A Novel Research Framework to Assess Water Quality Impacts of Urban Trees

Neely L. Law, PhD
Deb Caraco, P.E.
Bill Hodgins, P.E.
Mitch Pavao-Zuckerman, PhD
Sarah Ponte Cabral
Nancy Sonti, USFS
Susan Day, PhD*
Amy Blood*
Ted Weber

* University of British Columbia
WATERSHED YIELD AND RAINFALL INTENSITY
WATERSHED YIELD AND RAINFALL INTENSITY
Removing Trees Tripled streamflow, recovered by year 8

TREE SPECIES IMPACTS

- Red Maple
- Loblolly Pine
- White Oak
- Tulip Poplar
- Sweetgum
- Virginia Pine

- Found species specific transpiration and response to soil moisture
- Drought response
- Water use response to vapor pressure deficit varied by species
- Highlighted the need for species specific transpiration studies

RELEVANCE TO URBAN STORMWATER MANAGEMENT

- Plant-based monitoring of total daily water use
- Sap flow meter to measure water use
- Soil moisture meters for infiltration
- Weather station for relative humidity, temperature, rainfall, wind

Figure. Daily water-use estimates for a macadamia tree (6x816, 19.1 cm stem diameter) for the September period (27/08/18 to 2/10/18). Peak anthesis occurred for this tree from 12 to 23 September and the sap flow meters measured a marked increase in water use during this period (orange ellipse).

Note. Data supplied by Scott Horus from Rural Funds Management from trees mentioned in Stuart Ridge orchard 10 km north of Bundaberg.

MAKING URBAN TREES COUNT

“Or counting urban trees for stormwater credit”
Recommendations of the Expert Panel to Define BMP Effectiveness for Urban Tree Canopy Expansion

Karen Cappella, Sally Claggett, Keith Cline, Susan Day, Michael Galvin, Peter MacDonagh, Jessica Sanders, Thomas Whitlouw, Qingfu Xiao

Accepted conditionally by Forestry Work Group, June 23, 2016
Approved by Watershed Technical Work Group, September 1, 2016
Final Approval by Water Quality Goal Implementation Team, September 12, 2016

Prepared by
Neo L. Law, PhD, Center for Watershed Protection, Expert Panel Chair
Jeremy Hanson, Virginia Tech, Expert Panel Coordinator
1. Do urban forest characteristics that influence ecohydrology occur in common configurations and can these configurations be captured through the development of an urban forest typology?

2. Will more complex urban forest types (e.g., those having more canopy layers, greater density, more understory plants or shrubs, litter layers, etc.) reduce runoff volume to a greater extent than simpler configurations?

3. How do different tree species affect runoff response?
This study quantifies:
- Precipitation
- Throughfall (to measure interception)
- Evapotranspiration
- Runoff/Infiltration breakdown
HYPOTHESES

• **H1**: Urban forest characteristics that influence ecohydrology occur in common configurations and these configurations can be captured through the development of an urban forest typology.

• **H2**: More complex urban forest types (e.g., those having more canopy layers, greater density, more understory plants or shrubs, litter layers, etc.) will result in greater runoff volume reduction.
STUDY AREA

Criteria:
• Site accessibility
• Safety for the research equipment
• Recommended by Montgomery County
### Site Characteristics

- Maryland School for the Blind: Closed Canopy
- Asbury Methodist: Cluster/Single Trees Over Turfgrass
- Different mix of species in each setting
- A. rubrum in all locations

<table>
<thead>
<tr>
<th>Species</th>
<th>Closed Canopy</th>
<th>Cluster of Trees Over Turfgrass</th>
<th>Single Tree Over Turfgrass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree Species 1: Red maple, Acer rubrum</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Tree Species 2: Tulip poplar, Liriodendron tulipifera</td>
<td>✗</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tree Species 3: Sweet Gum, Liquidambar styraciflua</td>
<td>✗</td>
<td>✗</td>
<td></td>
</tr>
</tbody>
</table>
INSTRUMENTATION/MEASUREMENT

Weather Stations
- Under Canopy
- Outside Canopy

Soil Moisture Meters
- Under Tree Canopy
- Top 30 cm of soil

Sap Flux Sensors
- Thermal Dissipation Probes
- Proxy for Transpiration

Soil Samples
- Bulk Density
- Texture
- Organic Matter
ANTICIPATED E/T RESULTS

• Trees in the closed canopy type will have greater, rates and amount, of sap flow (transpiration) than the trees that are located over turfgrass.

