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A Nexus Approach to Systems Resilience

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UT-Austin INFEWS Seminar

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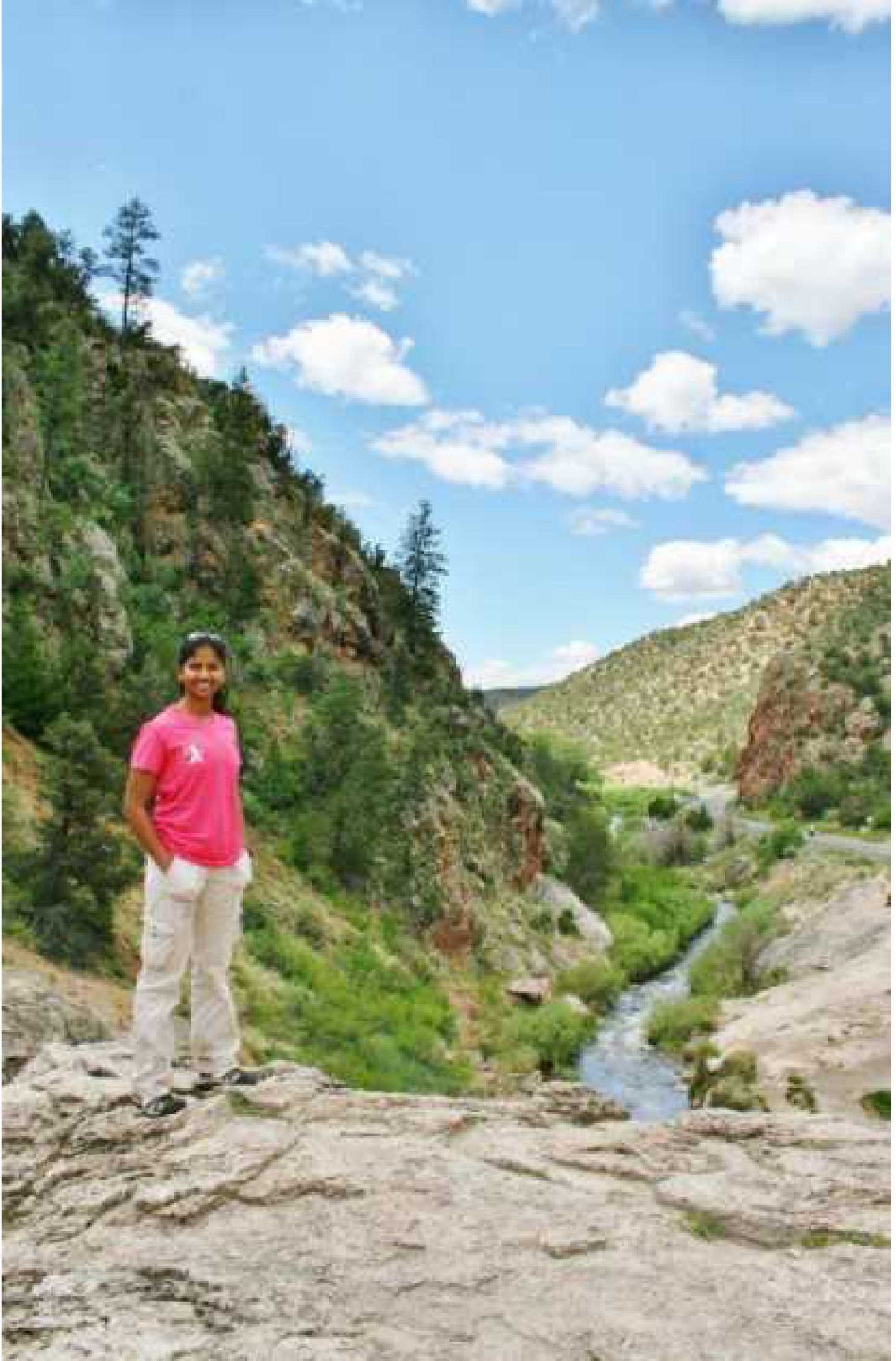
Outline

- Introductions
- FEW Nexus
- Systems Resilience
- Student Opportunities

Introductions

A brief overview about us, our department, & Sandia National Labs at-large



About me

- South Indian
- Northern Virginian
- Cavalier (UVA)
- Commodore (Vanderbilt)
- NSF Fellow

…

- Local Government
- Env Consultant
- Academic
- Sandian

…

- Hiker
- Dancer
- Climber

About me

Undergraduate degrees in Applied Mathematics and Geology from Western Washington University

Masters degree in Earth and Planetary Science from University of New Mexico

Started at Sandia in 2004

Research Interests:

- Water infrastructure and resilience
- Network analytics
- Real-time data analytics
- Solute transport
- Scale dependency
- Software design

Personal Interests:

- Anything outdoors with my family

Sandia National Laboratories

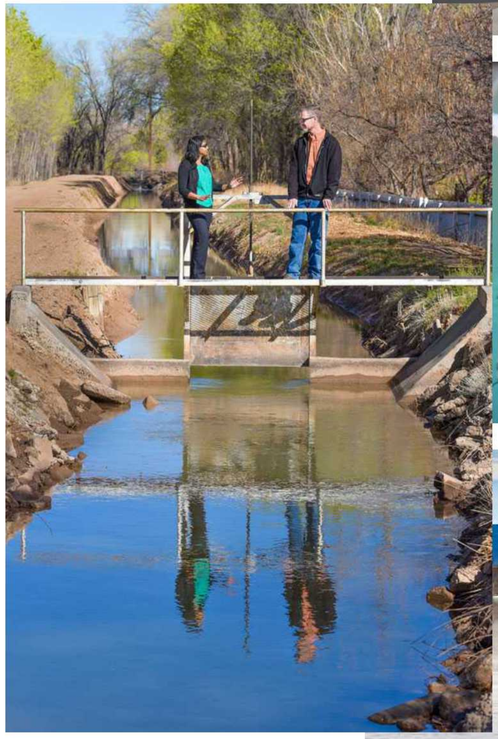
- Research at Sandia covers 5 major program portfolios
- Over 14,000 employees with offices in NM and CA
- Energy and Geosciences Center
  - Utilize and balance energy from all sources, improve the cradle-to-grave management of each energy source, and improve environmental stewardship.
- Renewable Energy Technologies Group
  - Reduces the cost, improves the resilience and reliability, and decreases the regulatory burden of wind, solar, and marine energy systems and investigates the intersection of water-energy-agriculture.

