Systems Level Approaches to Create More Sustainable Water Resources

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Reductionism versus Systems Analysis

“There will always be room for engineering reductionism but the greatest sustainability gains in the 21st century will be from systems analysis. In addition, stakeholder engagement and managing complexity will drive greater adoption of more sustainable infrastructure.”

John Crittenden, Presented at the Science Summit for Sustainable Water, July 13, 2014, Dalian, China
Water, Nutrient Recovery, Energy Recovery, Recreation, Heat Island Mitigation, Air Quality Improvement and Transportation
Low Impact Development (Reducing Storm Water Runoff, Erosion and Surface Water Contamination) - LID Best Management Practices (BMPs)

Rain Gardens for local flood control at Cuyahoga Falls, OH\textsuperscript{1}.

Green roof of City Hall in Chicago, IL.

Rainwater Harvesting tanks for residential water supply at Perth, Australia\textsuperscript{2}.

Increased walkability through greening of alleyways at Vancouver.

Porous parking lot at the Reliant stadium, Houston, TX\textsuperscript{3}.
Rain Water Harvesting from Roof Rain Harvesting, Cooling Condensate and Footing Dewatering and Treatment Using a Wet Land (Georgia Techs Engineered Biosystems Building)
Interdependency between Water Infrastructure and Socio-Economic Environment

Philadelphia case

- LID (low impact development) options instead of storage tunnel for CSO (combined sewer overflow) control in watershed areas;
- Total net benefit over the 40-year projection: 2 billion (LID for 25% runoff), 4.5 billion (LID for 100% runoff), 2009 USD.

Source: Philadelphia Water Department (2009) Philadelphia combined sewer overflow long term control plant update, supplemental document volume 2; Triple bottom line analysis
Xiamen Transit-Oriented Development| Xiamen, China

Advance Planning Group
Xiamen Transit-Oriented Development | Xiamen, China

Advance Planning Group
Water Flows with LID and Grey Water Reclamation: 2-story Apartment in Atlanta, GA (Gal/Capita-day)

Same Size Waste Water Treatment Plant

Small Water Treatment Plant

Potential of off-grid water supply

Smaller Flow, More Concentrated; Smaller Plant: Better energy and nutrient recovery.
Potential Water Savings

GR = greywater reclamation systems
RH = rainwater harvesting
XR = xeriscaping

- The error bars indicate maximum non-potable water savings for a combination of technologies when water use is not restricted to toilet flushing and irrigation.
Normalized Impacts by Category for 1 m³ of water (% annual US emissions per capita in 2008)

- Central Water Supply
- Rainwater Harvesting
- Greywater Reclamation

- Ozone depletion
- Global warming
- Smog formation
- Acidification
- Eutrophication
- Carcinogenic effects
- Non-Carcinogenic effects
- Respiratory effects
- Ecotoxicity
- Fossil fuel depletion
- Single Score

Y-axis: Impact values from 0.000 to 0.035.
Energy for Water in the U.S. (Reduced By LID)

About 4% of the total electricity consumption in the US is for the water and wastewater sector

Of the total energy required for water treatment, 80% is required for conveyance and distribution

Average Energy requirement for different water and wastewater treatment technologies

<table>
<thead>
<tr>
<th>Water Treatment*</th>
<th>kWh/MGal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Water Treatment</td>
<td>220</td>
</tr>
<tr>
<td>Groundwater Treatment</td>
<td>620</td>
</tr>
<tr>
<td>Brackish Groundwater Treatment</td>
<td>3,900-9,700</td>
</tr>
<tr>
<td>Seawater Desalination</td>
<td>9,700-16,500</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wastewater Treatment</th>
<th>kWh/MGal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trickling Filter</td>
<td>950</td>
</tr>
<tr>
<td>Activated Sludge</td>
<td>1,300</td>
</tr>
<tr>
<td>Advanced Treatment without Nitrification</td>
<td>1,500</td>
</tr>
<tr>
<td>Advanced Treatment with Nitrification</td>
<td>1,900</td>
</tr>
</tbody>
</table>

*Includes collection but does not include distribution

1 EPRI, Water & Sustainability, Volume 4, 2002
System-based Benefits of LID
Best Management Practices

Water & Wastewater
- Stormwater management
- Stormwater treatment
- Water recharge

Wastewater/Stormwater
- Storm sewers
- Combined sewers
- Wastewater systems

Green Infrastructure
- More Concentrated Wastewater
- Water Retained/Slowed by Green Infrastructure

