An Integrated Modeling and Decision Framework to Evaluate Adaptation Strategies for Sustainable Drinking Water Utility Management under Drought and Climate Change

advancing the science of water
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Agenda

• Water Research Foundation
• Project Motivation and Objectives
• Preliminary Results
  – Watershed Flow and Sediment Modeling
  – Mobilization and Transport of DOM and Sediments
  – Source Water Threshold and Modeling of TOC and DBP Precursors
  – Decision Tool for Evaluating Multiple Options
• Summary
WRF Background

- Research Cooperative
  — Governed by utilities
- Over $500M of research
- ~1,000 subscribers
- 50 year anniversary!
WRF Subscribers and Partners

- Number of Subscribers (980)
- Number of Partners (42)
<table>
<thead>
<tr>
<th>2016 Focus Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Key Research Topics and Programs</td>
</tr>
</tbody>
</table>

| New! Cyanobacterial Blooms and Cyanotoxins |
| Waterborne Pathogens in Distribution and Plumbing Systems |
| Intelligent Distribution Systems |
| Integrated Water Management: Planning for Future Water Supplies |
| Contaminants of Emerging Concern and Risk Communication |
| Water Utility Finances |
| Water Utility Infrastructure |
| Water Demand Forecasts and Management |
| Energy Efficiency and Integrated Water-Energy Planning |
| Biofiltration |
| NDMA and Other Nitrosamines |
Top 2015 Research Issues

**Cyanotoxins**
- **NEW** Research Focus Area
- 1<sup>st</sup> Most popular webcast
- 2<sup>nd</sup> most popular completed report downloads
- 2<sup>nd</sup> most popular topic for workshops
- 2 new projects

**Water Efficiency**
- **Existing** Research Focus Area
- 2<sup>nd</sup> most popular webcasts
- 1<sup>st</sup> Most popular topic for workshops
- 7 new projects

**Integrated Water Resources/Reuse**
- **Existing** Research Focus Area
- **Workshop** on Direct Potable Reuse
- 4 new projects
- **NEW** Knowledge Portal; another that is highly relevant
Water Research Foundation and Climate Change

• Between 2003 - 2016, 30 projects funded

• Total amount of funding
  – Foundation’s Contribution: Over $6 million
  – Total project value: Over $10 million

• Since late 1990s, the Foundation funded over 150 projects relevant to climate change
While it is safe to say that the impacts of climate change on water resources will vary widely by region, it is also relatively certain that no area will be untouched by these impacts. Potential climate change impacts on water utilities have been widely reported in publications by the Water Research Foundation.
EPA Grant - WRF’s Role

• Overall management of the project
  – Project Advisory Committee
  – Quarterly Reports
  – Final Report

• Coordinate water utility involvement

• Outreach
  – Facilitated workshops
  – Webcast
An integrated modeling and decision framework to evaluate adaptation strategies for sustainable drinking water utility management under drought and climate change

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&
Co-operative Institute for Research in Environmental Sciences (CIRES)
University of Colorado Boulder, CO
**Motivation**

Forcings

- Climate Extremes
  - Droughts/Floods
- Land cover changes
  - wildfire, bark beetle
- Regulatory Regimes

Droughts have a long term impact on drinking water quality

- Reduced streamflow $\rightarrow$ reduced dilution
- Potential for watershed fires $\rightarrow$ mobilization of DOM, metals, turbidity
- Droughts followed by floods $\rightarrow$ exacerbated water quality impacts
- Need for an integrated approach to understand the interactions

*Courtesy, drought.gov*
Current and Future Hydroclimate

- Increased frequency and severity of climate extremes – droughts, floods, heat and cold waves
- Reduction in streamflow, dilution

Courtesy, National Climate Change Assessment
• Integrated Framework for Understanding and modeling the Climate Extremes – Watershed Flow And Sediments – contaminant mobilization and Decision strategies
Objectives

• Understand flow and sediment generation from watersheds for drinking water supply
  – In particular, response to hydroclimate extremes