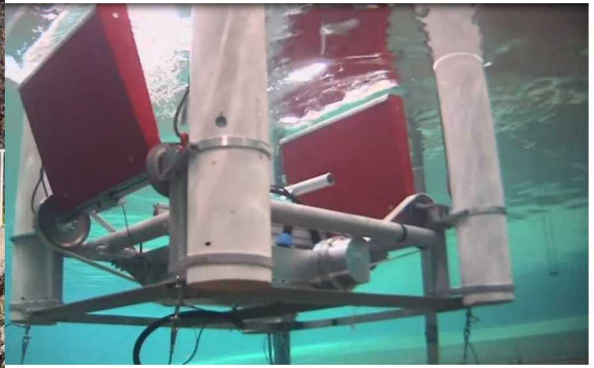
Wind Energy	Water Power	Concentrating Solar	PV Materials & Technologies	Energy & Water Sys Integration

Energy and Water Systems Integration

- Increase the security and resilience of the nation's energy and water systems.

  - Energy-food-water modeling and analysis
  - Data analytics for renewable energy
  - Climate impact to energy systems
  - Coupled human behavior and engineered systems
  - Grid modernization
  - Water security
  - Infrastructure resilience
  - Building energy efficiency
  - Open source software development





Learn more at http://water.sandia.gov

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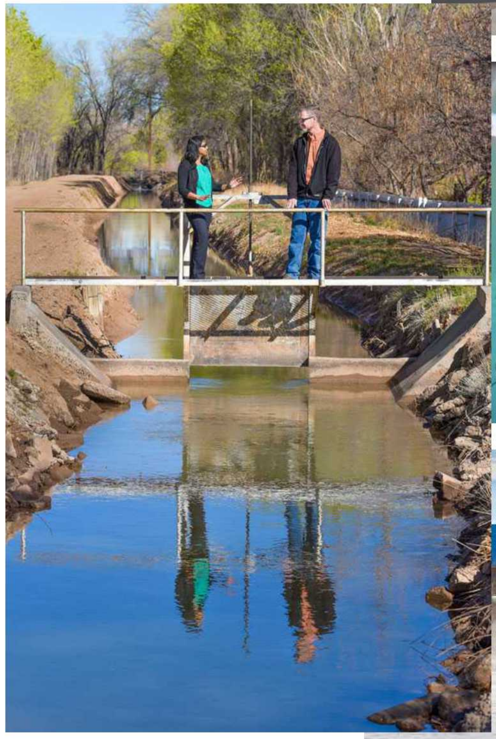

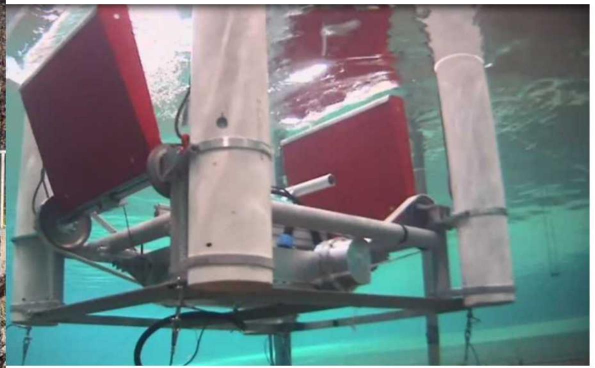

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FEW Nexus Analyses

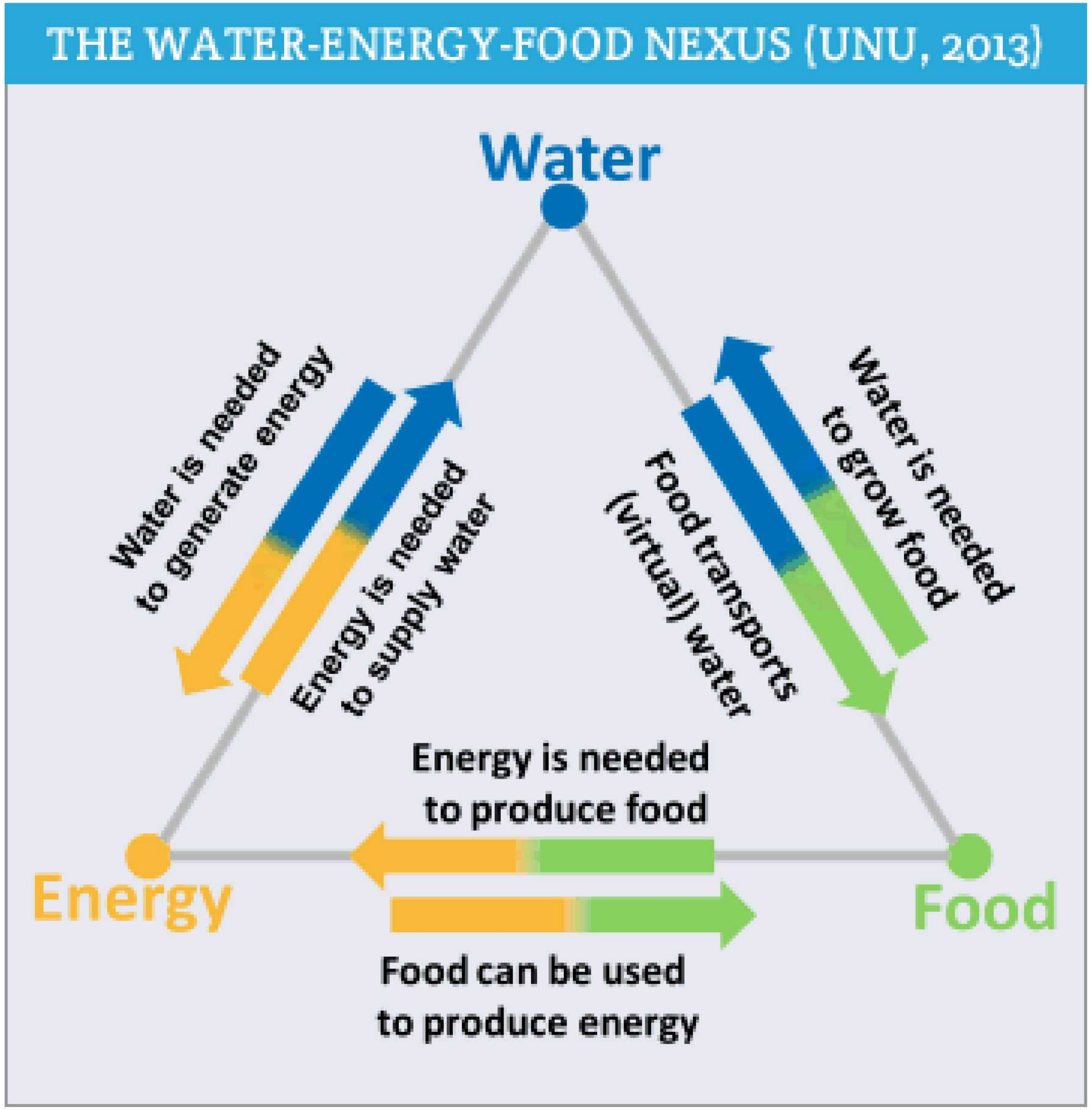
FEW Nexus

Catalyzed by 2011 Bonn Conference

Motivated by limited supply and growing demand for critical resources

- humans have already appropriated more than 50% of available renewable freshwater,
- converted more than 50% of arable land to crops or pasture, and
- tripled extraction of natural materials in the last 40 years