Water Resources
- Rainwater
- Surface water
- Groundwater
- Reclaimed water

Reduced/Delayed Flow

Enables:
- Energy Efficiency and Recovery (reduces energy demand)
- Nutrient Recovery (can be utilized for green infrastructure projects)

Transportation Infrastructure
- Pedestrian walkways
- Cycling

Food Infrastructure
- Urban agriculture

Energy Infrastructure
- Reduced heat island

Social Benefits
- Well-being
- Public health
- Property values
- Urban gardens

Can Enhance Other Infrastructures
Chicago Is Hoping to Retire the Word “Waste”
Plan: “Recovering Resources, Transforming Water”
Resources: Phosphorus, Class A biosolids, Energy & Water
Transportation, Land Use, Water
Water for Mobility Network: Metro Atlanta, 2010 and 2030 Conditions

Source: Jeffrey Yen (2011) A system model for assessing water consumption across transportation modes in urban mobility networks, Masters thesis
The Impact of the Hierarchy of Transportation Network On Land Development and Transportation Carbon Emissions

The geometric form of road network is similar between Washington DC and Atlanta. The difference in the hierarchy of transportation network accounts for 30% of density difference and 20% of carbon difference between Washington DC and Atlanta.

3,258 Person Per Square Mile
1.07 metric ton per capita per year
Structural Fractal Dimension = 2.80

1,378 Person Per Square Mile
1.52 metric ton per capita per year
Structural Fractal Dimension = 3.36

42% More Water For Transportation!
The Connection between Autonomous Vehicles, Green Space and Water

- 80% penetration of autonomous vehicles
- 28% of the cars we have today
- At least 72% reduction in parking space
- 24.7% reduction of impervious area and stormwater runoff
- Additional 17% of city land for green space and stormwater management
Energy and Water
Recapturing Lost Heat in Combined Heat & Power System

**Separate Electric Power**
- Input Energy (100 units)
- Generation Loss (65 units)
- Grid Loss (6 units)
- Useful Electricity (29 units)

**Combined Heat and Power**
- Input Energy (100 units)
- Total Loss (15 units)
- Useful Heat (50 units)
- Useful Electricity (35 units)

**Air-cooled Microturbine**

**Heating**
- Absorption Chiller

**Cooling**
Decentralized Energy Production at Perkins + Will, Atlanta Office

- Air Cooled Microturbines are used to for heating and cooling using Absorption Chillers and supply 40% of the total electricity.

**Adding Distributed Generation as part of the Grid:**

- Water Reduction: >50%
- CO₂ Reduction: 15 - 40%
- NOₓ Reduction: ~90%
Water as a Heat Source: False Creek Neighborhood Energy Utility Vancouver, BC

Sewage heat recovery supplies 70% of annual energy demand and reduces GHG emission by 50%
Agriculture: Urban Farming
# Controlled Environment Agriculture (CEA) 
Hydroponic Indoor Farms vs. Traditional Field Growth

<table>
<thead>
<tr>
<th></th>
<th>CEA Fresh Farms Romaine (Local Grown, Georgia)</th>
<th>Filed-Growth Romaine (California)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land Requirements</td>
<td>20 Acres</td>
<td>620 Acres</td>
</tr>
<tr>
<td>Leafy Green Production Yields Per Year</td>
<td>33 Million Heads</td>
<td>33 Million Heads</td>
</tr>
<tr>
<td>Fossil Fuel used during Growth Cycle (not including crop transport)</td>
<td>200 Gallons equiv. Diesel</td>
<td>3,720 Gallons Diesel</td>
</tr>
<tr>
<td>Food Miles</td>
<td>100 miles/truckload</td>
<td>2,577 miles/truckload</td>
</tr>
<tr>
<td>Fossil Fuel to Transport 100 Miles or CA to Local Markets</td>
<td>22,200 Gallons Diesel</td>
<td>571,000 Gallons Diesel</td>
</tr>
<tr>
<td>Carbon Footprint</td>
<td>3,000 metric ton CO2</td>
<td>12,000 metric ton CO2</td>
</tr>
<tr>
<td>Fresh Water used during Growth Cycle</td>
<td>1.2 Gallons per Head</td>
<td>9-42 Gallons per Head</td>
</tr>
<tr>
<td>Fresh Water Used to Wash Lettuce per heat for market</td>
<td>0.7 One Water per Head</td>
<td>2.5 Three Washings per Head</td>
</tr>
<tr>
<td>Total Fresh Water Annually</td>
<td>64 Million Gallons</td>
<td>0.3-1.5 Billion Gallons</td>
</tr>
<tr>
<td>Time from Harvest to Market</td>
<td>6-12 Hours</td>
<td>4-7 Days</td>
</tr>
</tbody>
</table>

