Water Research Foundation®

Celebrating 50 Years 1966–2016

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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advancing the science of water

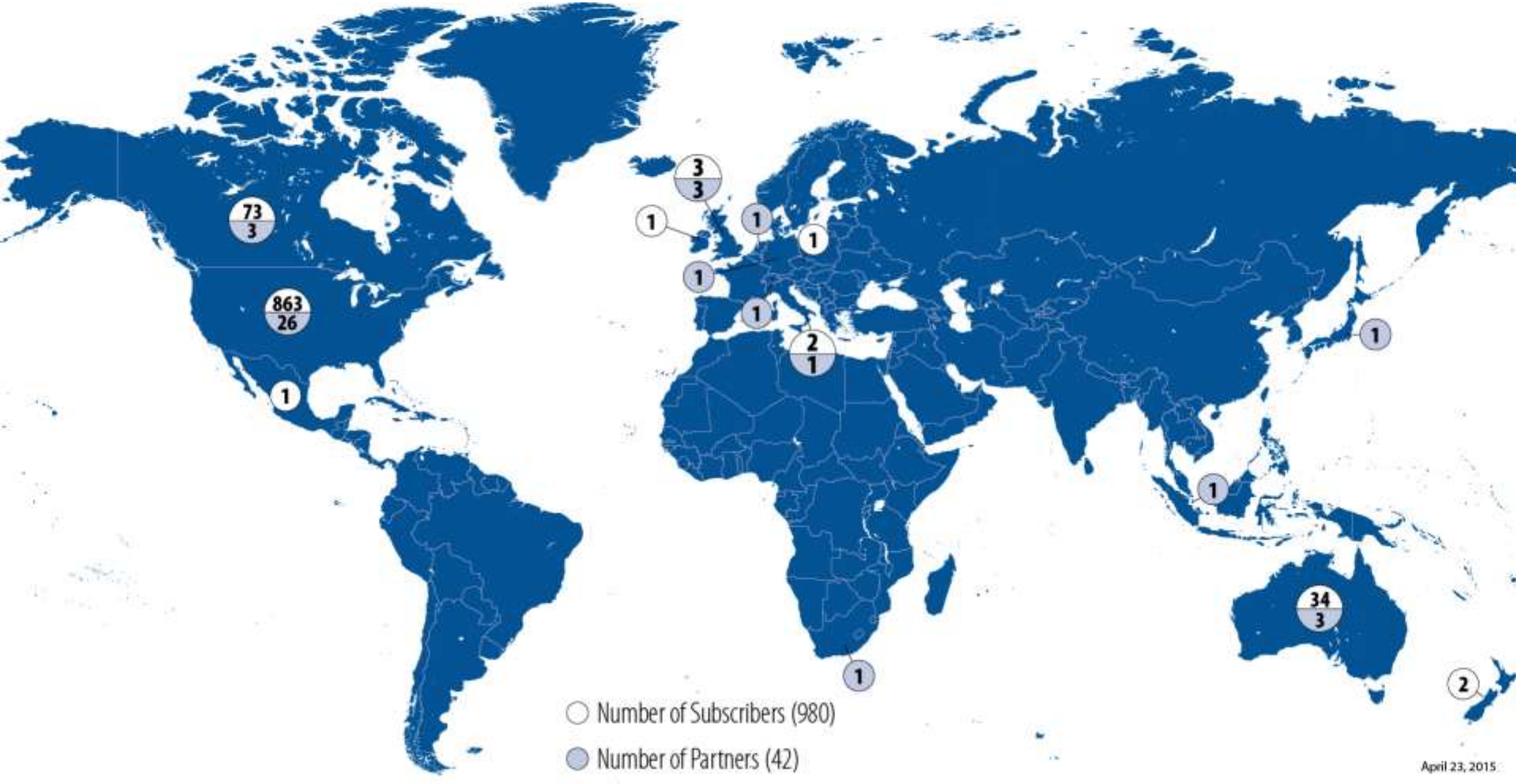
Agenda

- 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



2016 Focus Areas
Key Research Topics and Programs

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
- **1st Most popular** webcast
- **2nd most popular** completed report downloads
- **2nd most popular** topic for workshops
- **2 new** projects

Water Efficiency

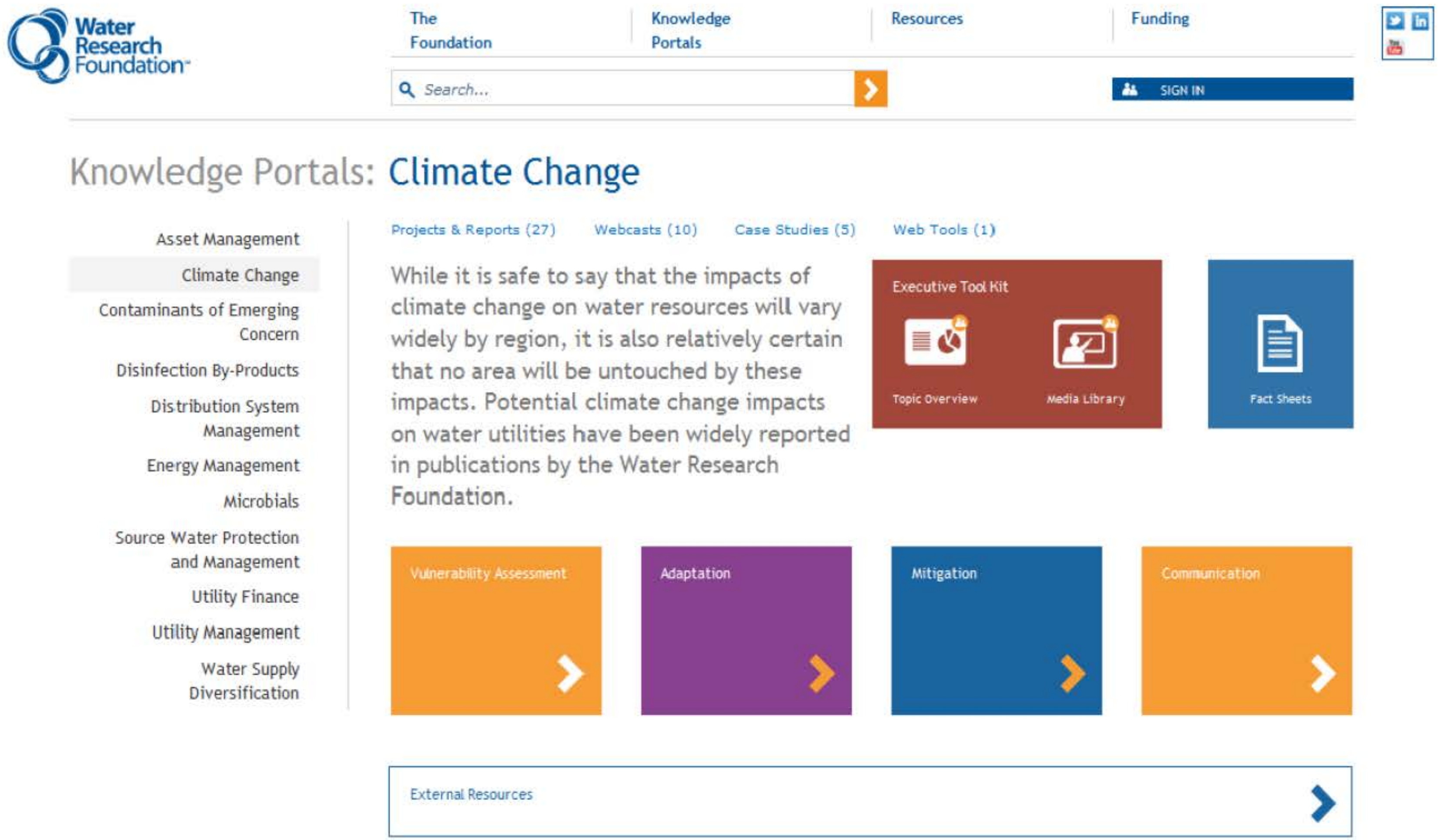
- **Existing** Research Focus Area
- **2nd most popular** webcasts
- **1st Most popular** topic for workshops
- **7 new** projects

