The Selection of an Urban Runoff Control Program using Decision Analysis

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Stormwater Effects

- Sediment (amount and quality)
- Habitat destruction (mostly through high flows [energy] and sedimentation)
- Eutrophication (nutrient enrichment)
- Low dissolved oxygen (from organic materials)
- Pathogens (urban wildlife vs. municipal wastewater)
- Toxicants (heavy metals and organic toxicants)
- Temperature
- Debris and unsafe conditions
- etc.

Probability distribution of rains (by count) and runoff (by depth).

Birmingham Rains:
- <0.5": 65% of rains (10% of runoff)
- 0.5 to 3": 30% of rains (75% of runoff)
- 3 to 8": 4% of rains (13% of runoff)
- >8": <0.1% of rains (2% of runoff)

Birmingham, AL, rains from 1952 through 1989

- 111 rains per year during this 37 year period
- Most rains < 3 inches
- About 5 rains a year between 3 and 8 inches
- 3 rains (in 37 years) > 8 inches
Suitable Controls for Almost Complete Elimination of Runoff Associated with Small Rains (<0.5 in.)

- Disconnect roofs and pavement from impervious drainages
- Grass swales
- Porous pavement walkways
- Rain barrels and cisterns for local reuse

Suitable Controls for Treatment of Runoff from Intermediate-Sized Rains (0.5 to 3 in.)

- Initial portions of these rains will be captured/infiltrated by on-site controls or grass swales, but seldom can infiltrate all of these rains
- Remaining portion of runoff should be treated to remove particulate-bound pollutants

Roof drain disconnections

Not this!

Rain Garden Designed for Complete Infiltration of Roof Runoff
Calculated Benefits of Various Roof Runoff Controls (compared to typical directly connected residential pitched roofs)

<table>
<thead>
<tr>
<th>Annual roof runoff volume reductions</th>
<th>Birmingham, Alabama (55.5 in.)</th>
<th>Seattle, Wash. (33.4 in.)</th>
<th>Phoenix, Arizona (9.6 in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat roofs instead of pitched roofs</td>
<td>13</td>
<td>21</td>
<td>25%</td>
</tr>
<tr>
<td>Cistern for reuse of runoff for toilet flushing and irrigation (10 ft. diameter x 5 ft. high)</td>
<td>66</td>
<td>67</td>
<td>88%</td>
</tr>
<tr>
<td>Planted green roof (but will need to irrigate during dry periods)</td>
<td>75</td>
<td>77</td>
<td>84%</td>
</tr>
<tr>
<td>Disconnect roof drains to loam soils</td>
<td>84</td>
<td>87</td>
<td>91%</td>
</tr>
<tr>
<td>Rain garden with amended soils (10 ft. x 6.5 ft.)</td>
<td>87</td>
<td>100</td>
<td>96%</td>
</tr>
</tbody>
</table>

Particulate Removal in Shallow Flowing Grass Swales and in Grass Filters

- Runoff from Pervious/impervious area
- Trapping of sediments and associated pollutants
- Reducing velocity of runoff
- Reduced volume and treated runoff
- Infiltration

TSS: 10 mg/L
TSS: 20 mg/L
TSS: 30 mg/L
TSS: 35 mg/L
TSS: 63 mg/L
TSS: 84 mg/L
TSS: 102 mg/L

University of Alabama swale test site at Tuscaloosa City Hall

Date: 10/11/2004
Conventional curbs with inlets directed to site swales

Porous paver blocks have been used in many locations to reduce runoff to combined systems, reducing overflow frequency and volumes (Sweden, Germany, and WI).

Not recommended in areas of heavy automobile use due to groundwater contamination (provide little capture of critical pollutants, plus most manufactures recommend use of heavy salt applications instead of sand for ice control).

Grass Swales Designed to Infiltrate Large Fractions of Runoff (Alabama).

Also incorporate grass filtering before infiltration

Bioretention and biofiltration areas having moderate capacity
Recent Bioretention Retrofit Projects in Commercial and Residential Areas in Madison, WI

Soil Compaction and Recovery of Infiltration Rates

- Typical site development dramatically alters soil density.
- This significantly reduces infiltration rates, especially if clays are present.
- Also hinders plant growth by reducing root penetration.

