Watershed Rainwater Harvesting: Analysis, Prioritization, and Design

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Why is this Important?

- Traditional stormwater management has been based on:
  - Conveyance and centralized control (Roy et al. 2008, Debo and Reese 2010)
  - Parameter stationarity (Denault et al. 2006)
- Negative impacts of traditional stormwater management:
  - Extended release rates and poor peak flow control for frequent, small events (Shaver et al. 2007, NRC 2008, Roy et al. 2008)
Stormwater Management

- Low Impact Development (LID)
  - Site-specific source controls targeting
    - Quantity (De Graf & Der Brugge 2010, Foraste & Hirshman 2010)
    - Quality (Roy et al. 2008, Lim et al. 2010, Spatari et al. 2011)

- Traditional LID research focused on
  - Smaller spatial scales (Sample and Heaney 2006, Gilroy and McCuen 2009)
  - Case-by-case, or pilot project, basis (Damodaram et al. 2010, Mandarano 2011)
Where are the gaps?

- **Reproducible** design methods and technical guidance
  - Schnieder & McCuen 2006, Burian & Pomeroy 2010

- Empirical results for watershed-scale hydrologic impacts (Jensen et al. 2010)
  - Yang and Li 2013

- Watershed-scale hydrologic (Spatari et al. 2011, Jia et al. 2012) and **economic analyses** (Godchalk et al. 2009)
Assessment issues...

- **Modeling requires**
  - Extensive datasets (Thomas et al. 2003, Jensen et al. 2010)
  - Time-intensive, manual delineation (Thomas et al. 2003, Sterr and Yui Lau 2012)

- **Challenges occur, including**
  - Accurate representation and parameter estimation (Burian and Pomeroy 2010)
  - Simplified, uniform application (Pataki et al. 2011)
Improvements?

- Publicly-available datasets (James et al. 2007)
  - Increasing resolution and spatial extent (Wechsler 2007, Amatya et al. 2013)

Image Classification

- Pixel-Based (PBIA)
  - Misclassifications due to heterogeneity and spatial signature (Hseih et al. 2001, Zhu and Blumberg 2002, Yang et al. 2010i)
- Object-Based (OBIA)
  - Excels with scale, context, geometry, and color (Yang et al. 2010ii, Wu and Yuan 2011)
Improvements?

- Site search methodologies improve weighing and filtering of multiple datasets (Malczewski 2004, Wang et al. 2010)
  - Multiple criteria decision analysis (MCDA) (Malczewski 2004)
  - Spatial clustering analysis (Jacquez 2008)
  - Translation of geospatially distributed data into representative surfaces
- Aids “Flow-regime management”
  - Burns et al. 2012
Why is this important to you?

- Leveraging publically-available and invested **datasets** for projects
- Improve the determination and allocation of **funding** for watershed projects
- Efficiently **model** alternative scenarios
- Improve the **targeting** of resources to meet cost-effectiveness thresholds
My Goals…

- Improve the **accuracy** of identifying and quantifying watershed-scale LID design parameters
  - OBIA

- Address **uniform** approaches to watershed-scale LID design and implementation
  - Suitability Protocol
  - Geospatial analysis framework

- Improve the **targeting** of resources to meet cost-effectiveness thresholds
  - Prioritization Protocol
  - Hydrologic and economic analyses
  - Geospatial analysis framework
  - Uncertainty analysis with Monte Carlo Methods
Objectives

Develop an **accurate** watershed-scale suitability-based protocol

Develop a **reproducible** watershed-scale prioritization protocol

Apply these protocols to study watershed **cost-effectiveness** of RWH

**Improve the targeting, implementation & design of site-suitable RWH, accurately accounting for cost-effectiveness**
Chollas Creek Watershed

- Drainage Area: 7,680 acres
- Hydrologic Soils: Groups C, D
- Total Imperviousness: 50%
- Directly Connected Imperviousness: 38%-46%
- Housing Density: 2,125 ppsm
- Flow Regime: Intermittent

Average Precipitation: 9.65 inch/year
1st Objective: “Develop an accurate watershed-scale Suitability Protocol”

1. Present the development of the Suitability Protocol
2. Demonstrate the Protocol’s accuracy
Suitability Protocol

- Local suitability **constraints** govern site-scale RWH implementation and design
- Watershed analysis requires **extensive and detailed** datasets
Suitability Protocol: Workflow

- **Objective:** “Develop an **accurate** watershed-scale Suitability Protocol”

1. Process Datasets: Elevation, Spectral (Imagery)

2. Object-Based Image Analysis (OBIA)

3. Quality Assessment (QA)

4. Geospatial Analysis (LIDSS)
Process datasets (Step 1)

- Spectral data via ENVI 4.8
- Normalized Difference Vegetation Index (NDVI)
- LASTools (Isenberg 2014)
- Zhu et al. 2012

Figure: Example of NDVI, where brighter areas represent vegetation.