Integrated Water Resources/Reuse

- **Existing** Research Focus Area
- **Workshop** on Direct Potable Reuse
- **4 new** projects
- **NEW** Knowledge Portal; another that is highly relevan

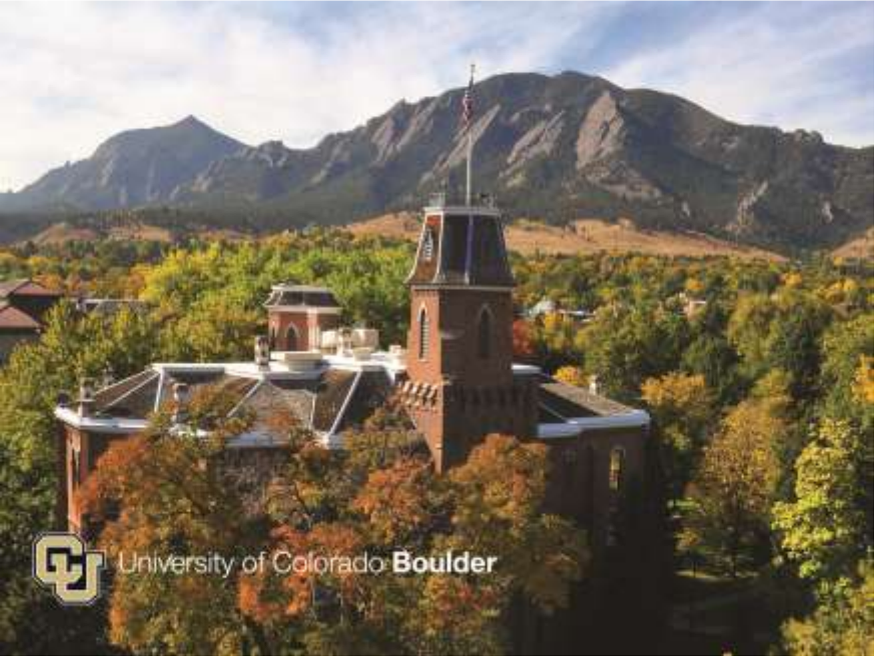
Water Research Foundation and Climate Change

- 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


Water Research Foundation
The Foundation
Knowledge Portals
Resources
Funding
Search...
SIGN IN
Knowledge Portals: Climate Change
Asset Management
Climate Change
Contaminants of Emerging Concern
Disinfection By-Products
Distribution System Management
Energy Management
Microbials
Source Water Protection and Management
Utility Finance
Utility Management
Water Supply Diversification
Projects & Reports (27)
Webcasts (10)
Case Studies (5)
Web Tools (1)
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.
Executive Tool Kit
Topic Overview
Media Library
Fact Sheets
Vulnerability Assessment
Adaptation
Mitigation
Communication
External Resources

EPA Grant - WRF's Role

- Overall management of the project
  - Project Advisory Committee
  - Quarterly Reports
  - Final Report
- Coordinate water utility involvement
  - Denver Water, Knoxville Utilities Board, Louisville Water Company, City of Tucson, El Paso Water Utilities, Albuquerque Water Utility, City of Austin, City of Houston, City of Sacramento, and Southern Nevada Water Authority.
- 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

Investigators:
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Joseph Kasprzyk
Ben Livneh
Fernando Rosario-Ortiz
Scott Summers

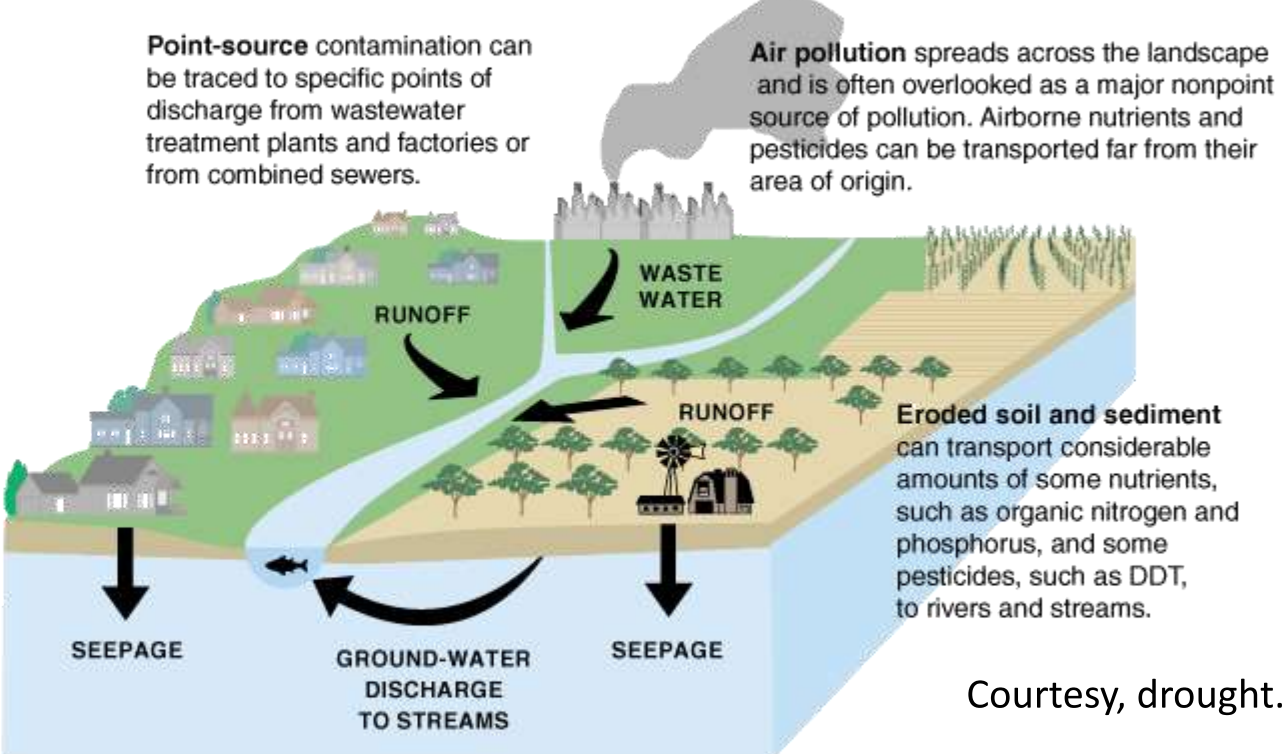
Grant Kickoff Meeting
Mar 30, 2016, Denver, CO

Department of Civil, Environmental and Architectural Engineering (CEAE)
&
Co-operative Institute for Research in Environmental Sciences (CIRES)
University of Colorado
Boulder, CO