Occurring within academic, industry, and policy spaces



Challenges

Complex interactions (including governance influences) are conceptually recognized

However, actual implementation often misses the mark

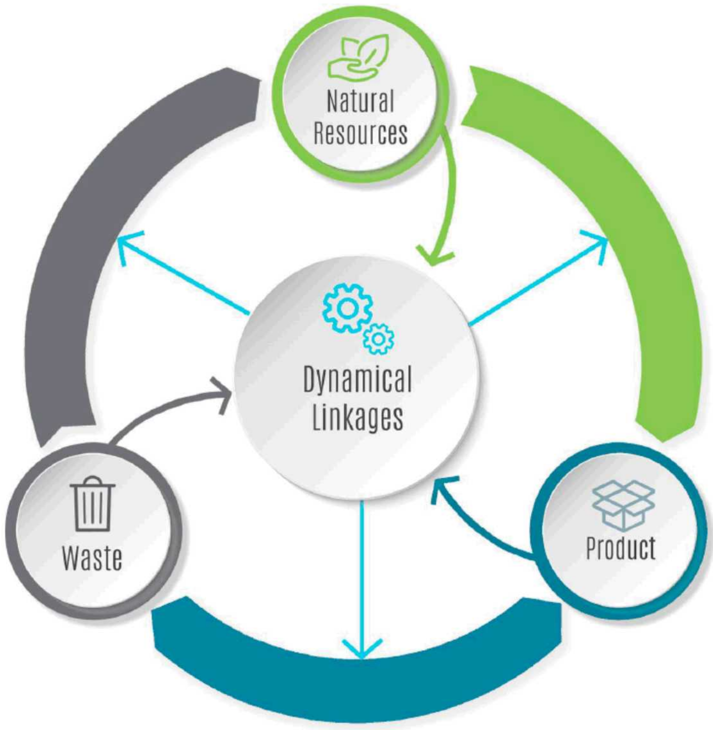
Oversights are driven by

- Imprecise terminology
- Limited consideration for waste
- Lack of dynamical linkages

$$\text{FEW Index} = \sqrt[3]{(\text{Food Sub-Index}) \times (\text{Energy Sub-Index}) \times (\text{Water Sub-Index})}$$

Willis, H. H., Groves, D. G., Ringel, J. S., Mao, Z., Efron, S., & Abbott, M. (2016). Developing the Pardee RAND food-energy-water security index, 60. https://doi.org/10.7249/TL165

Resource-Product-Waste Cycle



Combines key concepts from industrial ecology, sustainability science, system dynamics, and many more

More precise terminology is needed to better convey nuances
- Natural resource or finished product?
- Clarify order of interactions (e.g., drinking water treatment requires electricity, which in turn requires freshwater for cooling if generated from thermoelectric sources)
- Level of investment also strongly influenced by local environmental conditions

Waste streams
- Predominantly hidden
- 75% of US total material use
- Gaining some attention with LCA

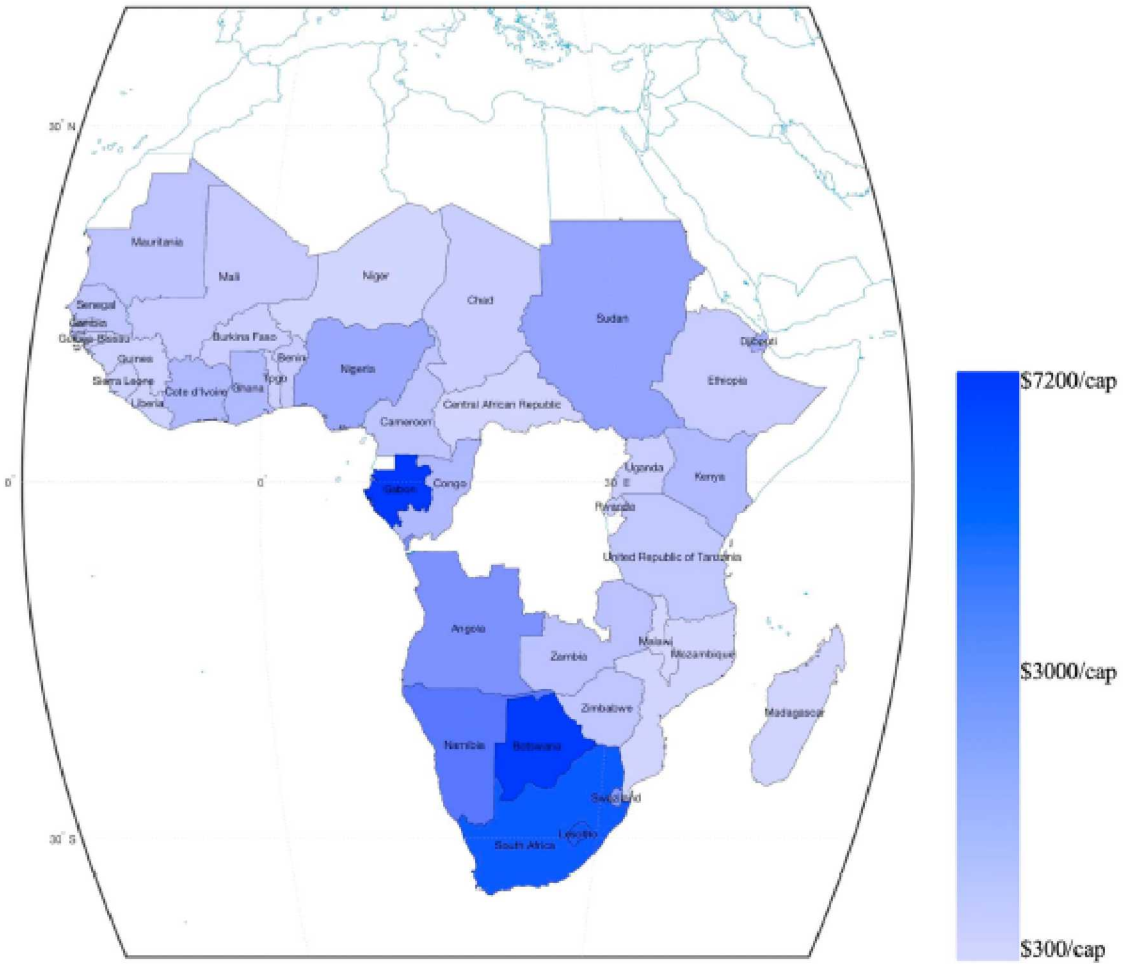
Dynamical Linkages
- Social and political dimensions
- Market and governance dynamics influence management and technology options