### Long-Term Sustainable Average Infiltration Rates

<table>
<thead>
<tr>
<th>Soil Texture</th>
<th>Compaction Method</th>
<th>Dry Bulk Density (g/cc)</th>
<th>Long-term Average Inft. Rate (in/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy Loam</td>
<td>Hand Standard</td>
<td>1.595 1.653 1.992</td>
<td>35 9 1.5</td>
</tr>
<tr>
<td></td>
<td>Modified</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silt Loam</td>
<td>Hand Standard</td>
<td>1.504 1.593 1.690</td>
<td>1.3 0.027 0.0017</td>
</tr>
<tr>
<td></td>
<td>Modified</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay Loam</td>
<td>Hand Standard</td>
<td>1.502 1.703 1.911</td>
<td>0.29 0.015 &lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Modified</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Compaction, especially when a small amount of clay is present, causes a large loss in infiltration capacity.
Soil Modifications for rain gardens and other biofiltration areas can significantly increase treatment and infiltration capacity compared to native soils.

Rob Harrison, Univ. of Wash., and Bob Pitt, Univ. of Alabama examined the benefits of adding large amounts of compost to glacial till soils at the time of land development (4" of compost for 8" of soil).

Test plots:
- UW test plot 1: Alderwood soil alone
- UW test plot 2: Alderwood soil with Cedar Grove compost (old site)
- UW test plot 3: Alderwood soil alone
- UW test plot 4: Alderwood soil with GroCo compost (old site)

### Enhanced Infiltration with Amendments

<table>
<thead>
<tr>
<th>Test Plot Description</th>
<th>Average Infiltration Rate (in/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UW test plot 1: Alderwood soil alone</td>
<td>0.5</td>
</tr>
<tr>
<td>UW test plot 2: Alderwood soil with Cedar Grove compost (old site)</td>
<td>3.0</td>
</tr>
<tr>
<td>UW test plot 3: Alderwood soil alone</td>
<td>0.3</td>
</tr>
<tr>
<td>UW test plot 4: Alderwood soil with GroCo compost (old site)</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Six to eleven times increased infiltration rates using compost-amended soils measured during long-term tests using large test plots and actual rains (these plots were 3 years old).

**Changes in Mass Discharges for Plots having Amended Soil Compared to Unamended Soil**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Surface Runoff Mass Discharges</th>
<th>Subsurface Flow Mass Discharges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runoff Volume</td>
<td>0.09</td>
<td>0.29 (due to ET)</td>
</tr>
<tr>
<td>Phosphate</td>
<td>0.62</td>
<td>3.0</td>
</tr>
<tr>
<td>Ammonia</td>
<td>0.56</td>
<td>4.4</td>
</tr>
<tr>
<td>Nitrate</td>
<td>0.28</td>
<td>1.5</td>
</tr>
<tr>
<td>Copper</td>
<td>0.33</td>
<td>1.2</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.061</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Increased mass discharges in subsurface water pollutants observed for many constituents (new plots).

**Tests on Soil Amendments**

- Many tests have been conducted to investigate filtration/ion exchange/sorption properties of materials that can be potentially used as a soil amendment.
Some laboratory and field pilot-scale test setups (EPA and WERF-supported research at Univ. of Alabama). Critical that tests use actual stormwater, not artificial mixtures.