CIRES

Water Research Foundation

Motivation



Courtesy, drought.gov

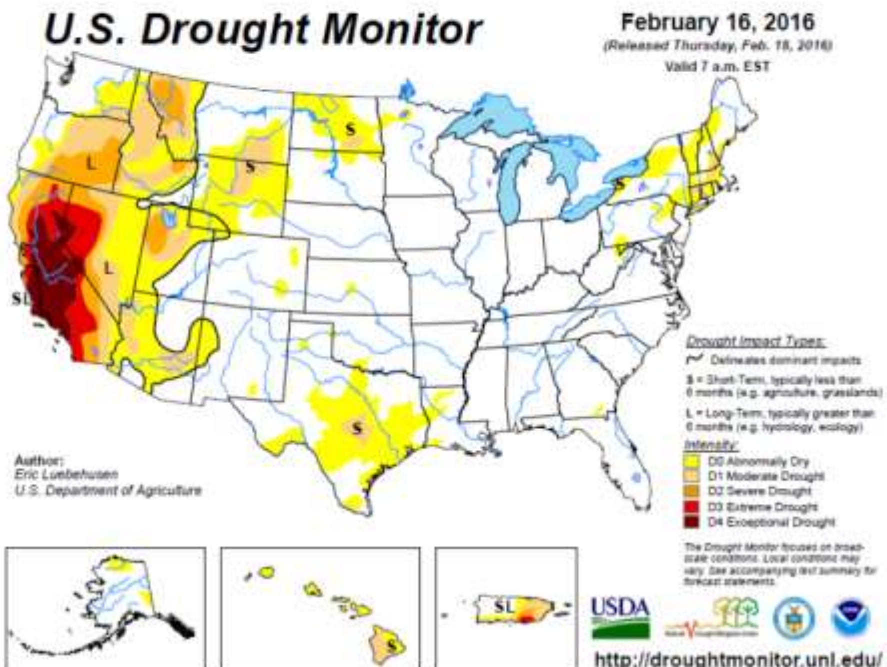
Forcings

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

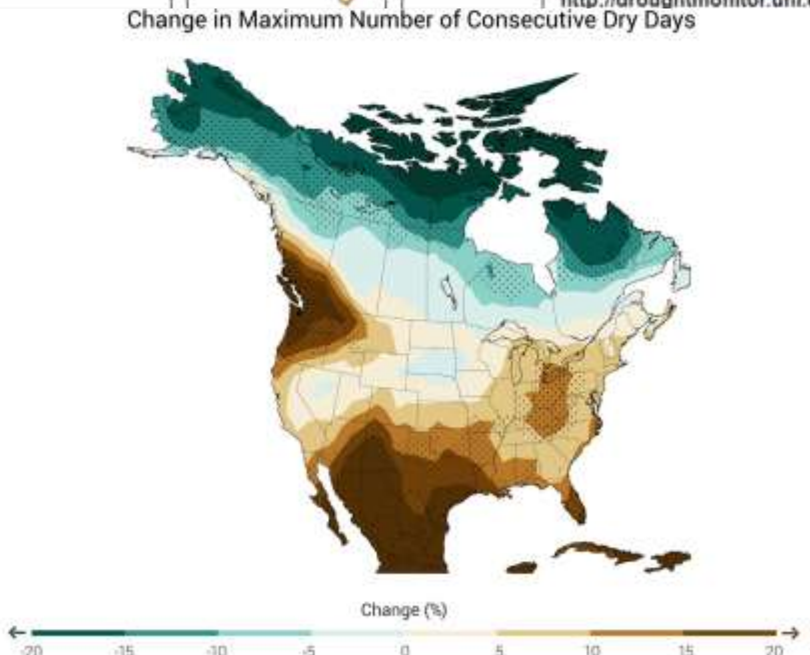
Droughts have a long term impact on drinking water quality