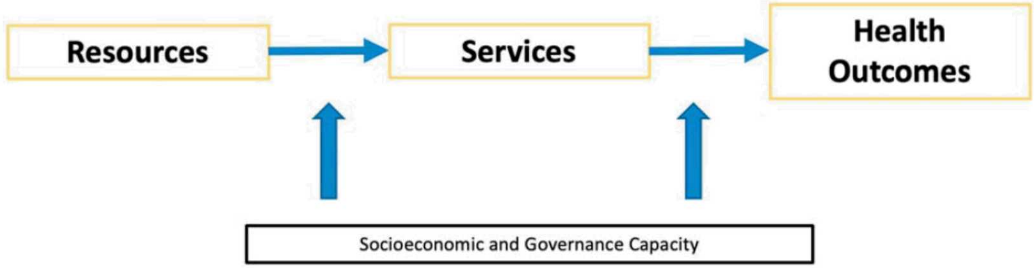
Gunda, T., & Tidwell, V. C. (2019). A Uniform Practice for Conceptualizing and Communicating Food-Energy-Water Nexus Studies. *Earth's Future*, 7(5), 504-515.

Four-Step Process

- Identify key nexus elements
- Map the full causal cycle
- Include underlying dynamical linkages
- Set boundaries for nexus study

Gunda, T., & Tidwell, V. C. (2019). A Uniform Practice for Conceptualizing and Communicating Food-Energy-Water Nexus Studies. *Earth's Future*, 7(5), 504-515.





National-level analyses

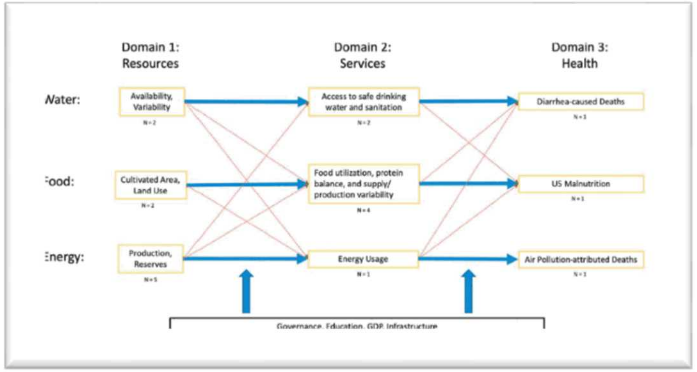
Collated data from publicly-available databases

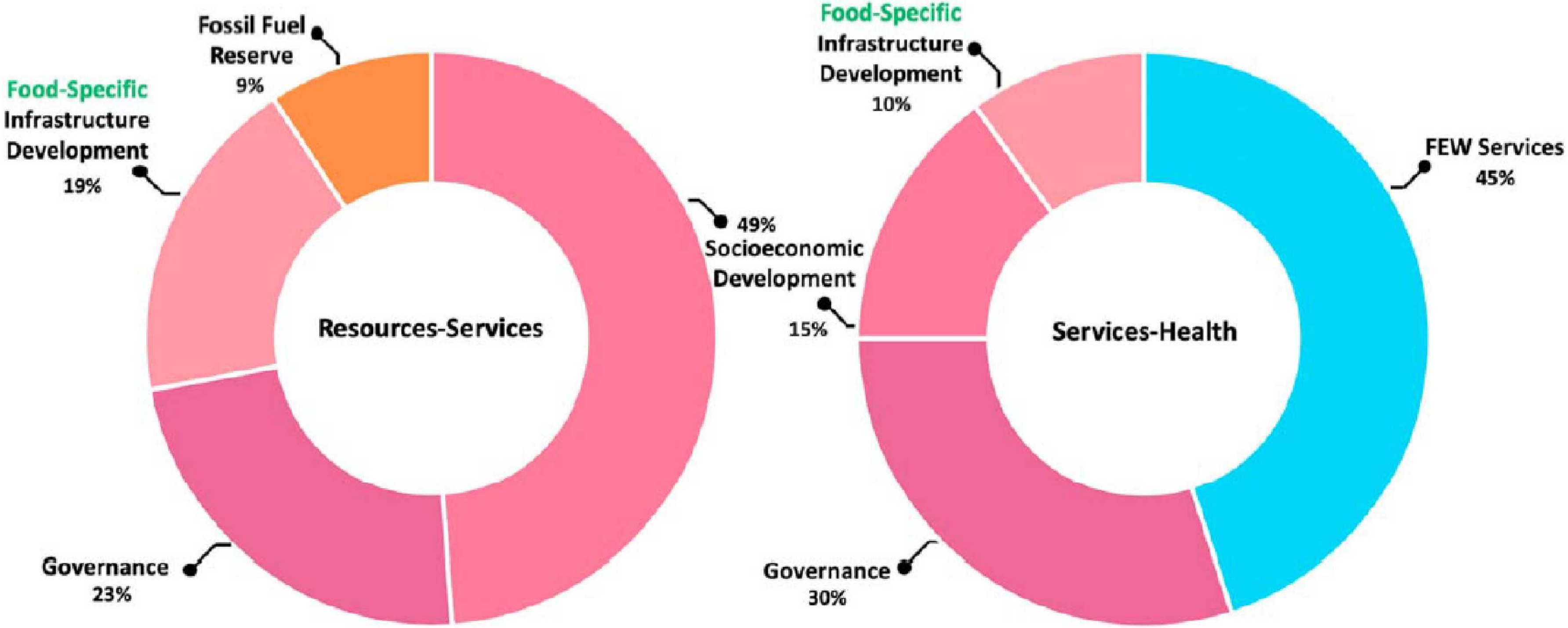
Data categorization & processing
- Is data available?
- What does data actually capture?

Regression analyses

Different Framing: FEW Nexus in Sub-Saharan Countries

Ding, K. J., Gunda, T., & Hornberger, G. M. (2019). Prominent Influence of Socioeconomic and Governance Factors on the Food-Energy-Water Nexus in sub-Saharan Africa. *Earth's Future*, 7(9), 1071-1087.