• Red maple will have a lower rate of transpiration compared to tulip poplar but will have greater overall amounts of transpiration and a resultant stronger effect on runoff reduction.

• Drivers of ET (Vapor Pressure Deficit (VPD); Soil Moisture)
- Transpiration Measurement
- Sap flux is a *proxy* for transpiration rates
- Granier-type thermal dissipation probe sap flux sensors inserted radially in stem
TRANSPIRATION METHOD

- Transpiration Measurement
- Sap flux is a proxy for transpiration rates
- Granier-type thermal dissipation probe sap flux sensors inserted radially in stem
- Voltage Difference is converted to grams $H_2O/cm^2$-d
  - $J_s (g \cdot m^{-2} \cdot s^{-1}) = 119((\Delta T_{max} - \Delta T)/ \Delta T)^{1.231}$
TRANSPERSION METHOD

- Transpiration Measurement
- Sap flux is a proxy for transpiration rates
- Granier-type thermal dissipation probe sap flux sensors
- Voltage Difference is converted to grams H₂O/cm²-d
- Area of Sapwood needed to determine the volume of H₂O; alternative method used literature values to relate DBH to sapwood area.
<table>
<thead>
<tr>
<th>SPECIES</th>
<th>CLOSED CANOPY</th>
<th>CLUSTER OF TREES OVER TURFGRASS</th>
<th>SINGLE TREE OVER TURFGRASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree Species 1: Red maple, Acer rubrum</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Tree Species 2: Tulip poplar, Liriodendron tulipifera</td>
<td>×</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tree Species 3: Sweet Gum, Liquidambar styraciflua</td>
<td>×</td>
<td>×</td>
<td></td>
</tr>
</tbody>
</table>
RESULTS ON A PER-DBH UNIT
SINGLE TREES HAVE HIGHER TRANSPIRATION IN ALMOST EVERY MONTH OF THE STUDY

2018

2019

<table>
<thead>
<tr>
<th>Month</th>
<th>2018</th>
<th>2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td></td>
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<tr>
<td>July</td>
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<td>August</td>
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<tr>
<td>September</td>
<td></td>
<td></td>
</tr>
<tr>
<td>October</td>
<td></td>
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</tr>
</tbody>
</table>

Legend:
- Single
- Cluster
- Closed Canopy
WHY DO INDIVIDUAL TREES HAVE THE HIGHEST PER-TREE TRANSPERSION RATES?

- Tree Density (Per-Tree or Per-DBH has different results than Per-Area)
- Exposure to Wind and Sun
- Greater Leaf Area for Single Trees

Birds Eye View of Tree Canopy
WHAT DRIVERS INFLUENCE TRANSPIRATION?

- Vapor Pressure Deficit
- Temperature
- Relative Humidity
- Wind Speed
- Soil Moisture
  - Measured in first 12”
WHY ISN’T THERE A STRONGER RELATIONSHIP BETWEEN SOIL MOISTURE AND TRANSPIRATION?

• Soil moisture is measured in the first 12”; tree roots may be drawing from deeper beneath the soil.
• There is likely a timing/interaction issue
  • Higher transpiration is possible when moisture content is high, but
  • Transpiration reduces soil moisture
POTENTIAL FUTURE RESEARCH: TRANSPERSION

- Detailed site assessment to determine a per-DBH transpiration rate on a per-acre rather than per-tree basis.
- Allows for a more direct measure of transpiration volume between different tree planting settings.
- Use data from this study to develop a time-series model relating soil moisture to transpiration.
STORMWATER RUNOFF HYPOTHESES

- Trees in a closed canopy setting will reduce runoff volume more than single trees.
- Trees in the cluster setting will have an intermediate performance.
WATER BALANCE