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

Current and Future Hydroclimate



Courtesy, National Climate Change Assessment

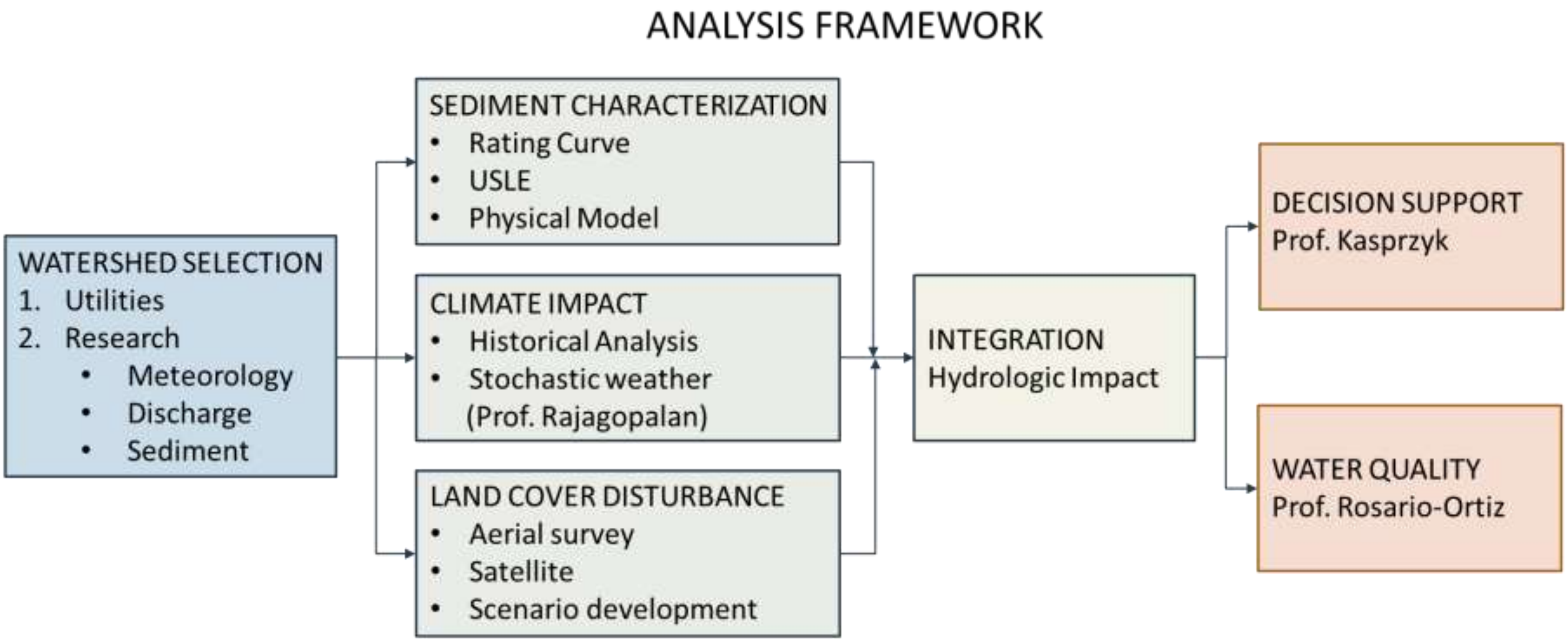


- Increased frequency and severity

Of climate extremes – droughts,
floods,

Heat and cold waves

- Reduction in streamflow, dilution



- 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

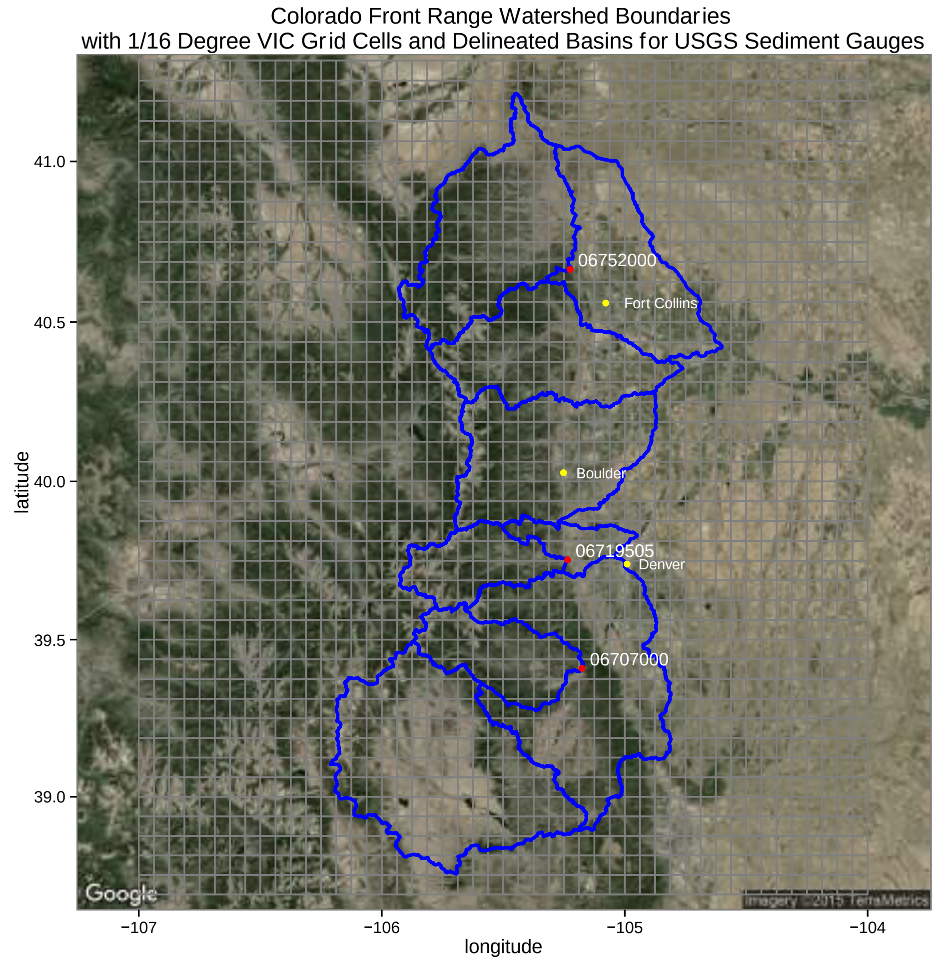
- Develop source water thresholds for *Turbidity and DBP precursors (TOC)*
  - Regulatory constraints and Extreme Value Theory

- 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

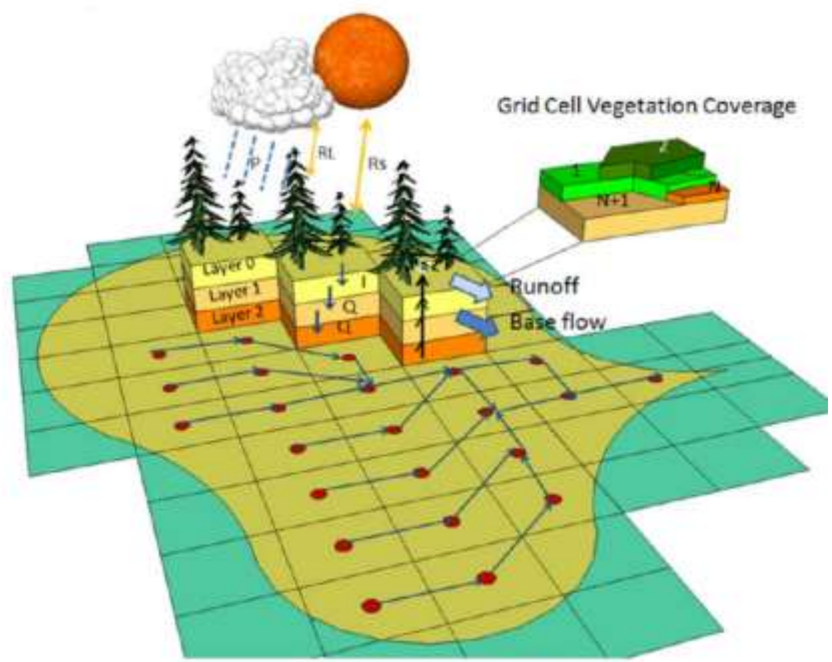
Watershed Flow and Sediment Modeling

- 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 Pouder at Fort Collins, CO**
2. **Clear Creek at Golden, CO**
3. **North Fork of the Upper South Platte**

Watershed Flow and Sediment Modeling

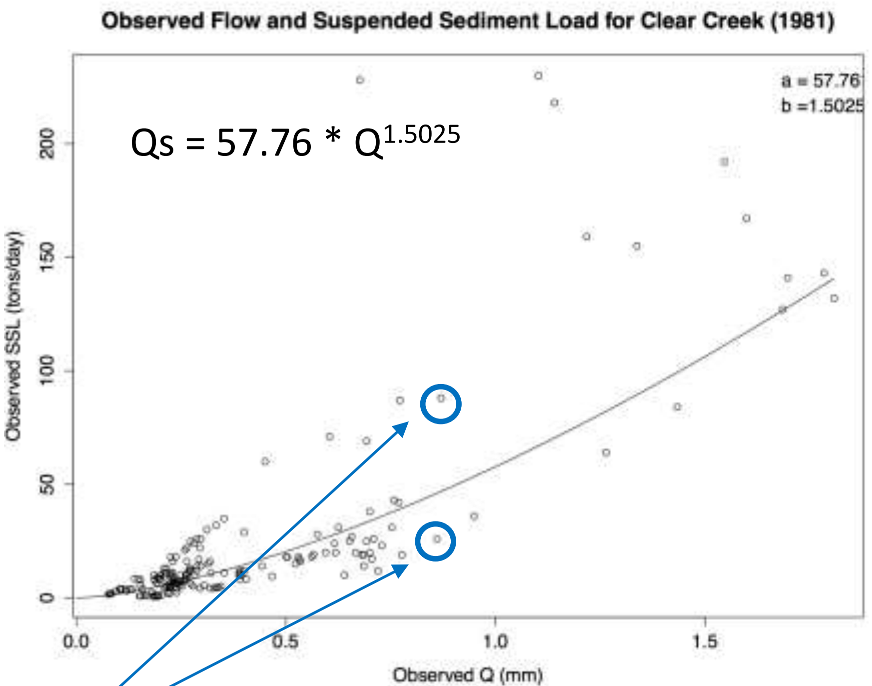
- Methodology

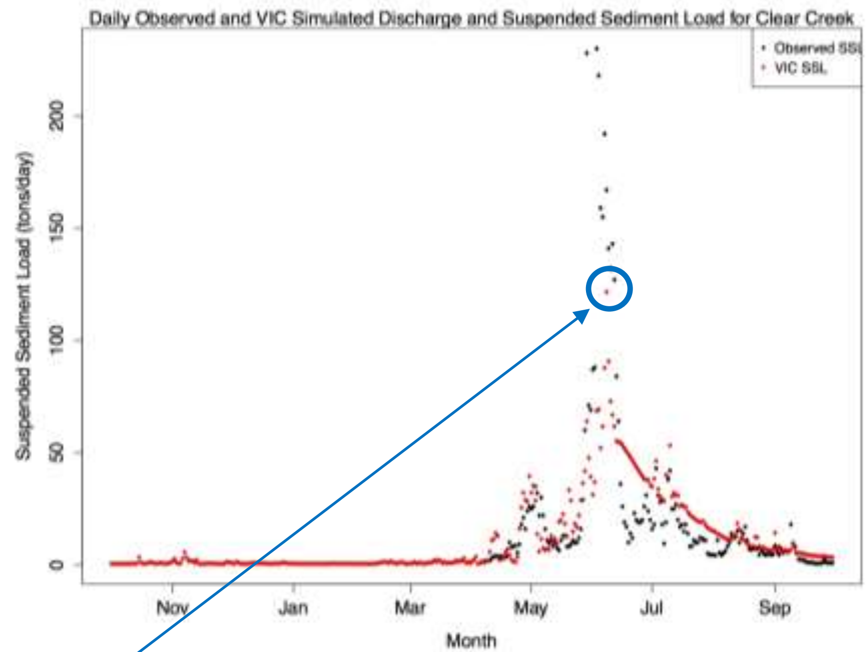
Model Ensemble: Soil Loss Methods to be Coupled with VIC

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

Watershed Flow and Sediment Modeling

- Preliminary Results





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 streamfflow
- 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

Burn Severity	Low	Moderate	High
Peak Temperature	225	350	500
Organic Matter (OM) Changes	OM begins to combust	Enhanced OM combustion	Complete Combustion

Method adopted from (Fernandez, Cabeneiro and Carballas 1997).