• Understand mobilization and transport of DOM and sediments (i.e. turbidity) through watersheds to treatment plants

• Develop source water thresholds for Turbidity and DBP precursors (TOC)
  – Regulatory constraints and Extreme Value Theory

• Evaluation suite of adaptation and operation strategies
  – Watershed management, treatment plant modification etc.
  – Social, economic and policy impacts with Multi-objective optimization and Multi-criteria Analysis
Study Watershed Selection

- Climatologically Diverse Regions
- Availability of good data
- Relationship with utilities

- Colorado Frontrange
ACTIVITY 1
WATERSHED FLOW AND SEDIMENT MODELING
Watershed Flow and Sediment Modeling

- **Motivation: Why model sediment?**

Water Quality:
- Added constituents to streams
- Increased turbidity:
  - Disinfection byproducts (DBPs)
  - Ecological impacts
    - Alters water chemistry and geomorphology of streambed
  - Reservoir management

Extreme wet event after a drought can mobilize sediment
- Higher turbidity
- Higher nutrient concentrations
- Higher dissolved organic matter (DOM)

Wildfire
- Soil hydrophobicity
- Vegetation decrease
- Buffalo Creek, CO
  - Large alluvial fan due to extreme rain event after wildfire disturbance
Watershed Flow and Sediment Modeling

• **Tasks**

Model suspended sediment flow rates in the Colorado Front Range in relation to climate change and land-cover disturbance

1. Climate Change (Drought)
2. Land-Cover Disturbance (Wildfire)

Additional considerations

1. Characterize Uncertainty (explore multiple methods)
2. Make modifications general to allow for other WQ parameters considered
Watershed Flow and Sediment Modeling

• **Methodology**

**Couple Sediment Modules within a Land Surface Model: VIC**

Variable Infiltration Capacity (VIC; Liang et al., 1994)

- 1 hour timestep
- Daily output
- 1/16° resolution
- Forcing files from Livneh et al. (2015)

• **Front Range Subbasins:**
  1. Cache La Poudre at Fort Collins, CO
  2. Clear Creek at Golden, CO
  3. North Fork of the Upper South Platte
## Watershed Flow and Sediment Modeling

### Methodology

Model Ensemble: Soil Loss Methods to be Coupled with VIC

<table>
<thead>
<tr>
<th>Method/Model</th>
<th>Method/Model Type</th>
<th>Lumped/Distributed</th>
<th>Event Based/Continuous</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monovariate Rating Curve</td>
<td>Empirical</td>
<td>Lumped</td>
<td>Continuous</td>
<td>Glysson, 1987</td>
</tr>
<tr>
<td>Multi-variate Rating Curve</td>
<td>Empirical</td>
<td>Lumped</td>
<td>Continuous</td>
<td>Gray, 2008</td>
</tr>
<tr>
<td>USLE/MUSLE</td>
<td>Empirical</td>
<td>Lumped</td>
<td>Event Based</td>
<td>Wischmeier and Smith, 1978; Renard and Ferreira, 1993</td>
</tr>
<tr>
<td>SWAT</td>
<td>Conceptual</td>
<td>Distributed</td>
<td>Continuous</td>
<td>Arnold et al., 1998</td>
</tr>
<tr>
<td>HEC-RAS</td>
<td>Conceptual</td>
<td>Lumped</td>
<td>Both</td>
<td>Brunner, 1995</td>
</tr>
<tr>
<td>WEPP</td>
<td>Physical</td>
<td>Distributed</td>
<td>Continuous</td>
<td>Nearing et al., 1989</td>
</tr>
<tr>
<td>KINEROS2</td>
<td>Physical</td>
<td>Distributed</td>
<td>Event Based</td>
<td>Smith et al., 1995</td>
</tr>
<tr>
<td>DHSVM</td>
<td>Physical</td>
<td>Distributed</td>
<td>Continuous</td>
<td>Wigmosta et al., 1994</td>
</tr>
</tbody>
</table>
Watershed Flow and Sediment Modeling