- Estimate Interception from Rain Gage Data
- Estimate Infiltration from:
  - Soil Moisture Meters
  - “Throughfall” (rainfall measured beneath the canopy)
  - Green-Ampt Equation
- Runoff = Throughfall-Infiltration

Runoff = Throughfall - Infiltration

Diagram shows:
- Canopy interception
- Soil moisture storage and uptake
- Evaporation
- Transpiration
INTERCEPTION

FACTORS THAT INFLUENCE

• Storm Depth and Intensity
• Tree Canopy “Leaf Area Index”
• Canopy Complexity

CALCULATION

Interception = Rainfall (Measured outside the canopy) - Throughfall (Measured Under the Canopy)

Calculated for individual storms
Eliminated some outlier values
Computed annual (all seasons) and growing-season values
INTERCEPTION RESULTS
(FRACTION OF RAINFALL DEPTH)
FACTORS INFLUENCING RUNOFF DEPTH

- Soil
  - Density
  - Moisture
  - Organic Matter
- Runoff Depth/Intensity
- Tree Canopy
- Understory
SOIL CONDITIONS AT EACH SITE

- Soil types were mostly similar.
- The “Northwest” site at the Maryland School for the Blind (closed canopy) had high organic matter, and was also often saturated.
- Single Tree setting had the lowest organic matter.
- The cluster setting had the highest bulk density (a measure of soil compaction).
- Bulk density is similar to undisturbed soils (not compacted).

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Bulk Density (g/cc)</th>
<th>Organic Matter (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed - (NW)</td>
<td>Loam-Clay Loam</td>
<td>1.31</td>
</tr>
<tr>
<td>Closed - (SE)</td>
<td>Loam</td>
<td>1.22</td>
</tr>
<tr>
<td>Single</td>
<td>Loam</td>
<td>1.22</td>
</tr>
<tr>
<td>Cluster</td>
<td>Loam</td>
<td>1.33</td>
</tr>
</tbody>
</table>
MEASUREMENTS NEEDED TO QUANTIFY RUNOFF DEPTHS

Rainfall
- Under Canopy
- Open

Soil Moisture
- Continuous
- Measured in First 12” of Soil
Runoff Computed Using the Green-Ampt Infiltration Model

Runoff when rainfall intensity exceeds infiltration rate

Calibrate to reproduce monitored soil moisture
Initial Soil Moisture/Runoff Model Results:
August 21-22, 2018 Asbury Single

- Modeled Moisture
- Measured Moisture
- Runoff
- Rainfall

Soil Moisture Content (Unitless) vs. Time (hrs)
Precipitation/Runoff (cm)
RUNOFF COEFFICIENT

- Highly variable
- Storm durations/ pre-event moisture highly variable.
- Some potential measurement error.
- This is not a paired analysis (few points overlapped at Asbury; MDSFB only has one setting/ typology)
RUNOFF VOLUME: SETTING COMPARISON

- Compares runoff coefficient for storms between 1 and 4 cm
- Includes the effects of interception and impacts on soil
- Typical runoff coefficient for grass is 0.2, but highly variable from site to site.
- Only 3 storms in this analysis for the Cluster site.
RUNOFF VOLUME: TOTAL OVER OBSERVED STORMS

- Cluster setting had too few storms to make a meaningful comparison.
- The Closed setting achieves about 17% reduction through interception, compared with 12% for Single.
- About 15% of throughfall converted to runoff for closed, compared with 26% for Single.

<table>
<thead>
<tr>
<th>CANOPY</th>
<th>N</th>
<th>RAINFALL SUM(CM)</th>
<th>THROUGHFALL SUM(CM)</th>
<th>RUNOFF SUM(CM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLOSED</td>
<td>10</td>
<td>24.5</td>
<td>20.4</td>
<td>3.06</td>
</tr>
<tr>
<td>CLUSTER</td>
<td>3</td>
<td>7.80</td>
<td>6.10</td>
<td>1.68</td>
</tr>
<tr>
<td>SINGLE</td>
<td>9</td>
<td>22.6</td>
<td>20.1</td>
<td>5.20</td>
</tr>
</tbody>
</table>
FUTURE RESEARCH/ANALYSIS FOR RUNOFF COMPARISONS