Source: CEA Capital Holdings

Caveat: CEA have not build the farms at scale. The optimistic yields and operational parameters need verification.
Vertical Farming

What is Vertical Farming:
• Produce grown in racks with natural or artificial light
• Hydroponic or Aquaponic

Produce:
leafy greens, fruits, vegetables, microgreens
• Claim 90 - 97% less water
• Serve local regions → smaller carbon footprint from transportation
• 75% less labor
• Smaller impact on land use
• Grow year-round

Current Investigations:
• Production capacity
• Nutrient, Energy, Emissions, and Water (NEEW) Flows
• Economic viability
• Impact on urban system resilience and sustainability
• Relationship with food supply and availability

VertiCrop, Vancouver, CA - http://www.verticrop.com/
Farmed Here, Chicago, IL - http://farmedhere.com/
Ecosystem Services
Land use and ecosystem services in Beijing

- Woodland and cropland were the two largest land use types.
- Built-up land expanded the most, by 157%. Cropland had the greatest decrease of 38%.

The changes of comprehensive ecosystem service from 1984 to 2015.

<table>
<thead>
<tr>
<th></th>
<th>Year 1984</th>
<th>Year 2015</th>
<th>Change rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon storage+</td>
<td>2.76</td>
<td>2.67</td>
<td>−3%</td>
</tr>
<tr>
<td>Water yield+</td>
<td>7.92</td>
<td>7.60</td>
<td>−4%</td>
</tr>
<tr>
<td>Nitrogen export−</td>
<td>9.46</td>
<td>8.47</td>
<td>−11%</td>
</tr>
<tr>
<td>Phosphorus export−</td>
<td>1.95</td>
<td>1.53</td>
<td>−22%</td>
</tr>
<tr>
<td>Sediment export−</td>
<td>3.88</td>
<td>3.28</td>
<td>−16%</td>
</tr>
<tr>
<td>Habitat quality+</td>
<td>1.41</td>
<td>1.26</td>
<td>−11%</td>
</tr>
<tr>
<td>Grain production+</td>
<td>2.90</td>
<td>0.61</td>
<td>−80%</td>
</tr>
<tr>
<td>Vegetable production+</td>
<td>1.14</td>
<td>2.05</td>
<td>+306%</td>
</tr>
<tr>
<td>Fruit production+</td>
<td>1.76</td>
<td>7.14</td>
<td>+79%</td>
</tr>
</tbody>
</table>

+ means the positive indicator, the larger the indicator value, the better the ecosystem service.

− means the negative indicator, the larger the indicator value, the worse the ecosystem service.

The average comprehensive ecosystem service of Beijing showed a decreasing trend over the past 30 years.
Land use and ecosystem services in Atlanta

- From 1985 to 2012, the forest accounted for the largest proportion in Atlanta.

- Forest and wetland had the greatest proportion of decreases, which were 42% and 34%, respectively.

- Low and high intensity developed land increased most, by 157% and 394%, respectively.

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Change rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon storage</td>
<td>−23%</td>
</tr>
<tr>
<td>Water yield</td>
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</tr>
<tr>
<td>Nitrogen export</td>
<td>+28%</td>
</tr>
<tr>
<td>Phosphorus export</td>
<td>+49%</td>
</tr>
<tr>
<td>Sediment export</td>
<td>+17%</td>
</tr>
<tr>
<td>Habitat quality index</td>
<td>−27%</td>
</tr>
<tr>
<td>Recreation opportunity</td>
<td>−35%</td>
</tr>
<tr>
<td>Food supply</td>
<td>−36%</td>
</tr>
</tbody>
</table>
ADOPTION AND PREFERENCES
Urban Systems Complexity

Emergence of desirable amenities (high Tax Revenue and Quality of Life) & undesirable amenities (e.g., poor air quality, low tax revenue, traffic congestion, flooding, etc.)
Big Data for Social Decision and Urban Complexity Modeling

Collect
- Social Media
- Blogs
- Twitter
- News
- Product Reviews

Analyze
- Enrich and prepare social media content with metadata

Modeling
- Agent-based urban model and visualization

Topic Modeling
- Language Identification
- Document Clustering
- Entity Extraction
- Sentiment Analysis
Agent-based Modeling: Simulating the Adoption Rate for More Sustainable Urban Development