• Preliminary Results

\[ Q_s = 57.76 \times Q^{1.5025} \]

Two magnitudes of SSL for the same discharge
Requires multivariate approach

VIC rating curve simulation underestimates peak SSL
Watershed Flow and Sediment Modeling

• Future Tasks

  • Calibrate VIC streamflow
  • Implement other sediment modules (MUSLE, physically base approaches)
  • Quantify uncertainty:
    • Hourly versus daily timestep
    • Parameteric uncertainty
    • Hydrograph flow event size
  • Analyze stochastic nature of observed sediment
    • Extreme value distributions
    • Gamma, Weibull, Exponential distribution
  • Explore integrating current framework with other contaminants
ACTIVITY 2
MOBILIZATION AND TRANSPORT OF DOM AND SEDIMENTS
Motivation

• Understand the mobilization (and chemical reactivity) of DOC and sediments after watershed perturbations
  – Wildfires
  – Drought
• Approach
  – Evaluate the changes in organic carbon mobilization after drought and wildfires
  – Evaluate the necessary parameters to incorporate the effect of perturbations into water quality models
Tasks

• Laboratory burn testing to evaluate a priori the effects of wildfires on organic carbon properties and mobilization
• Evaluate the impact of drought and wildfire on sediment mobilization
• Evaluate flux of DOC from sediments
• Characterize DOM reactivity
• Assess also impact of floods on water quality
Preliminary Data

- Evaluated the changes in DOC export from soils before and after simulated wildfire
  - DOC properties
  - DBP formation potential

<table>
<thead>
<tr>
<th>Burn Severity</th>
<th>Low</th>
<th>Moderate</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Temperature</td>
<td>225</td>
<td>350</td>
<td>500</td>
</tr>
<tr>
<td>Organic Matter (OM) Changes</td>
<td>OM begins to combust</td>
<td>Enhanced OM combustion</td>
<td>Complete Combustion</td>
</tr>
</tbody>
</table>

Method adopted from (Fernandez, Cabeneiro and Carballas 1997).
## DOC Yield per Unit Mass

<table>
<thead>
<tr>
<th>Sample</th>
<th>WSOC (mg-C/mg-solid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HG Soil Unburned</td>
<td>0.37</td>
</tr>
<tr>
<td>HG Soil 225</td>
<td>0.98</td>
</tr>
<tr>
<td>HG Soil 350</td>
<td>0.62</td>
</tr>
<tr>
<td>HG Soil 500</td>
<td>0.01</td>
</tr>
<tr>
<td>PBR Soil Unburned</td>
<td>0.74</td>
</tr>
<tr>
<td>PBR Soil 225</td>
<td>1.07</td>
</tr>
<tr>
<td>PBR Soil 350</td>
<td>0.34</td>
</tr>
<tr>
<td>PBR Soil 500</td>
<td>0.01</td>
</tr>
</tbody>
</table>
## DBP Formation (50 g/LCT)

<table>
<thead>
<tr>
<th>Sample</th>
<th>HAA5 Yield (μg/mgC)</th>
<th>TTHM Yield (μg/mgC)</th>
<th>HAN Yield (μg/mgC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCT</td>
<td>2.09</td>
<td>2.99</td>
<td>3.72</td>
</tr>
<tr>
<td>HG Soil Unburned</td>
<td>83.18</td>
<td>7.44</td>
<td>1.14</td>
</tr>
<tr>
<td>HG Soil 225</td>
<td>157.8</td>
<td>120.0</td>
<td>9.43</td>
</tr>
<tr>
<td>HG Soil 350</td>
<td>57.71</td>
<td>23.20</td>
<td>7.11</td>
</tr>
<tr>
<td>HG Soil 500</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PBR Soil Unburned</td>
<td>97.61</td>
<td>38.85</td>
<td>2.79</td>
</tr>
<tr>
<td>PBR Soil 225</td>
<td>152.5</td>
<td>74.77</td>
<td>14.87</td>
</tr>
<tr>
<td>PBR Soil 350</td>
<td>78.76</td>
<td>23.76</td>
<td>14.78</td>
</tr>
<tr>
<td>PBR Soil 500</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Ultrahigh resolution mass spectrometry