- Add soil moisture meters in turf areas.
- More years of data.
  - Capture a wider array of storm events.
  - Develop a relationship that incorporates pre-event moisture.
  - Better able to capture seasonal differences
- More sites
  - Site/storm conditions are confounded with canopy/setting
- Movement of water through deeper soil layers
  - Wells?
  - Deep pits to evaluate soil restrictive layers/perched groundwater
- Stemflow
  - Measure at the same sites?
THINGS WE STILL DON’T UNDERSTAND

Scale
• We evaluated transpiration from individual trees, but transpiration might be taking water from a wider spatial area
• Interactions between trees in the forest setting

Deep root systems
• What is a reasonable depth to assume transpiration is taking water from?
• Is it a simple water balance, or do deep roots access deep groundwater?

Role of the Understory
• Transpiration/ runoff reduction
Trees will perform differently in terms of stormwater mitigation based on their immediate surroundings. We used ecohydrological landscape characteristics to develop a typology, grouping trees with others that have similar ecohydrological benefits.
Ecohydrological Landscape Characteristics (ELCs):
Features within the urban forest that influence city hydrology.

- Ground Cover
- Canopy Density
- Number of Trees
- Leaf Area
- Understory
- Tree Size
METHOD POTENTIALLY ALLOWS PLANNERS TO UNDERSTAND DIFFERENCES AMONG TREE CANOPY TYPES

- Buildings are grayed
- Black is ground level under and near canopy
- The dark to light grey indicate canopy height
METHOD TAKES INTO ACCOUNT THE TREE AND ITS SURROUNDINGS
STORMWATER TREE CREDITS IN SOLOCO

- Project of Beaufort County in 2019-2020
- Significant similarities to the Virginia Stormwater Management Manual, the DC SWM and other states
- A regional effort of the South Carolina Southern Low Country
- Intergovernmental agreements shared cost of preparation
• Southern Low Country of South Carolina
LID PRACTICES TO MEET 85TH AND 95TH PERCENTILE STORMS

### Table 3.3. Pollutant Removal Efficiencies of Structural BMPs.

<table>
<thead>
<tr>
<th>BMP</th>
<th>Water Quality Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Runoff Reduction</td>
</tr>
<tr>
<td>Bioretention - No Underdrain</td>
<td>100%¹</td>
</tr>
<tr>
<td>Bioretention – Internal Water Storage</td>
<td>75%²</td>
</tr>
<tr>
<td>Bioretention - Standard</td>
<td>60%²</td>
</tr>
<tr>
<td>Permeable Pavement - Enhanced</td>
<td>100%¹</td>
</tr>
<tr>
<td>Permeable Pavement - Standard</td>
<td>30%²</td>
</tr>
<tr>
<td>Infiltration</td>
<td>100%¹</td>
</tr>
<tr>
<td>Green Roof</td>
<td>100%²</td>
</tr>
<tr>
<td>Green Roof - Irrigated</td>
<td>50%³</td>
</tr>
<tr>
<td>Rainwater Harvesting</td>
<td>100%¹</td>
</tr>
<tr>
<td>Impervious Surface Disconnection</td>
<td>40%³</td>
</tr>
<tr>
<td>Grass Channel</td>
<td>10%³</td>
</tr>
<tr>
<td>Grass Channel - Amended Soils</td>
<td>20%³</td>
</tr>
<tr>
<td>Dry Swale</td>
<td>60%³</td>
</tr>
<tr>
<td>Wet Swale</td>
<td>0%¹</td>
</tr>
<tr>
<td>Regenerative Stormwater Conveyance</td>
<td>0%¹</td>
</tr>
<tr>
<td>Filtering Systems</td>
<td>0%³</td>
</tr>
<tr>
<td>Storage Practices</td>
<td>0%³</td>
</tr>
<tr>
<td>Stormwater Ponds</td>
<td>0%¹</td>
</tr>
<tr>
<td>Stormwater Wetlands</td>
<td>0%¹</td>
</tr>
<tr>
<td>Tree Planting and Preservation</td>
<td>see section 4.12</td>
</tr>
<tr>
<td>Proprietary Practices</td>
<td>see section 4.13</td>
</tr>
<tr>
<td>Conservation Areas</td>
<td>see section 4.14</td>
</tr>
</tbody>
</table>
PRESERVE EXISTING TREES