### Capture of Stormwater Particulates by Different Soils, Media, and Amendments

<table>
<thead>
<tr>
<th>Material</th>
<th>0.45 to 3µm</th>
<th>3 to 12µm</th>
<th>12 to 30µm</th>
<th>30 to 60µm</th>
<th>60 to 120µm</th>
<th>120 to 250µm</th>
<th>&gt;250µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porous pavement surface (asphalt or concrete)</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>10%</td>
<td>25%</td>
<td>50%</td>
<td>100%</td>
</tr>
<tr>
<td>Coarse gravel</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>10%</td>
</tr>
<tr>
<td>Fine sand</td>
<td>10%</td>
<td>33%</td>
<td>85%</td>
<td>90%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Loam soil</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>25%</td>
<td>50%</td>
<td>100%</td>
</tr>
<tr>
<td>Activated carbon, peat, and fine sand</td>
<td>40%</td>
<td>45%</td>
<td>80%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

**Measured Particle Sizes, Including Bed Load Component, at Monroe St. Detention Pond, Madison, WI**

- **E. coli**
  - \( P = 0.016 \)

- **Enterococci**
  - \( P = 0.008 \)

**PEAT-SAND FILTER: Pilot-Scale Testing, Fall 1999**
COD and phosphorus concentrations vary as a function of particle size.

**Laboratory Media Studies**
- Rate and Extent of Metals Capture
  - Capacities (partitioning)
  - Kinetics (rate of uptake)
- Effect of pH & pH changes due to media, particle size, interfering ions, etc
- Packed bed filter studies
- Physical properties and surface area determinations

**Cation Exchange Capacities for Different Media**

<table>
<thead>
<tr>
<th>Media</th>
<th>CEC (meq/100 g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat Moss</td>
<td>22</td>
</tr>
<tr>
<td>Compost</td>
<td>19</td>
</tr>
<tr>
<td>Activated Carbon</td>
<td>5.4</td>
</tr>
<tr>
<td>Zeolite</td>
<td>6.9</td>
</tr>
<tr>
<td>Cotton Waste</td>
<td>3.8</td>
</tr>
<tr>
<td>Agrofiber</td>
<td>9.4</td>
</tr>
<tr>
<td>Sand</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Compost leached soluble P during all conditions, especially if anaerobic.
Unfortunately, peat harvesting is a surface mining operation of a non-renewable resource. Locally available organic wastes, appropriately processed, should be investigated as a preferable soil amendment.

Conservation Design Approach for New Development

- Better site planning to maximize resources of site
- Emphasize water conservation and water reuse on site
- Encourage infiltration of runoff at site but prevent groundwater contamination
- Treat water at critical source areas and encourage pollution prevention (no zinc coatings and copper, for example)
- Treat runoff that cannot be infiltrated at site

![Sediment Discharges for Different Rain Depths](image1)

- Conventional Development
- Conservation Design

![Volume and Sediment Reductions for Different Rain Depths](image2)

- Sediment Reductions
- Volume Reductions
Stormwater Infiltration Controls in Urban Areas

- Bioretention areas
- Rain gardens
- Porous pavement
- Grass swales
- Infiltration Basins
- Infiltration Trenches
- Subsurface Dispersal

Suspended Solids Control at Monroe St. Detention Pond, Madison, WI (USGS and WI DNR data)

Consistently high TSS removals for all influent concentrations (but better at higher concentrations, as expected)

Critical Source Area Control

Covering fueling area

Berm around storage tanks
Multi-Chambered Treatment Train (MCTT) for stormwater control at large critical source areas
Milwaukee, WI, Ruby Garage Maintenance Yard MCTT

Pilot-Scale MCTT Test Results
Ruby Garage MCTT samples

EPA-funded SBIR2 Field Test Site Monitoring Equipment, Tuscaloosa, AL

Upflow filter insert for catchbasins
Able to remove particulates and targeted pollutants at small critical source areas. Also traps coarse material and floatables in sump and away from flow path.

Performance Plot for Mixed Media on Suspended Solids for Influent Concentrations of 500 mg/L, 250 mg/L, 100 mg/L and 50 mg/L.

HydroInternational, Ltd.
Benthic macroinvertebrate populations on natural and artificial substrates have been extensively used to indicate receiving water effects.

WinSLAMM predicts biological conditions in receiving waters based on reduced runoff quantities and effective impervious areas.

WinSLAMM calculates flow-duration curves for site, with and without controls.