Prominent Influence of Socioeconomic and Governance Factors

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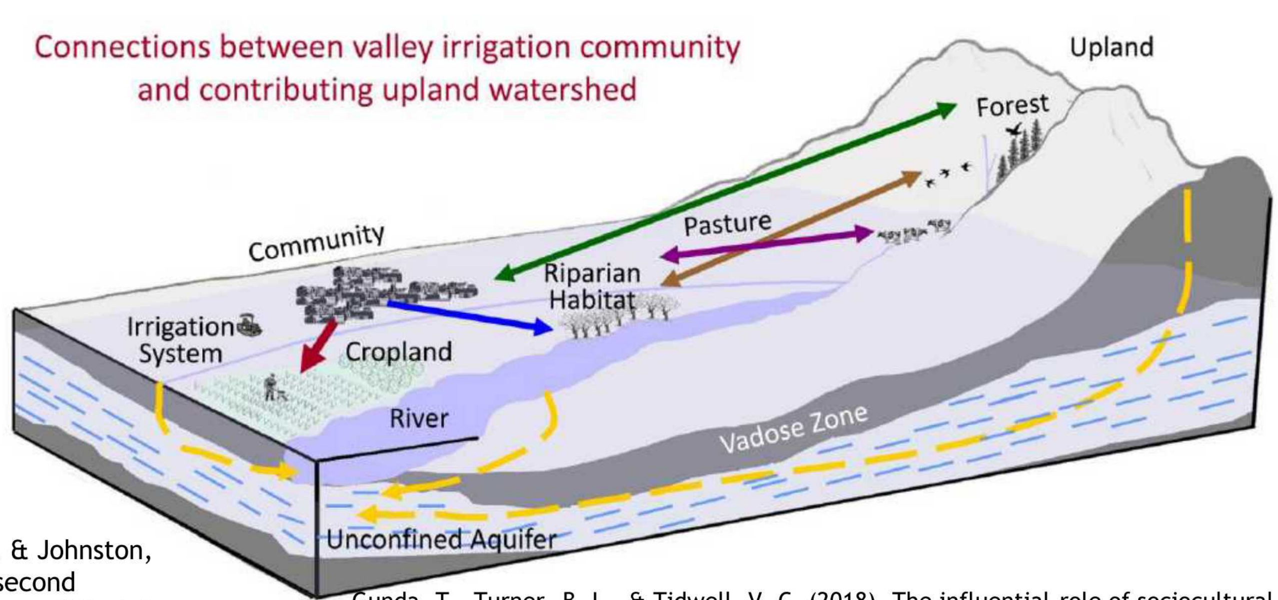
Nexus Framing

- Frameworks are useful but look beyond labels (Acequia study)
- RPW and RSH frames are not meant to be static tools → framing may evolve as the field evolves
- Clearly communicate what you did do:
  - ODD protocol for agent-based models (Grimm et al., 2020)
  - "RPW-DSDA" contains explicit sections for: Overview, Dynamical linkages, Scale, Data sources, and Analysis (Gunda and Tidwell, 2019)
  - Assumptions, limitations, etc. should be captured in descriptions



Grimm, V., Railsback, S. F., Vincenot, C. E., Berger, U., Gallagher, C., DeAngelis, D. L., ... & Johnston, A. S. (2020). The ODD protocol for describing agent-based and other simulation models: A second update to improve clarity, replication, and structural realism. *Journal of Artificial Societies and Social Simulation*, 23(2).

Gunda, T., Turner, B. L., & Tidwell, V. C. (2018). The influential role of sociocultural feedbacks on community-managed irrigation system behaviors during times of water stress. *Water Resources Research*, *54*(4), 2697-2714.

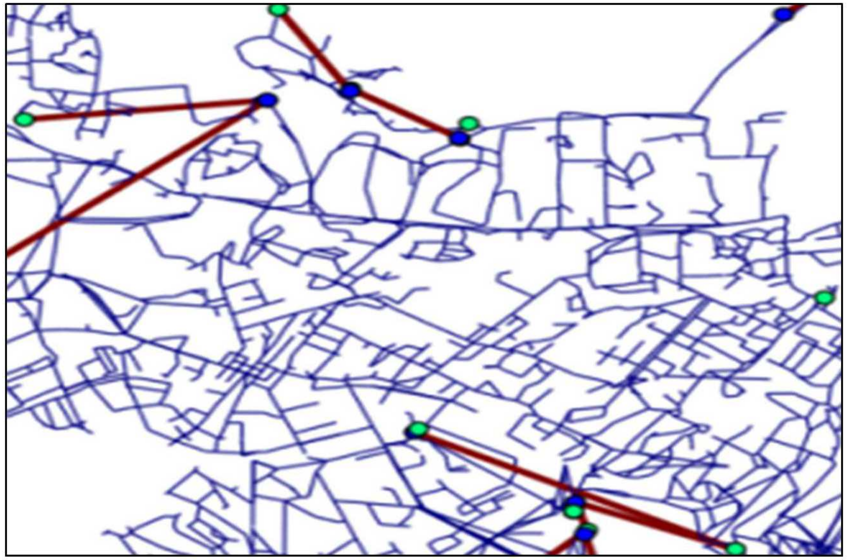
Systems Resilience

Resilience and System Definition

NIAC defines **infrastructure resilience** as "the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event" (NIAC, 2009)

Resilience of **drinking water systems** is influenced by

- Design
- Maintenance
- Operations
- Governance
- Water chemistry and indented use
- Human behavior and perception
- Interdependence with other infrastructure



National Infrastructure Advisory Council (NIAC). (2009). Critical Infrastructure Resilience, Final Report and Recommendations, U.S. Department of Homeland Security, Washington, D.C., Accessed September 20, 2014.

Quantifying Resilience

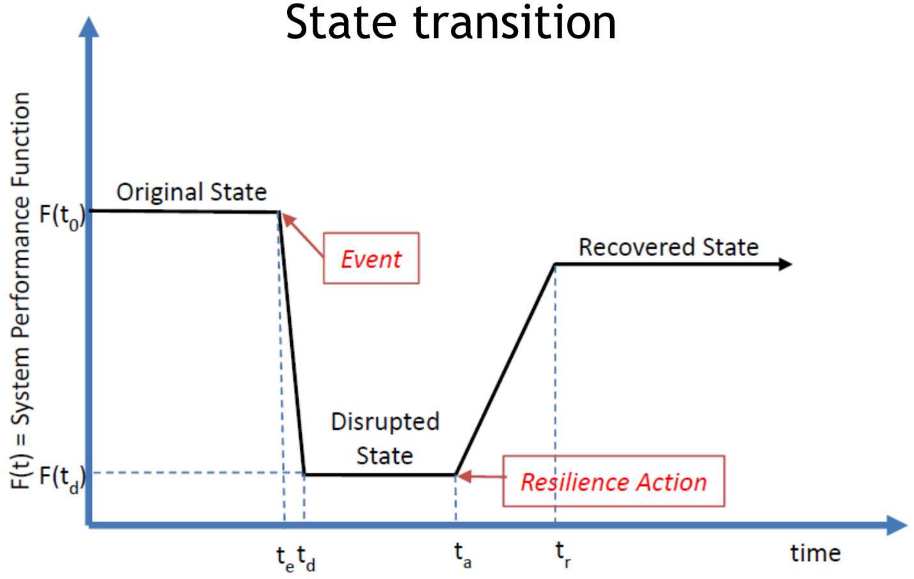
Numerous metrics have been suggested to quantify reliability, robustness, redundancy, and security for water distribution systems

- Topographic metrics
- Hydraulic metrics
- Water quality metrics
- Economic metrics

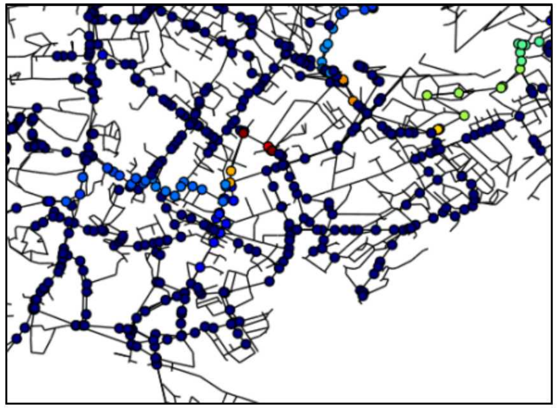
State transition plots graphically represent the meaning of resilience, but we also need to translate this information to the component level.