**Business As Usual (BAU)**

- Percentage of households as compared to total households after 30 years
- Percentage of households in single-family houses as compared to total households after 30 years
- Percentage of households in apartments as compared to total households after 30 years

**More Sustainable Development (MSD)**

- Impact fee for Low Impact Development non-compliance penalty:
  - $13,000 per unit for single-family house
  - $1,500 per unit for apartment home

**Principal Agents:** Prospective Homebuyer, Homeowners, Developers, Government

**Implemented Policy Tool**

- After 30 years:
  - 40% reduction in potable water demand from centralized plant in MSD as compared to BAU
  - 36% increase in net property tax revenue generation in MSD as compared to BAU

Source: Lu. et al., ES&T, 2013
Water, Energy, Cost and Air Quality
The SMARTRAQ project

- Supports research on land use impact on transportation and air quality
- 1.3 million parcels in the 13 metropolitan Atlanta non-attainment counties
SMARTRAQ DATA AND ATTRIBUTES

- Address
- Road Type
- City
- Zip Code
- Owner Occupied
- Commercial/Residential
- Zoning
- Sale Price
- Sale Date
- Tax Value
- Assessed Value
- Improvement Value
- Land Value
- Year Built
- No. of Stories
- Bedrooms
- Parking
- Acreage

- Land Use Type
- Number of Units
- X,Y Coordinate
- Estimated Sq Feet
- Total Sq Feet
Projected Growth Scenarios for Atlanta

Business As Usual
Year 2030

More Compact Development
Year 2030
Atlanta Water Demand for New Residential and Commercial Buildings in More Compact Growth Scenario (with low flow fixtures + decentralized CCHP system)

Installation of Air Cooled Microturbines save 2.8 times the amount of water used for domestic consumption.
Potential GHG and Cost Reductions in 2030

By 2030, implementation of CCHP in all new and existing residential and commercial buildings could reduce CO$_2$ emissions by ~ 0.04Gt CO$_2$, NOx emissions by ~ 25000 Tons, and decrease energy costs by $600 million per year for the Metro Atlanta region.

<table>
<thead>
<tr>
<th>CO$_2$ Emissions</th>
<th>NOx Emissions</th>
<th>Energy Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>NoCCHP</td>
<td>CCHP only</td>
<td>CCHP w/ netmet</td>
</tr>
<tr>
<td>58</td>
<td>31</td>
<td>18</td>
</tr>
<tr>
<td>-47%</td>
<td>-69%</td>
<td>-64%</td>
</tr>
</tbody>
</table>
Emergent Property: Ozone in ATL

Credit: Ted Russel
ECONOMIC ANALYSES
Can virtual water trade save water resources? Insights from production fragmentation and water scarcity

Xi Liu, College of Management and Economics, Tianjin University, Tianjin 300072, China
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Guozhu Mao*, School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China
Jian Zuo, School of Architecture & Built Environment; Entrepreneurship, Commercialisation and Innovation Centre (ECIC), The University of Adelaide, SA 5005, Australia
This section explains the methodology and is based on a country composed of $G$ regions and $N$ sectors. These regions are connected through the interregional trade of intermediate and final products, and each region is connected with the world economy through international imports and exports. The economic linkages among these regions can be described by the following equation:

$$
\begin{bmatrix}
X^1 \\
X^2 \\
\vdots \\
X^g
\end{bmatrix} =
\begin{bmatrix}
A^{11} & A^{12} & \cdots & A^{1g} \\
A^{21} & A^{22} & \cdots & A^{2g} \\
\vdots & \vdots & \ddots & \vdots \\
A^{g1} & A^{g2} & \cdots & A^{gg}
\end{bmatrix}
\begin{bmatrix}
X^1 \\
X^2 \\
\vdots \\
X^g
\end{bmatrix} +
\begin{bmatrix}
\sum_r^G Y^{1r} + EX^1 \\
\sum_r^G Y^{2r} + EX^2 \\
\vdots \\
\sum_r^G Y^{gr} + EX^g
\end{bmatrix}
$$
Virtual water flow direction: northwest, northeast, central regions to north coast and east coast; southwest, central regions to south coast.

Policy implications: virtual water trade may aggravate the water stress
Sankey diagram for the bilateral water trade in eight regions for three trade patterns