DOC Yield per Unit Mass

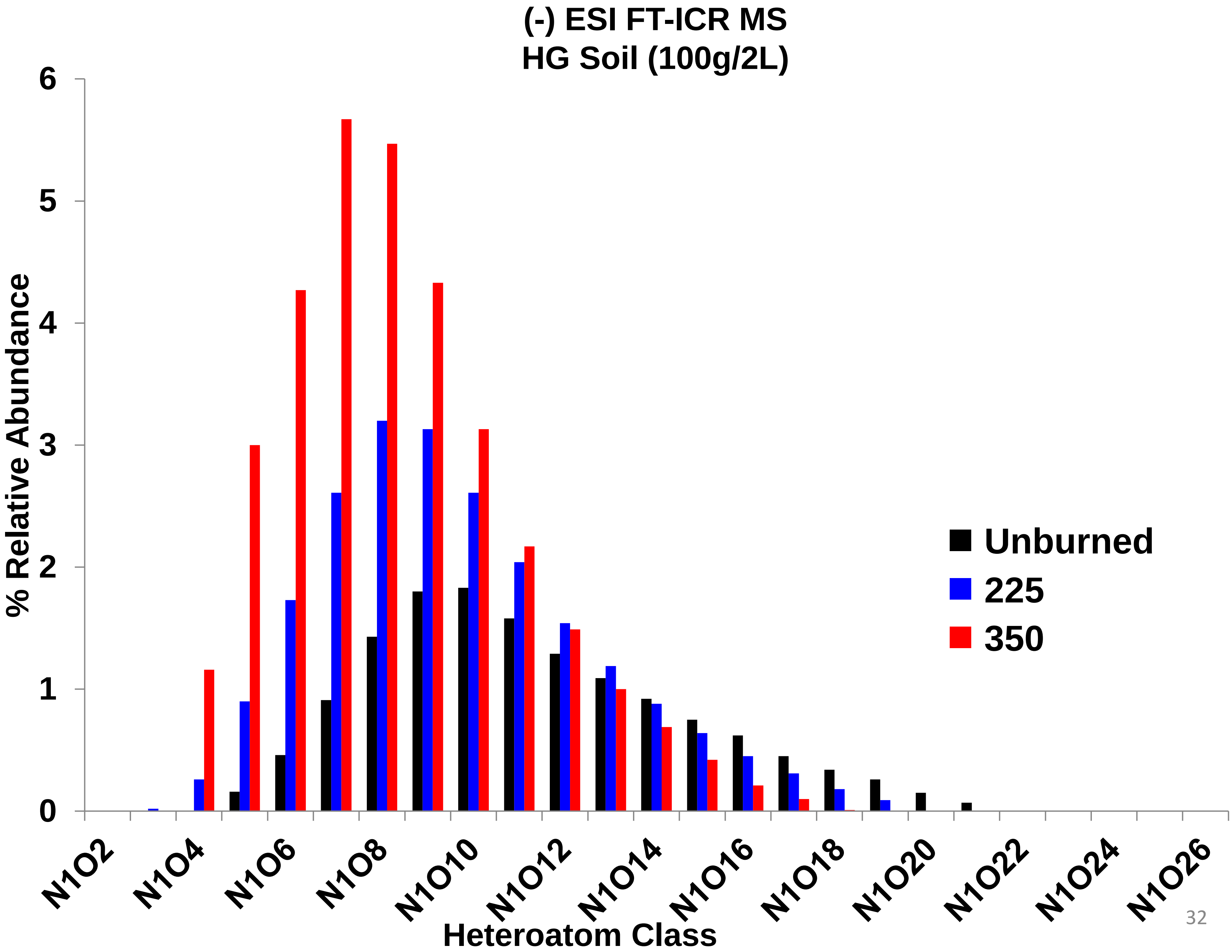
Sample	WSOC (mg-C/mg-solid)
HG Soil Unburned	0.37
HG Soil 225	0.98
HG Soil 350	0.62
HG Soil 500	0.01
PBR Soil Unburned	0.74
PBR Soil 225	1.07
PBR Soil 350	0.34
PBR Soil 500	0.01

DBP Formation (50 g/LCT)

Sample	HAA5 Yield (μg/mgC)	TTHM Yield (μg/mgC)	HAN Yield (μg/mgC)
LCT	2.09	2.99	3.72
HG Soil Unburned	83.18	7.44	1.14
HG Soil 225	157.8	120.0	9.43
HG Soil 350	57.71	23.20	7.11
HG Soil 500	-	-	-
PBR Soil Unburned	97.61	38.85	2.79
PBR Soil 225	152.5	74.77	14.87
PBR Soil 350	78.76	23.76	14.78
PBR Soil 500	-	-	-

Ultrahigh resolution mass spectrometry

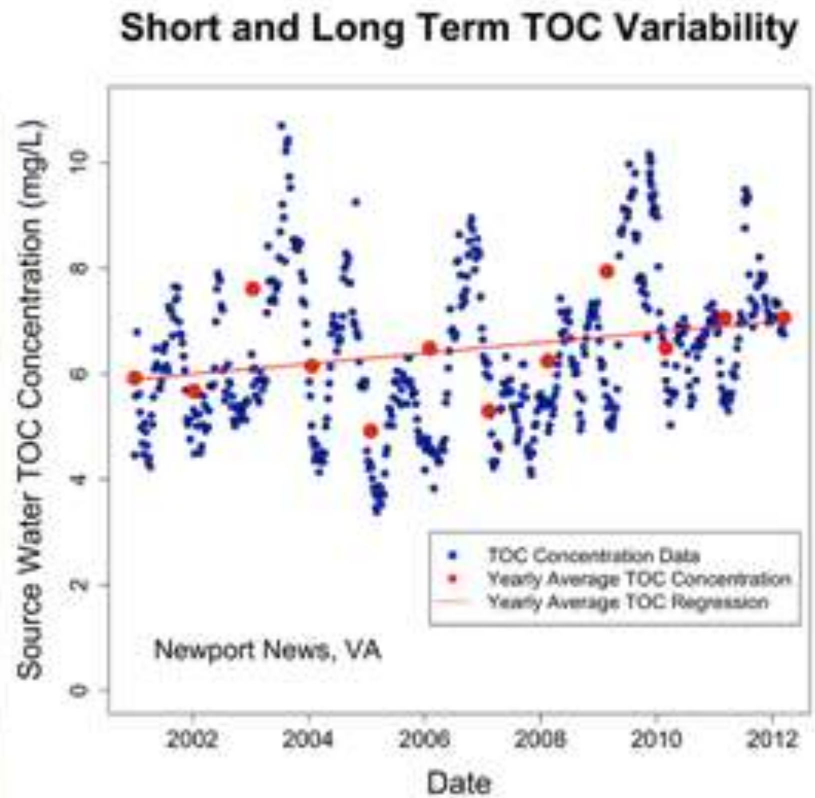
- National High Magnetic Field Laboratory in Tallahassee, FL
- Use a solid phase extraction method to separate DOM from inorganic compounds
- Determine molecular formulas for all ionizable compounds in solution
  - CHO
  - CHON
- Better understand precursors for N-DBP formation that are exported from fire impacted locations


(-) ESI FT-ICR MS
HG Soil (100g/2L)
% Relative Abundance
0
1
2
3
4
5
6
Unburned
225
350
N1O2
N1O4
N1O6
N1O8
N1O10
N1O12
N1O14
N1O16
N1O18
N1O20
N1O22
N1O24
N1O26
Heteroatom Class