- System performance function, event, and resilience action must be clearly defined
- Resilience is typically defined as a system measure, but could be measured for individual components of the network

State transition



Component level analysis



Utility Specific Questions

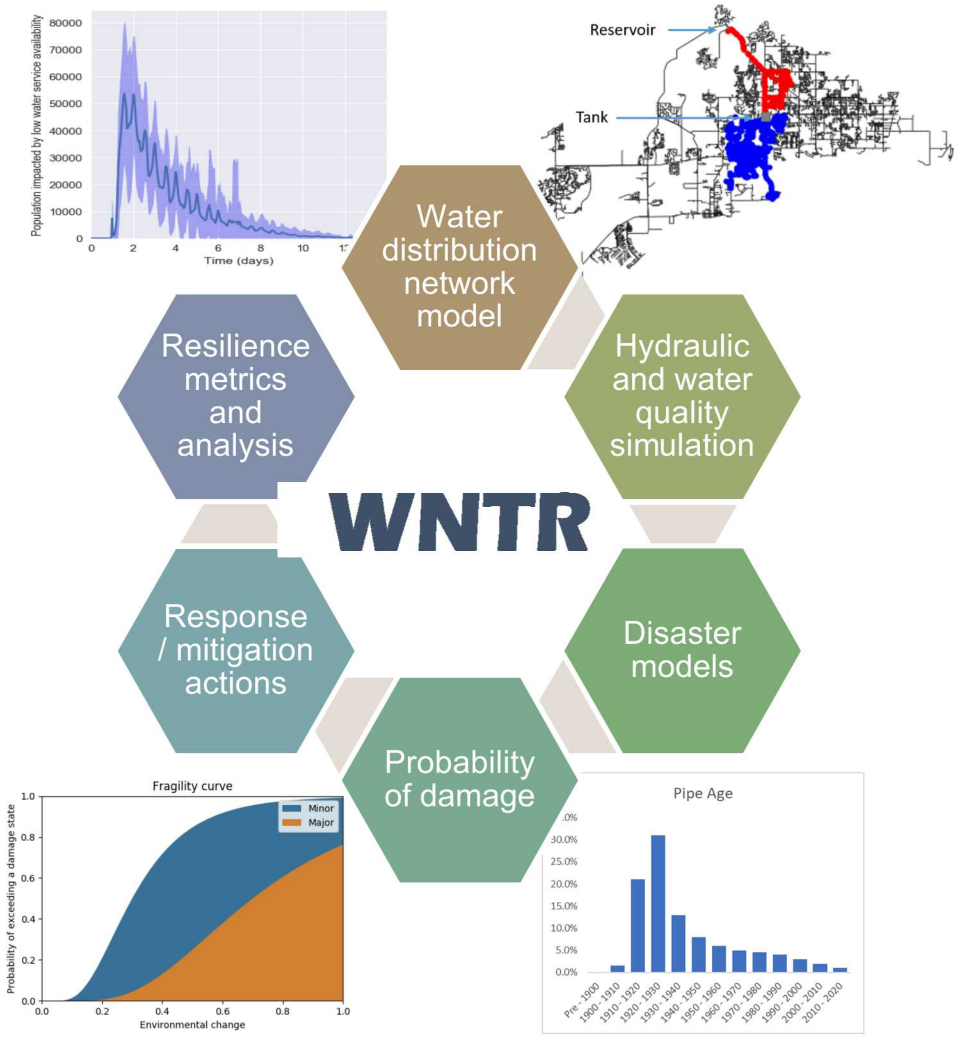
- What type of infrastructure damage could be caused by:
  - A magnitude 7 earthquake (e.g., Napa Valley, CA)?
  - A hurricane (e.g., Harvey in TX, Maria in PR)?
  - A regional power outage (e.g., Northeast Blackout)?
  - A contamination incident (e.g., Flint MI, Elk River Spill in WV)?
  - A tornado (e.g., Joplin, MO)?
- How long can the system continue to provide water to customers?
- How many people will be impacted?
- What is the best response in the immediate aftermath?
- Which components should be hardened to minimize future disruptions?

Simulation and analysis tools can help water utilities explore how their system will respond to expected, and unexpected, events

Water Network Tool for Resilience (WNTR)

WNTR is a Python package designed to analyze water distribution network failure and recovery

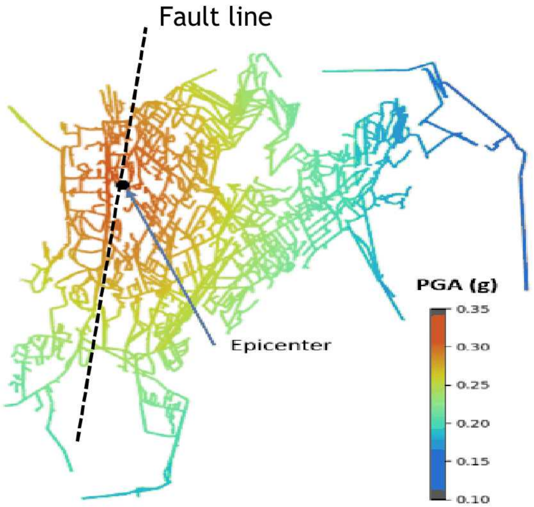
- Quantify resilience for a wide range of hazards
  - Pipe breaks
  - Power outages
  - Contamination incidents
  - Earthquakes
  - Landslides
  - Hurricanes
  - Cyber attacks
- Evaluate and prioritize resilience-enhancing actions
  - Isolate and repair pipe breaks
  - Change valve and tank operation to maintain water service
  - Install backup generation
  - Plan flushing or water conservation mandates
  - Evaluate sampling locations
  - Evaluate fire fighting capacity