Figure: Example of returns for laser pulses (ESRI 2013).
Image Analysis (Step 2)

- OBIA via eCognition (2014)
Yellow outlines represent the classified rooftop areas.
Quality Assessment: QA (Step 3)

Quality assessment methods similar to those implemented by Whiteside et al. (2014) and with recommendations from Congalton (1991).
Quality Assessment: QA (Step 3)

<table>
<thead>
<tr>
<th>Feature Areas</th>
<th>Rooftop</th>
<th>Unclassified</th>
<th>Total Classified</th>
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<tr>
<td>Rooftop</td>
<td>170,947</td>
<td>61,192</td>
<td>232,138</td>
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<td>Unclassified</td>
<td>67,136</td>
<td>1,332,638</td>
<td>1,399,775</td>
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<td>Total Validated</td>
<td>238,083</td>
<td>1,393,830</td>
<td>1,631,913</td>
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</table>

92%
**WHY?**

To identify suitable locations that represent your criteria

---

### Output from Suitability Protocol

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
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<td>1470</td>
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Suitability Protocol: Results

- Classification Comparison
  - **UNIFORM** - 14,412 households at an average rooftop area of 1,000-ft² (331 acres total)
  - **LIDSS** - 12,813 households at an average rooftop area of 2,300-ft² (662 acres total)
2nd Objective: “Develop a *reproducible* watershed-scale prioritization protocol”

1. Present the development of the Prioritization Protocol
2. Demonstrate the reproducibility of the Protocol
Prioritization Protocol: Workflow

Base hydrologic model development

Economic Thresholds

Hydrologic Thresholds

Geospatial analysis of results

GI hydrologic model adaptation

SWMM

User

RWHA

SWMM

WERF

Excel

PriorLID

SWMM
Input from Suitability Protocol

Base + RWH (60 gallons)

\[ \text{Volume} = \text{Area} \times WQCV_{depth} \]

Number per Household = \( \frac{\text{Volume}}{\text{Nominal Size}} \)

RWHA
Cost Estimation

- WERF BMP and LID Cost Tools
  - Cisterns (Houdeshel et al. 2011)
- Equivalent Annual Cost (EAC)
- Total annual costs ($P$)
- Total number of interest periods ($N$)
- Interest Rate ($i$)

$$EAC = P \left[ \frac{i(1 + i)^N}{(1 + i)^N - 1} \right]$$

1. Capital Cost of Purchasing
2. Replacement Cost at Year 50
3. Annual O&M
4. 62-year Time Period
5. 3.5% Interest Rate
Geospatial Analysis

Cost

Reduction

Cost-Effectiveness
Iterative classification

Classification groups pixels according to similar values (i.e. cost-effectiveness).

Addresses the need to identify homogeneous classes representing subcatchment cost-effectiveness values.

Basis of Prioritization and Hydrologic Assessment

Cost-Effectiveness (i.e. Priority)
3rd Objective: “Apply these protocols to study watershed cost-effectiveness of RWH”

- Target: watershed-scale cost-effectiveness with suitably-designed and prioritized RWH practices throughout the study area

Is it beneficial to prioritize subcatchment RWH distribution to elicit watershed-scale impacts?
Suitability Protocol: Results

- **LIDSS Output**
  - 13,566 total number of households
  - 2,300-ft\(^2\) average rooftop area (1,500-ft\(^2\) – 5,600-ft\(^2\))

- **RWHA**
  - **Inputs**
    - With nominal **60-gallon** RWH barrels
    - Targeting the capture of the 85\(^{th}\) percentile, or WQCV event, depth of **0.65-in (16.5-mm)**
  - **Output**
    - Average of **17** RWH units per household (11 – 38)

- **Cost Estimation**
  - Total EAC of **$3.16 MIL**
Prioritization Protocol: Cost & Hydrologic Results

Watershed reductions for Priority Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average Annual Volumetric Reduction</th>
<th>Average Annual Peak Flow Rate Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>LID227 (max)</td>
<td>20%</td>
<td>24%</td>
</tr>
<tr>
<td>HIGH-MID</td>
<td>13%</td>
<td>19%</td>
</tr>
<tr>
<td>HIGH</td>
<td>8%</td>
<td>11%</td>
</tr>
<tr>
<td>MID</td>
<td>5%</td>
<td>8%</td>
</tr>
<tr>
<td>LOW</td>
<td>6%</td>
<td>5%</td>
</tr>
<tr>
<td>NULL</td>
<td>1%</td>
<td>0.4%</td>
</tr>
</tbody>
</table>
Priority Cost-Effectiveness: Results