- Inventory existing trees
- Identify trees to preserve
- Protect trees and soil during construction
- Protect trees after construction
<table>
<thead>
<tr>
<th>Trees planted with minimum caliper 1.5”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum rootable soil volumes</td>
</tr>
<tr>
<td>Small and large tree quantities</td>
</tr>
<tr>
<td>Soil volume requirement</td>
</tr>
<tr>
<td>Assumed volume reduction</td>
</tr>
<tr>
<td>Used in runoff reduction spreadsheet tool</td>
</tr>
<tr>
<td>Tree Type</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>Planted Tree – Small</td>
</tr>
<tr>
<td>Planted Tree – Large</td>
</tr>
<tr>
<td>Preserved Tree – Small</td>
</tr>
<tr>
<td>Preserved Tree – Large</td>
</tr>
<tr>
<td>Preserved Tree – Special</td>
</tr>
</tbody>
</table>
# Stormwater Tree Credits in SOLOCO

<table>
<thead>
<tr>
<th>BMPs</th>
<th>Contributing Drainage Area</th>
<th>Water Quality Credits</th>
<th>Retention (ft)</th>
<th>TSS Removal Achieved</th>
<th>Total N Removal Achieved</th>
<th>Bacteria Removal Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forest Cover Drawing to BMP</td>
<td>Area (square feet)</td>
<td>Total % Removal</td>
<td>Volume from Direct Drainage</td>
<td>Volume from Upstream Practices</td>
<td>Total Volume Captured by BMP</td>
</tr>
<tr>
<td></td>
<td>Turf Cover Drawing to BMP</td>
<td>Area (square feet)</td>
<td>Bacteria % Removal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Improvised Cover Drawing to BMP</td>
<td>Area (square feet)</td>
<td>Volume from BMP (public feet)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Bioretention - No Underdrain**: Area: 0
- **Bioretention - NW**: Area: 0
- **Bioretention - Standard**: Area: 0
- **Pervious Pavement - Enhanced**: Area: 0
- **Pervious Pavement - Standard**: Area: 0
- **Infiltration**: Area: 0
- **Green Roof**: Area: 0
- **Rainwater Harvesting**: Area: 0
- **Impervious Surface Disconnection**: Area: 0
- **Grass Channel**: Area: 0
- **Grass Channel - Amended Soil**: Area: 0
- **Dry Swale**: Area: 0
- **Wet Swale**: Area: 0
- **ESC**: Area: 0
- **Storage Systems**: Area: 0
- **Storage Practices**: Area: 0
- **Stormwater Ponds**: Area: 0
- **Stormwater Wetlands**: Area: 0
- **Proprietary Practice**: Area: 0

<table>
<thead>
<tr>
<th>BMPs</th>
<th>Total</th>
<th>Total</th>
<th>Total</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

| Total Number of Trees | 0 | 0 | 0 | 0 | 0 |

**Center for Watershed Protection**
RUNOFF REDUCTION VOLUME

- Stormwater retention volume SWRv
- Volume reduction assists with SWRv
- Small and large tree quantities
- Soil volume requirement
- Assumed volume reduction
- Used in runoff reduction spreadsheet tool
SOLOCO IMPLEMENTATION

- Beaufort County Effective 1Q 2021
- Town of Bluffton Ordinance September 2021
- City of Hardeeville currently in Council Workshops
- Jasper County – TBD
- City of Beaufort – TBD
- Town of Port Royal - TBD
QUESTIONS
Making Urban Trees Count Resources

Center for Watershed Protection https://www.cwp.org/making-urban-trees-count/


Transpiration rates of red maple (Acer rubrum L.) differ between management contexts in urban forests of Maryland, USA Sarah Ponte, Nancy F. Sonti, Tuana H. Phillips & Mitchell A. Pavao-Zuckerman https://doi.org/10.1038/s41598-021-01804-3

Southern Low Country Stormwater Design Manual