Relationship between Directly Connected Impervious Areas, Volumetric Runoff Coefficient, and Expected Biological Conditions

WinSLAMM calculates flow-duration curves for site, with and without controls.
Flow-Duration Curves for Different Stormwater Conservation Design Practices

Capture and Reuse of Roof Runoff for Supplemental Irrigation

<table>
<thead>
<tr>
<th>Tankage Volume (ft³) per 4,000 ft² Building</th>
<th>Percentage of Annual Roof Runoff used for Irrigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000</td>
<td>56%</td>
</tr>
<tr>
<td>2,000</td>
<td>56</td>
</tr>
<tr>
<td>4,000</td>
<td>74</td>
</tr>
<tr>
<td>8,000</td>
<td>90</td>
</tr>
<tr>
<td>16,000</td>
<td>98</td>
</tr>
</tbody>
</table>

Stormwater Control Categories in the International Stormwater “BMP” Database:

**Structural Controls:**
- Detention ponds
- Grass filter strips
- Infiltration basins
- Media filters
- Porous pavement
- Retention ponds
- Percolation trenches/wells
- Wetland basins
- Wetland channels/swales
- Hydrodynamic devices

**Non-Structural Controls:**
- Education practice
- Recycling practice
- Maintenance practice
- Source controls

Decision Analysis

- With so much data available, and so many options that can be analyzed, how does one select the “best” stormwater control program?
- The least costly that meets the objective?
Possible, if only have one numeric standard:

If 80% SS reduction goal, the least costly would be wet detention. In this example, grass swales, street cleaning, and catchbasins cannot reach this level of control. If 40% SS reduction goal, then grass swales wins.

But, recall that there are many elements that must be considered:

- Sediment (amount and quality) habitat destruction (mostly through high flows [energy] and sedimentation)
- Eutrophication (nutrient enrichment)
- Low dissolved oxygen (from organic materials)
- Pathogens (urban wildlife vs. municipal wastewater)
- Toxicants (heavy metals and organic toxicants)
- Temperature
- Debris and unsafe conditions
- etc.

A multi-attribute decision analysis procedure can be used to examine many conflicting objectives. One example is by Keeney and Raiffa (*Decision Analysis with Multiple Conflicting Objectives*). This method uses utility curves to describe the benefits of varying levels of control and tradeoff coefficients that compare the different objectives. The first step is to determine the outcomes for several alternative stormwater control programs that will be compared. WinSLAMM can assist with this using the batch processor:

This is an example WinSLAMM batch processor output, showing many features (including costs, performance, habitat effects, etc.) for eight alternative programs:
Example ranges of attributes, and trade-offs:

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Range of attribute value for acceptable options</th>
<th>Trade-offs between remaining attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total annual cost ($/year)</td>
<td>$40,217 to 83,364</td>
<td>0.20</td>
</tr>
<tr>
<td>Land needs (acres)</td>
<td>2.3 to 4.5 acres</td>
<td>0.08</td>
</tr>
<tr>
<td>Rv</td>
<td>0.06 to 0.29</td>
<td>0.30</td>
</tr>
<tr>
<td>% of time flow &gt;1 cfs</td>
<td>0.5 to 4 %</td>
<td>0.05</td>
</tr>
<tr>
<td>% of time flow &gt;10 cfs</td>
<td>0 to 0.05 %</td>
<td>0.18</td>
</tr>
<tr>
<td>Particulate solids yield (lbs/yr)</td>
<td>2,183 to 10,192 lbs/y</td>
<td>0.07</td>
</tr>
<tr>
<td>Part. Phosphorus yield (lbs/yr)</td>
<td>5.5 to 25 lbs/yr</td>
<td>0.12</td>
</tr>
<tr>
<td>Sum = 1.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Example Utility Values for Attributes:

- Total annual cost: straight line, with $83,364 = 0 and $40,217 = 1.0.