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Average Annual Hydrologic-Effectiveness (L/$)</th>
<th>Average Annual Cost-Effectiveness ($/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LID227</td>
<td>3.11</td>
<td>$0.40</td>
</tr>
<tr>
<td>HIGH-MID</td>
<td>3.22</td>
<td>$0.38</td>
</tr>
<tr>
<td><strong>HIGH</strong></td>
<td><strong>3.30</strong></td>
<td><strong>$0.37</strong></td>
</tr>
<tr>
<td>MID</td>
<td>3.13</td>
<td>$0.40</td>
</tr>
<tr>
<td>LOW</td>
<td>3.02</td>
<td>$0.42</td>
</tr>
<tr>
<td>NULL</td>
<td>2.19</td>
<td>$0.63</td>
</tr>
</tbody>
</table>

**Graph:**
- X-axis: Exceedance Probability
- Y-axis: Annual Cost-Effectiveness (L/$)
- Legend: LID, HIGH-MID, HIGH, MID, LOW, NULL

**Legend Colors:**
- LID: Orange
- HIGH-MID: Red
- HIGH: Blue
- MID: Green
- LOW: Yellow
- NULL: Pink
Watershed: Cost v. Benefit

User-Defined Watershed Reduction | Estimated Cost ($MIL)
--- | ---
2.5% | $0.41
5% | $0.80
10% | $1.58
15% | $2.36
20% | $3.14

Randomly applied RWH for a total of $1.53MIL resulted in a long-term volumetric reduction of 10% (291 ML/year).

\[ y = 0.064x - 0.0015 \]
\[ R^2 = 0.9975 \]
A 10% - 20% increase in imperviousness has been shown to negatively impact hydrologic, geomorphic, and biological watershed characteristics (Paul & Meyer 2001).

\[
y = 0.9754x + 0.1771
\]
Conclusions: Uncertainty

- RWH **buffers** the impact of increasing subcatchment outflow with variations in imperviousness

![Graph showing the relationship between reduction in outflow and reduction in simulated runoff coefficient. The equation for the line is given as \( y = 0.9754x + 0.1771 \).]
Conclusions: Suitability

- Households can be **accurately** identified and quantified with the Protocol, applying Object-based image analysis & Geospatial analysis of design constraints
- Compared with the **UNIFORM** method, **LIDSS** quantified 11% less number of households and **51%** greater area
- **Rooftop disconnection** can not be downplayed

**OBIA Accuracy: 92%**

<table>
<thead>
<tr>
<th>Hydrologic Response</th>
<th>Temporal Resolution</th>
<th>Watershed $\Delta(\text{UNIFORM, LIDSS})$</th>
<th>Subcatchment $\Delta(\text{UNIFORM, LIDSS})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outflow Volume Reduction</td>
<td>Long-Term (1948-2012)</td>
<td>+44% [<strong>LIDSS</strong>]</td>
<td>+46% [<strong>LIDSS</strong>]</td>
</tr>
<tr>
<td>Outflow Volume Reduction</td>
<td>Annual</td>
<td>+44% (34%-51%) [<strong>LIDSS</strong>]</td>
<td>+50% [<strong>LIDSS</strong>]</td>
</tr>
<tr>
<td>Peak Outflow Rate Dampening</td>
<td>Annual</td>
<td>+51% (22%-122%) [<strong>LIDSS</strong>]</td>
<td>+52% [<strong>LIDSS</strong>]</td>
</tr>
</tbody>
</table>
Conclusions: Prioritization

- RWH units can be sized, modeled and analyzed with respect to hydrology and economics
- Subcatchment implementation of RWH can be prioritized using the Protocol, which iteratively classifies based on cost-effectiveness

Priority Zones can guide finer-scale analyses of RWH scenarios
Conclusions: Implications

- Hydrologic reductions **linearly** increase with implementation costs, regardless of location or priority

**Is it beneficial to prioritize subcatchment RWH distribution to elicit watershed-scale impacts?**

- Chart showing linear relationships between long-term reductions in watershed runoff and implementation costs.
- Equation: \( y = 0.064x - 0.0015 \)
- Coefficient of determination: \( R^2 = 0.9975 \)
Regional Application

- Portland (POR); 1999-2007
  - 85\textsuperscript{th} Percentile Event – 0.49 in (12.4 mm)
  - Average Annual – 39.1 in (994 mm)
Takeaways

- Classification software & methodologies
- Geospatial methods & analyses
- Other green infrastructure, low impact development, sustainable urban drainage systems....
Thank you

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