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

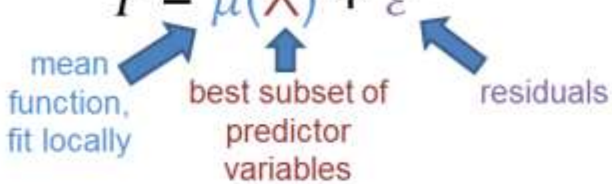
- Source water TOC is an important constituent in DBP formation
- Streamflow is a key variable in modeling TOC
  - Data difficult to get
  -
- **We Hypothesize** - Climate and land surface variables can be used to directly model source water TOC concentrations.
- This has significant implications
  - 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

Temperature	Precipitation	Palmer Drought Severity Index (PDSI)	Normalized Difference Vegetation Index (NDVI)
T7D = 7 day average temperature prior to TOC reading	P7D = 7 day total precipitation prior to TOC reading	PDSI1M = PSDI monthly mean, one month prior to TOC reading	NDVI = NDVI at the time of the TOC reading
T15D = 15 day average temperature prior to TOC reading	P15D = 15 day total precipitation prior to TOC reading	PDSI2M = PSDI monthly mean, two months prior to TOC reading	NDVI1M = NDVI one month prior to TOC reading
T30D = 30 day average temperature prior to TOC reading	P30D = 30 day total precipitation prior to TOC reading	PDSI3M = PSDI monthly mean, three months prior to TOC reading	NDVI2M = NDVI two months prior to TOC reading
T30D1M = 30 day average temperature prior to TOC reading, 1 month lag	ddweek = number of dry days in the week prior to TOC reading		NDVI3M = NDVI three months prior to TOC reading
T30D2M = 30 day average temperature prior to TOC reading, 2 month lag	ddmonth = number of dry days in the month prior to TOC reading		
T30D3M = 30 day average temperature prior to TOC reading, 3 month lag			

- Local Polynomial Model:

$$Y = \mu(X) + \varepsilon$$



$$Y_i = \mu(x_i) + \varepsilon_i$$

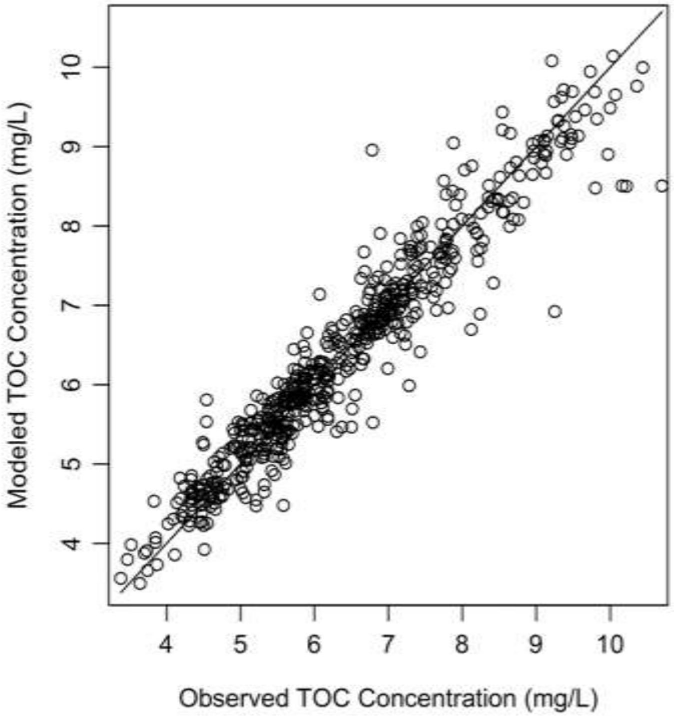
(Loader, 1999)

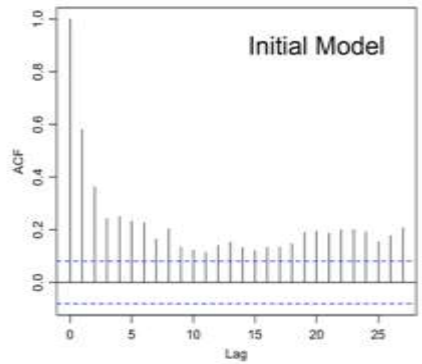
TOC – Case Studies

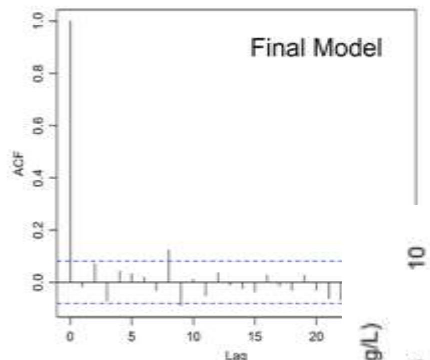
Case Studies		Predictor Variables	Link function	Alpha (α)	p (degree)	gcv score	NSE statistic	Hypothesis test p-value
Harwood's Mill WTP, Newport News, VA		- T30D3M - P7D - Previous TOC concentration (lag 1)	Log	0.97	2	0.004	0.92	9.79e-06
Miller WTP, Cincinnati, OH		**Base Model:** - T30D2M - PDSI1M	Inverse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

