>
<td>Primary</td>
<td>Tool Output</td>
<td>Tool Output</td>
<td>0.58 / 1.20</td>
</tr>
</tbody>
</table>

Aug. 2017
Where we started

- Water quality treatment performance as %-removals.
- Large storm peak flow control
- End-of-pipe SCMs

What’s available now

- Empirical evidence. Lots of it.
- Frequency distributions, advanced statistics
- Hydrograph analysis
- Green Infrastructure SCMs
I invite you to Stevens’ Living Laboratory

Generating evidence-based criteria for the future of urban stormwater management.
Education & Outreach

Newark International Airport 1893-2017

knee of the curve = cost-effective design

NJ data from [https://www.ncdc.noaa.gov/cdo-web/](https://www.ncdc.noaa.gov/cdo-web/)