• National High Magnetic Field Laboratory in Tallahassee, FL
• Use a solid phase extraction method to separate DOM from inorganic compounds
• Determine molecular formulas for all ionizable compounds in solution
  – CHO
  – CHON
• Better understand precursors for N-DBP formation that are exported from fire impacted locations
(-) ESI FT-ICR MS
HG Soil (100g/2L)

% Relative Abundance

Heteroatom Class

Unburned
225
350

N1O2 N1O4 N1O6 N1O8 N1O10 N1O12 N1O14 N1O16 N1O18 N1O20 N1O22 N1O24 N1O26
Future Tasks

• Sampling of CLP watershed
• Characterization of the mobilization of DOC
• Characterization of sediment mobilization parameters
• Coupling with model from Activity 1
ACTIVITY 3
SOURCE WATER THRESHOLD AND MODELING OF TOC AND DBP PRECURSORS
Motivation

• Source water TOC is an important constituent in DBP formation
• Streamflow is a key variable in modeling TOC
  – Data difficult to get
  –
• **We Hypothesize** - Climate and land surface variables can be used to directly model source water TOC concentrations.
• This has significant implications
  – Obviates the need for streamflow
  – Enables projection of TOC concentrations at short (seasonal) and long (multi-decades) time scales, from climate forcings
  – Samson et al. (ES&T, 2016, in press)
# Land and Climate Predictors of TOC

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Precipitation</th>
<th>Palmer Drought Severity Index (PDSI)</th>
<th>Normalized Difference Vegetation Index (NDVI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T7D = 7 day average temperature prior to TOC reading</td>
<td>P7D = 7 day total precipitation prior to TOC reading</td>
<td>PDS1M = PDSI monthly mean, one month prior to TOC reading</td>
<td>NDVI = NDVI at the time of the TOC reading</td>
</tr>
<tr>
<td>T15D = 15 day average temperature prior to TOC reading</td>
<td>P15D = 15 day total precipitation prior to TOC reading</td>
<td>PDS12M = PDSI monthly mean, two months prior to TOC reading</td>
<td>NDVI1M = NDVI one month prior to TOC reading</td>
</tr>
<tr>
<td>T30D = 30 day average temperature prior to TOC reading</td>
<td>P30D = 30 day total precipitation prior to TOC reading</td>
<td>PDS13M = PDSI monthly mean, three months prior to TOC reading</td>
<td>NDVI2M = NDVI two months prior to TOC reading</td>
</tr>
<tr>
<td>T30D1M = 30 day average temperature prior to TOC reading, 1 month lag</td>
<td>ddweek = number of dry days in the week prior to TOC reading</td>
<td></td>
<td>NDVI3M = NDVI three months prior to TOC reading</td>
</tr>
<tr>
<td>T30D2M = 30 day average temperature prior to TOC reading, 2 month lag</td>
<td>ddmonth = number of dry days in the month prior to TOC reading</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T30D3M = 30 day average temperature prior to TOC reading, 3 month lag</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Local Polynomial Model:**

![Local Polynomial Model](image)

\[ Y = \mu(X) + \varepsilon \]

\[ Y_i = \mu(x_i) + \varepsilon_i \]