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

Representative Results

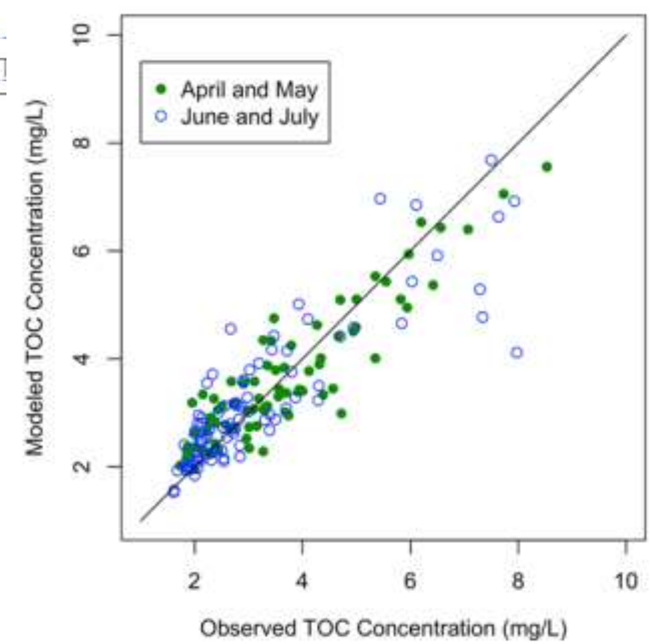






Harwood Mill, OH

Battaso Plant, Boulder, CO



Future Tasks

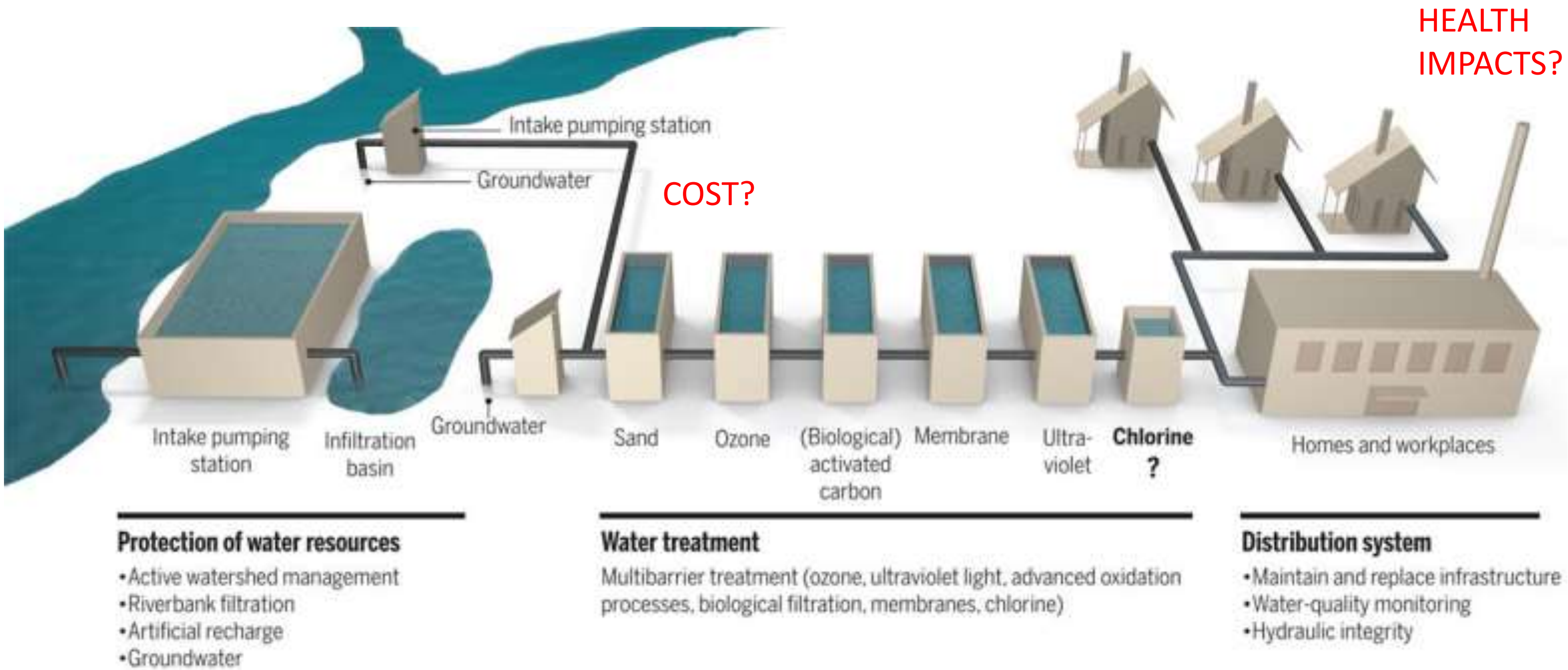
- Model threshold exceedances using Extreme Value Theory
- Future projections of TOC using climate projections and land use changes
- Develop models for Turbidity as a function of sediments
- Explore relationships with other DBP precursors

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 ES-1: Extreme Weather-Related Event Response, Adaptation Costs*

	Immediate	Future	Per year
Number of Responses	23	18	5
Median	$353,000	$10,000,000	$61,000
Average	$58,900,000	$181,000,000	$295,000
Minimum	$1,000	$52,000	$10,000
Maximum	$1,200,000,000	$3,000,000,000	$1,000,000

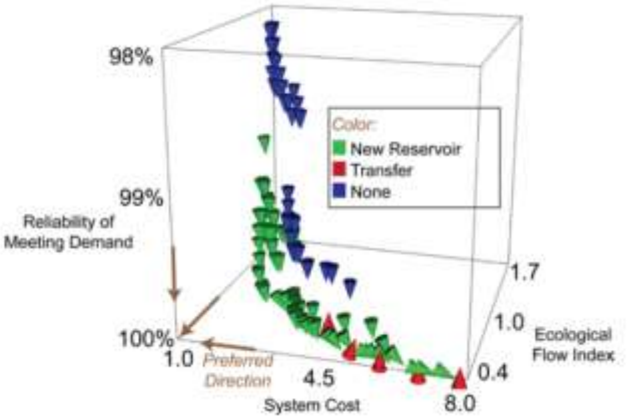
* Costs of US Dollar and the Australian Dollar were approximately equal at the time of writing