Example Utility Values for Other Attributes (cont):

- Part. Phosphorus yield (lbs/yr): straight line, with 25 lbs/yr = 0 and 5.5 lbs/yr = 1.0
- Land needs (acres): straight line, with 4.5 acres = 0 and 2.3 acres = 1.0
- Particulate solids yield (lbs/yr): straight line, with 10,192 lbs/yr = 0 and 2,183 lbs/yr = 1.0
- % of time flow >1 cfs Utility value
  - <1            1.0
  - 1 – 3         0.75
  - 3.1 – 10      0.25
  - >10           0
### Attribute Values and Associated Utilities for Example

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 1</td>
<td>83,364</td>
<td>0</td>
<td>4.5</td>
<td>0</td>
<td>10,192</td>
<td>0</td>
<td>25</td>
<td>0</td>
<td>0.12</td>
</tr>
<tr>
<td>Option 5</td>
<td>49,142</td>
<td>0.79</td>
<td>4.5</td>
<td>0</td>
<td>4,133</td>
<td>0.76</td>
<td>10</td>
<td>0.77</td>
<td></td>
</tr>
<tr>
<td>Option 6</td>
<td>54,622</td>
<td>0.67</td>
<td>4.5</td>
<td>0</td>
<td>2,183</td>
<td>1.0</td>
<td>5.5</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Option 7</td>
<td>40,217</td>
<td>1</td>
<td>2.3</td>
<td>1</td>
<td>6,937</td>
<td>0.41</td>
<td>17</td>
<td>0.41</td>
<td></td>
</tr>
<tr>
<td>Option 8</td>
<td>45,698</td>
<td>0.87</td>
<td>2.3</td>
<td>1</td>
<td>4,125</td>
<td>0.76</td>
<td>10</td>
<td>0.77</td>
<td></td>
</tr>
</tbody>
</table>

### Calculation of Factors for Each Option (cont.), Sum of Factors, and Overall Rank

<table>
<thead>
<tr>
<th>Stormwater Control Option</th>
<th>Rv utility</th>
<th>Rv factor</th>
<th>Mod flow utility</th>
<th>Mod flow factor</th>
<th>High flow utility</th>
<th>High flow factor</th>
<th>Sum of factors</th>
<th>Overall Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 1</td>
<td>0.25</td>
<td>0.075</td>
<td>0.25</td>
<td>0.0125</td>
<td>0.75</td>
<td>0.135</td>
<td>0.2225</td>
<td>5</td>
</tr>
<tr>
<td>Option 5</td>
<td>0.75</td>
<td>0.225</td>
<td>0.75</td>
<td>0.0375</td>
<td>1.0</td>
<td>0.18</td>
<td>0.7455</td>
<td>4</td>
</tr>
<tr>
<td>Option 6</td>
<td>1.0</td>
<td>0.30</td>
<td>1.0</td>
<td>0.05</td>
<td>1.0</td>
<td>0.18</td>
<td>0.8540</td>
<td>2</td>
</tr>
<tr>
<td>Option 7</td>
<td>0.75</td>
<td>0.225</td>
<td>0.75</td>
<td>0.0375</td>
<td>0.75</td>
<td>0.135</td>
<td>0.7555</td>
<td>3</td>
</tr>
<tr>
<td>Option 8</td>
<td>1.0</td>
<td>0.30</td>
<td>1.0</td>
<td>0.05</td>
<td>1.0</td>
<td>0.18</td>
<td>0.9290</td>
<td>1</td>
</tr>
</tbody>
</table>

### Appropriate Combinations of Controls

- No single control is adequate for all problems
- Only infiltration reduces water flows, along with soluble and particulate pollutants. Only applicable in conditions having minimal groundwater contamination potential.
- Wet detention ponds reduce particulate pollutants and may help control dry weather flows. They do not consistently reduce concentrations of soluble pollutants, nor do they generally solve regional drainage and flooding problems.
- A combination of bioretention and sedimentation practices is usually needed, at both critical source areas and at critical outfalls.

### Combinations of Controls Needed to Meet Many Stormwater Management Objectives

- Smallest storms should be captured on-site for reuse, or infiltrated
- Design controls to treat runoff that cannot be infiltrated on site
- Provide controls to reduce energy of large events that would otherwise affect habitat
- Provide conventional flood and drainage controls

![Birmingham, AL Rain & Runoff Distributions (’81-’89)](image)
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