(Loader, 1999)
### TOC – Case Studies

<table>
<thead>
<tr>
<th>Case Studies</th>
<th>Predictor Variables</th>
<th>Link function</th>
<th>Alpha (α)</th>
<th>p (degree)</th>
<th>gcv score</th>
<th>NSE statistic</th>
<th>Hypothesis test p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harwood’s Mill WTP, Newport News, VA</td>
<td>- T30D3M - P7D - Previous TOC concentration (lag 1)</td>
<td>Log</td>
<td>0.97</td>
<td>2</td>
<td>0.004</td>
<td>0.92</td>
<td>9.79e-06</td>
</tr>
<tr>
<td>Miller WTP, Cincinnati, OH</td>
<td><strong>Base Model:</strong> - T30D2M - PDSI1M</td>
<td>Inverse</td>
<td>0.11</td>
<td>1</td>
<td>0.030</td>
<td>0.51 (for additive model)</td>
<td>2.77e-08</td>
</tr>
<tr>
<td></td>
<td><strong>Residual Model:</strong> - NDVI1M</td>
<td>Identity (Gaussian family)</td>
<td>0.06</td>
<td>1</td>
<td>0.179</td>
<td></td>
<td>1.94e-04</td>
</tr>
<tr>
<td>Betasso WTP, Boulder, CO</td>
<td>April and May - T15D - PDSI1M - PDSI3M</td>
<td>Inverse</td>
<td>0.35</td>
<td>1</td>
<td>0.069</td>
<td>0.82</td>
<td>0.0367</td>
</tr>
<tr>
<td></td>
<td>June and July - T30D1M - P30D - PDSI1M</td>
<td>Log</td>
<td>0.60</td>
<td>1</td>
<td>0.057</td>
<td>0.75</td>
<td>0.0576</td>
</tr>
</tbody>
</table>

**Boulder, CO (Betasso WTP):** Significant influence of snowmelt; very high organic matter peaks in spring months
Representative Results

Harwood Mill, OH

Battaso Plant, Boulder, CO
Future Tasks

- Model threshold exceedances using Extreme Value Theory

- Future projections of TOC using climate projections and land use changes

- Develop models for Turbidity as a function of sediments

- Explore relationships with other DBP precursors
ACTIVITY 4
DECISION TOOL FOR EVALUATING MULTIPLE OPTIONS
Motivation

• What changes do **extreme events have on water quality**?
• What **entities** are impacted by changes in water quality?
• How **severe** are the consequences for treatment plants?
• What **decisions** can be made to mitigate these problems?
• At what **scale (large vs. small)** can/should treatment plants consider these impacts?
Motivation

- Water Research Foundation study on water treatment plant response to extreme events
  - 46 major water treatment plants in US and Australia
  - Surveyed costs related to extreme events
  - Top concern for utilities: risk assessment planning and procedures

<table>
<thead>
<tr>
<th></th>
<th>Immediate</th>
<th>Future</th>
<th>Per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Responses</td>
<td>23</td>
<td>18</td>
<td>5</td>
</tr>
<tr>
<td>Median</td>
<td>$353,000</td>
<td>$10,000,000</td>
<td>$61,000</td>
</tr>
<tr>
<td>Average</td>
<td>$58,900,000</td>
<td>$181,000,000</td>
<td>$295,000</td>
</tr>
<tr>
<td>Minimum</td>
<td>$1,000</td>
<td>$52,000</td>
<td>$10,000</td>
</tr>
<tr>
<td>Maximum</td>
<td>$1,200,000,000</td>
<td>$3,000,000,000</td>
<td>$1,000,000</td>
</tr>
</tbody>
</table>

* Costs of US Dollar and the Australian Dollar were approximately equal at the time of writing

Stanford and Wright (2014)
Tasks

1. Information to Inform Decision Making
   – Feedback on treatment challenges associated with source water quality
   – Buy-in from partner utilities through collaboration with Water Research Foundation

2. Optimization to generate alternatives
   – Simulation models coupled with powerful search tools
   – Contributes a set of solutions that balance objectives

3. Follow-up workshop
   – Study how the science can best be used to inform decision making
Review of Decision Support Systems (DSS) for Water Treatment

- Invited to emerging investigators series of *Environmental Science: Water Research and Technology*
- Review existing DSS
- Recommendations for including multiple objectives, climate change and extremes, and robustness concepts

1. Determine stakeholders, decision makers, and modelers
   - Managers
   - Operators
   - Government Officials
   - Modelers