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

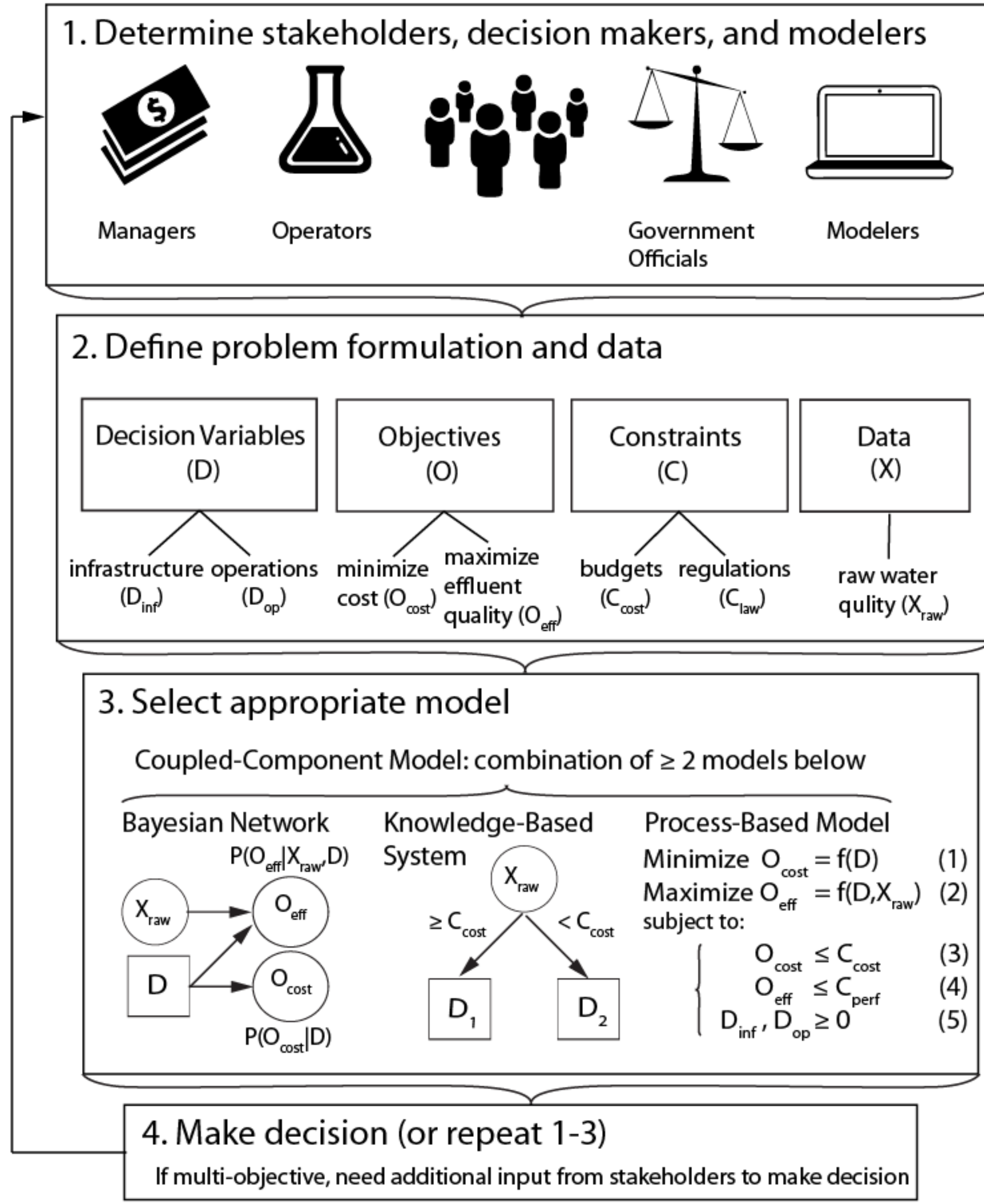
Workshop with stakeholders



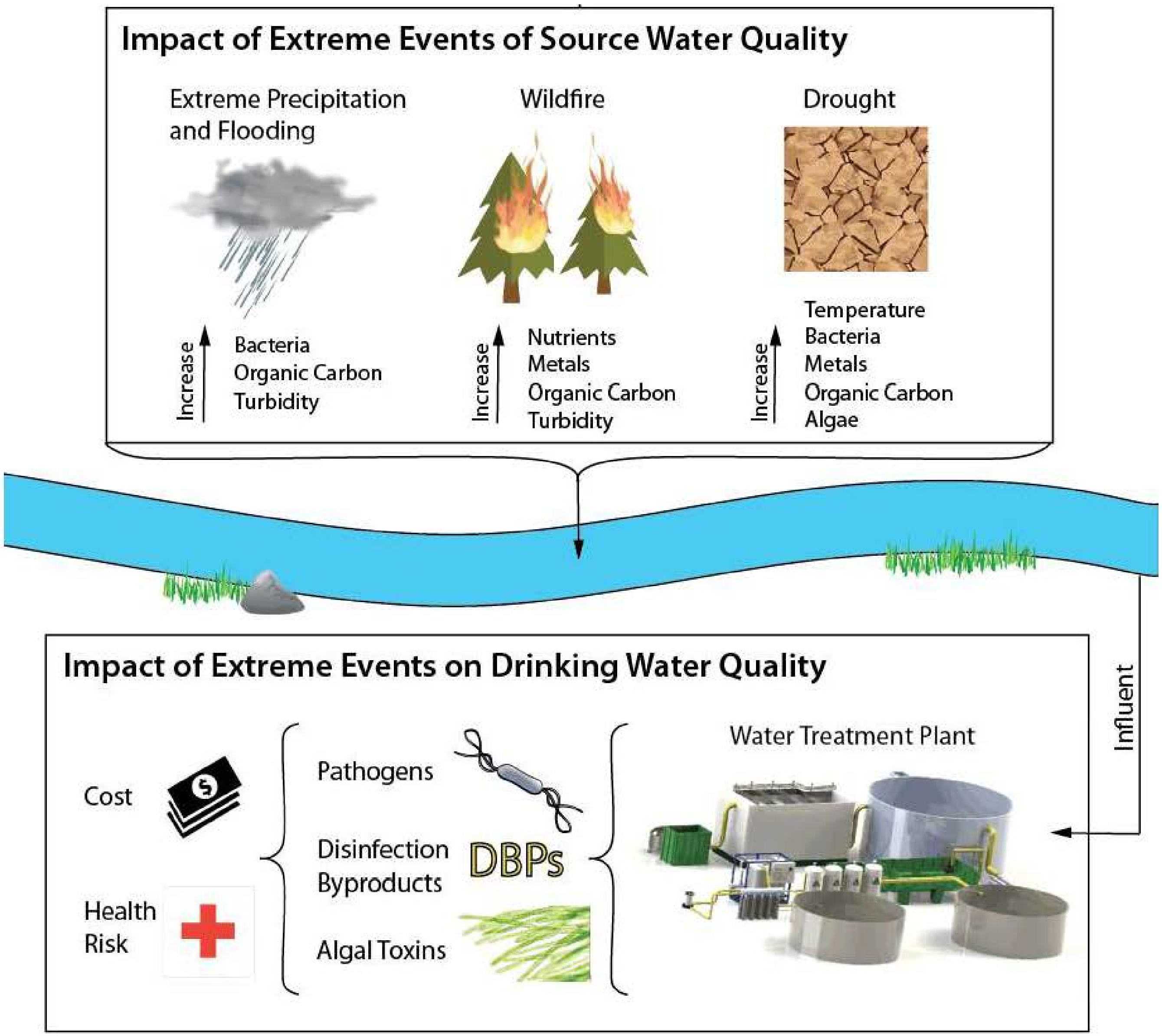
Tradeoff example for water supply planning

Review of Decision Support Systems (DSS) for Water Treatment

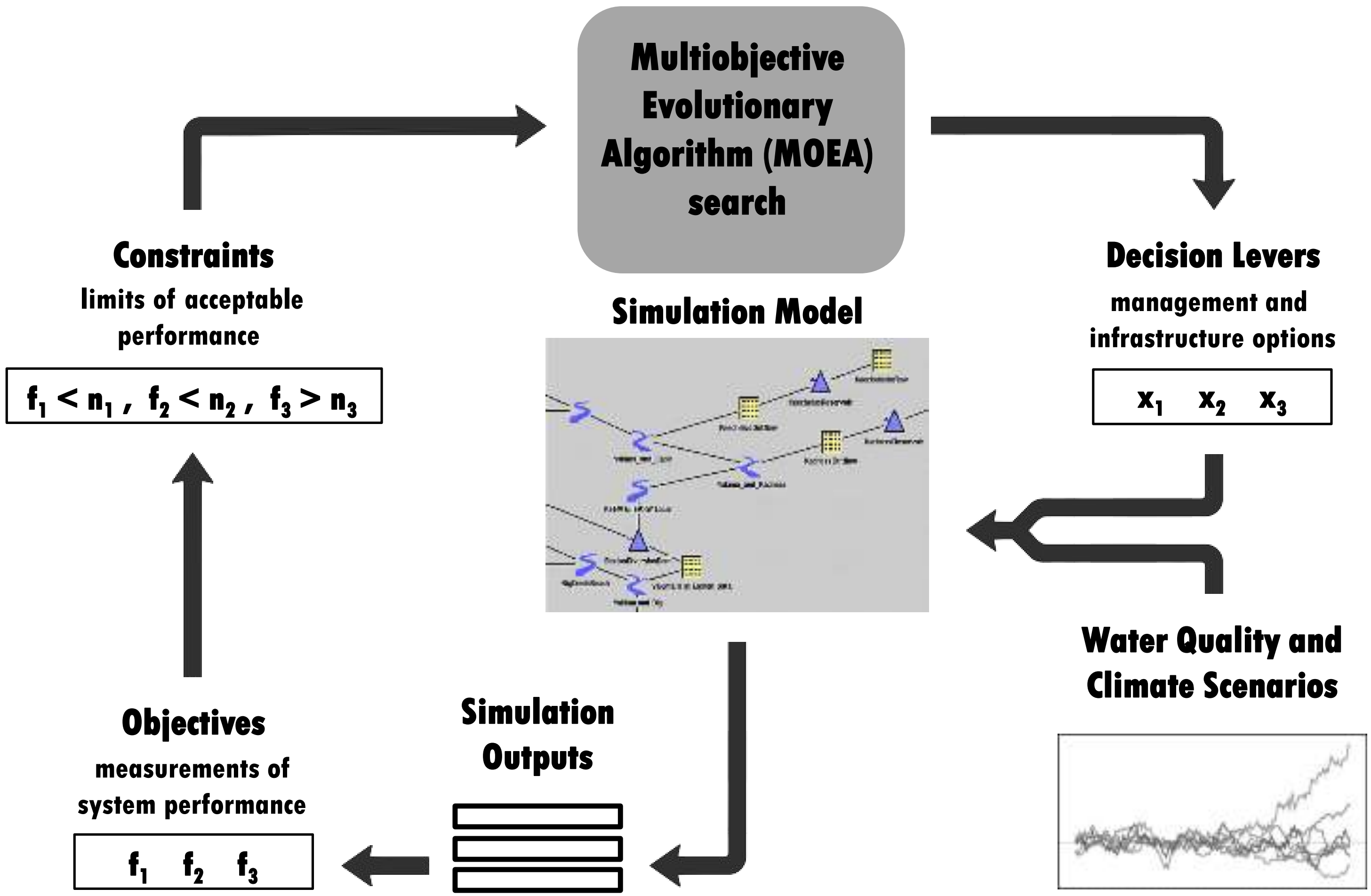
- Invited to emerging investigators series of *Environmental Science: Water Research and Technology*
- Review existing DSS
- Recommendations for including multiple objectives, climate change and extremes, and robustness concepts



Factors for our DSS



DSS Methodology: Simulation-Optimization



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

Water Research Foundation®
Celebrating 50 Years
1966–2016

Thank you!!

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advancing the science of water

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