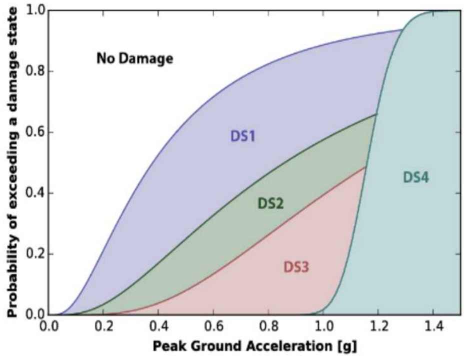


https://github.com/sandialabs/wntr
http://wntr.readthedocs.io

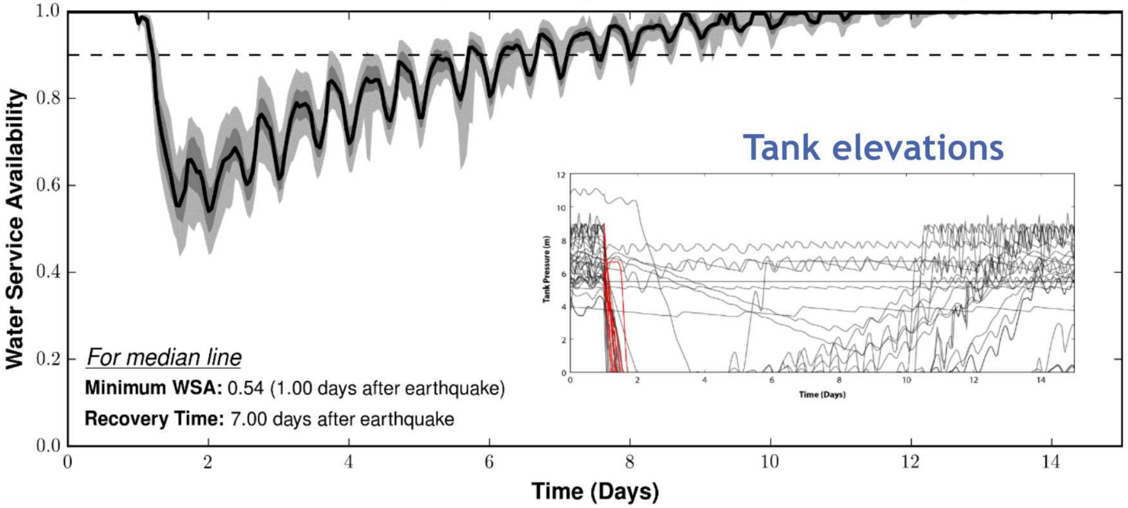
Earthquake Analysis

- Based on 2014 Napa Earthquake
- Assess water service availability and fire fighting capacity following an earthquake along a NS fault that bisects a water utility
- Damage a function of soil type, pipe material, and PGA using fragility curves
- Repair strategy
  - Set number of pipe, tank, and pump repair crews
  - Prioritization for largest leak and pumps closest to the reservoir





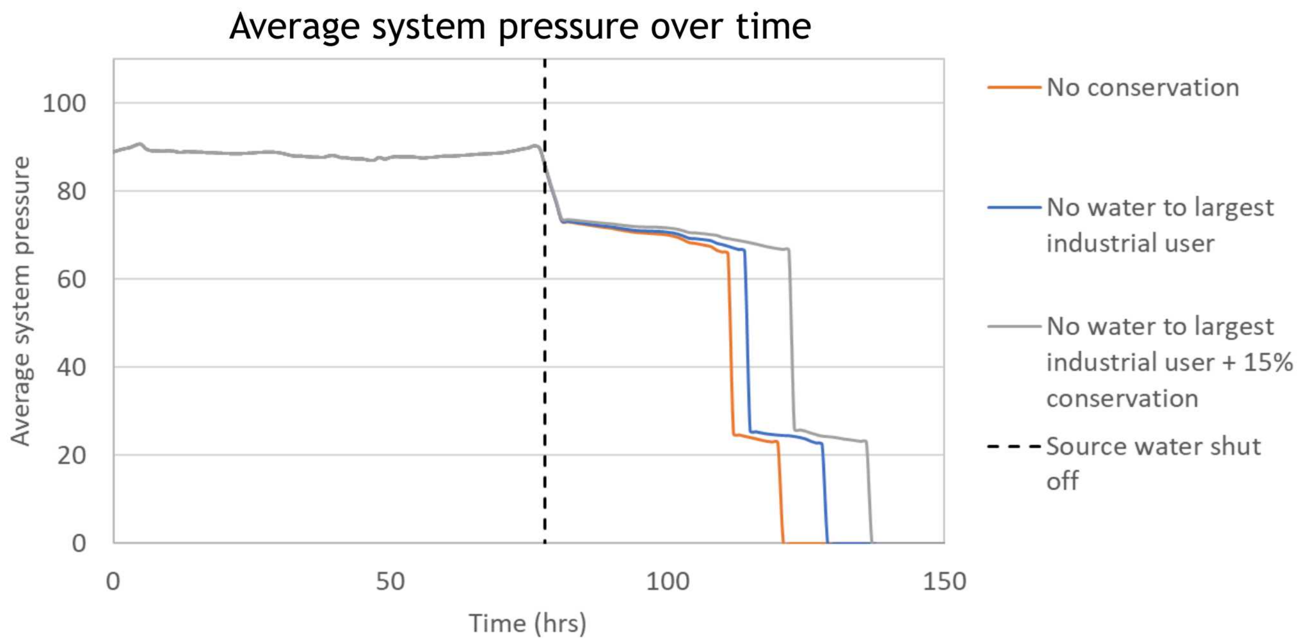
Central epicenter, 6.5 magnitude earthquake

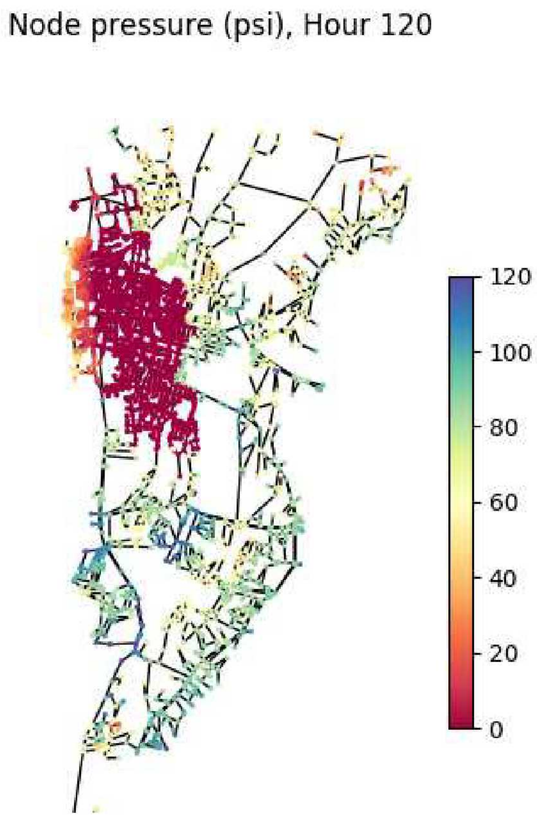


Klise, K.A., Bynum, M., Moriarty, D. and Murray, R., 2017. A software framework for assessing the resilience of drinking water systems to disasters with an example earthquake case study. *Environmental Modelling & Software*, *95*, pp.420-431.