2. Define problem formulation and data
   - Decision Variables (D)
   - Objectives (O)
   - Constraints (C)
   - Data (X)
   - Infrastructure operations (D_{inf})
   - Operations (D_{op})
   - Minimize cost (O_{cost})
   - Maximize effluent quality (O_{eff})
   - Budgets (C_{cost})
   - Regulations (C_{raw})
   - Raw water quality (X_{raw})

3. Select appropriate model
   - Coupled-Component Model: combination of ≥ 2 models below
     - Bayesian Network
     - Knowledge-Based System
     - Process-Based Model
     - Minimize O_{cost} = f(D) (1)
     - Maximize O_{eff} = f(D,X_{raw}) (2)
     - Subject to:
       - O_{cost} ≤ C_{cost} (3)
       - O_{eff} ≤ C_{perf} (4)
       - D_{inf}, D_{op} ≥ 0 (5)

4. Make decision (or repeat 1-3)
   - If multi-objective, need additional input from stakeholders to make decision
Factors for our DSS

Impact of Extreme Events of Source Water Quality
- Extreme Precipitation and Flooding
  - Bacteria
  - Organic Carbon
  - Turbidity
- Wildfire
  - Nutrients
  - Metals
  - Organic Carbon
  - Turbidity
- Drought
  - Temperature
  - Bacteria
  - Metals
  - Organic Carbon
  - Algae

Impact of Extreme Events on Drinking Water Quality
- Cost
- Pathogens
- Disinfection Byproducts (DBPs)
- Water Treatment Plant
- Health Risk
- Algal Toxins
DSS Methodology: Simulation-Optimization

Multiobjective Evolutionary Algorithm (MOEA) search

Constraints
limits of acceptable performance
\[ f_1 < n_1, f_2 < n_2, f_3 > n_3 \]

Decision Levers
management and infrastructure options
\[ x_1, x_2, x_3 \]

Simulation Model

Water Quality and Climate Scenarios

Objectives
measurements of system performance
\[ f_1, f_2, f_3 \]

Simulation Outputs

Simulation Model

Water Quality and Climate Scenarios

Constraints
limits of acceptable performance
\[ f_1 < n_1, f_2 < n_2, f_3 > n_3 \]

Decision Levers
management and infrastructure options
\[ x_1, x_2, x_3 \]

Simulation Model

Water Quality and Climate Scenarios

Objectives
measurements of system performance
\[ f_1, f_2, f_3 \]

Simulation Outputs
Summary

• Identified Study Watersheds

• Preliminary modeling of Sediments and streamflow

• Developed preliminary thresholds for TOC and DBPs
  – Modeling them using climate variables

• Literature review of decision strategies in water utility context
Thank you!!

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WRF - Climate Change Research

- Identifying and Developing Climate Change Resources for Water Utilities: Content for Central Knowledge Repository Website
- Climate Change Impacts on the Regulatory Landscape: Evaluating Opportunities for Regulatory Change
- Vulnerability Assessment and Associated Risk Management Tools for Climate Change: Helping Water Utilities Assess Potential Impacts and Select Adaptation Options
- Impacts of Underground Carbon Geological Sequestration on the Water Quality of Groundwater
- Analysis of Changes in Water Use Under Regional Climate Change Scenarios
- Developing a New Approach to Planning and Design of Water Assets to Ensure Sustainability Under Climate Change
WRF - Climate Change Research

- Analysis Of Reservoir Operations Under Climate Change
- Groundwater Sustainability Under Climate Change
- Drinking Water Pump Station Design And Operation For Maximum Life Cycle Energy Efficiency
- Water Quality Impacts Of Extreme Weather-Related Events
- Responding to Climate Change by Applying Adaptive Management Techniques to Infrastructure Management
- Water Footprint/Value of Water
- Impact of Climate Change on the Ecology of Algal Blooms
- Effective Communication of Climate Change Effects to Stakeholders
- Managing Drought: Learning from Australia