Compromised Source Water Analysis

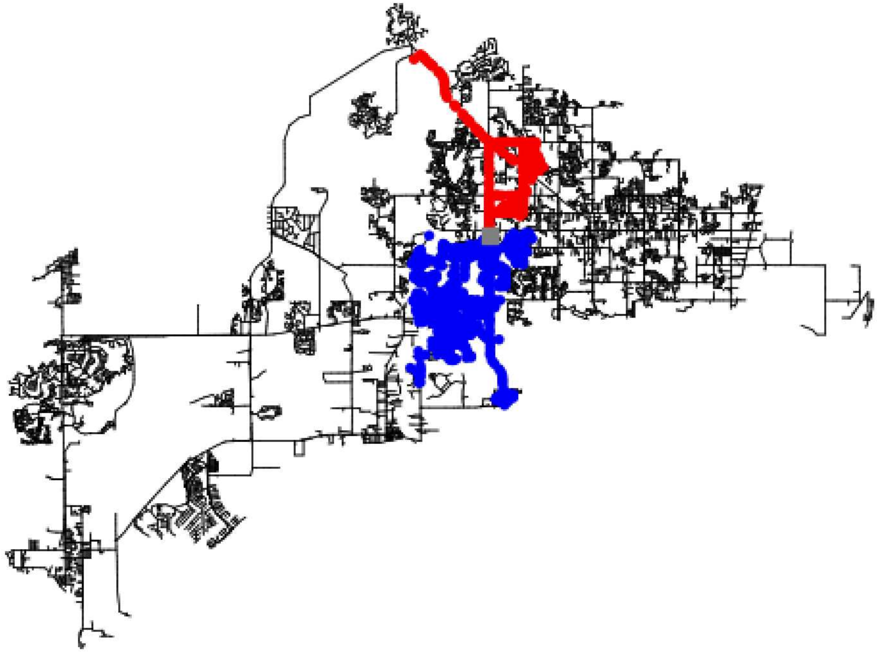
- Case study with the City of Poughkeepsie, NY
- Loss of source due to river contamination, treatment plant failure, winter storm freezing intake, or power outage
- Track water pressure and water service availability over time
- Test mitigation strategies



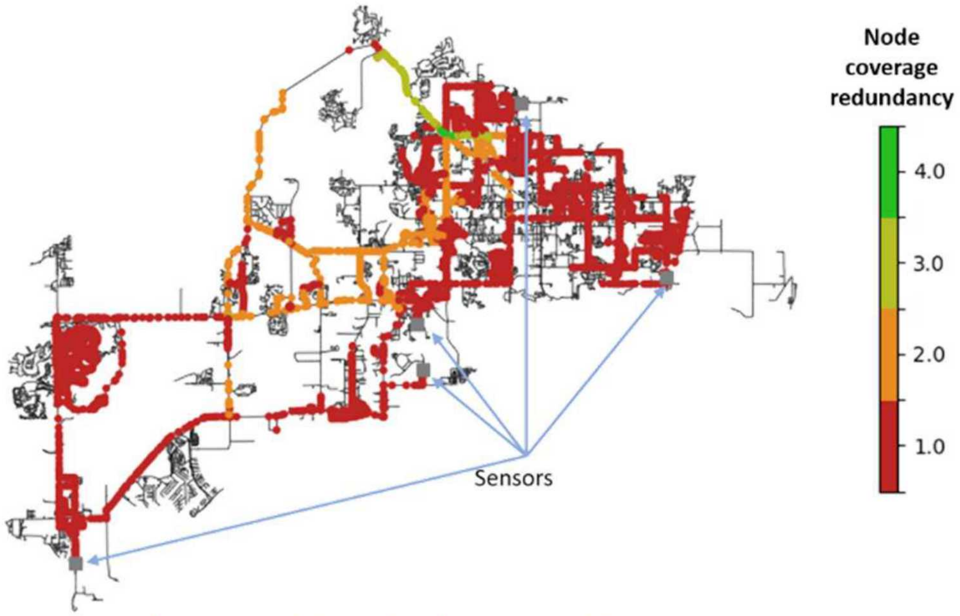


Hydraulic Connectivity and Sensor Placement

- Evaluate critical paths between water treatment plant and customers
- Compute upstream and downstream nodes from tanks, valves, pumps



- Optimize the location and type of sensors to minimize damage or maximize detection capabilities
- Evaluate redundancy of a sensor network
- Related open-source Python packages, developed at Sandia: Pyomo and Chama



https://github.com/Pyomo
https://github.com/sandialabs/chama

Current Research

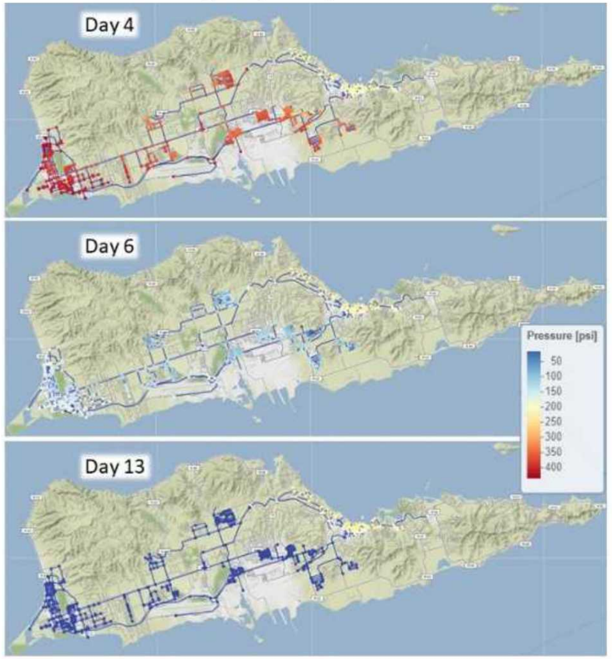
US Virgin Islands and Puerto Rico

- Hurricane, earthquake, drought, flood, sea level rise
- Centralized/decentralized water systems
- Multi-infrastructure analysis
- Simulation and optimization techniques

- Partnership with Naval Post Graduate School and Virgin Islands Water and Power Authority
- Water-power resilience analysis in response to Category 5 hurricanes (Irma and Maria) that hit the US Virgin Islands in 2017
- Impact of power pole and co-located water pump failure given hurricane wind speed and power pole fragility
- Results are used to recommend hurricane mitigation via system hardening and redesign

Location of electric power infrastructure serving water pump stations

Water pressure after power outage at a single pump station



Wille, D, 2019, Simulation Optimization for Operational Resilience of Interdependent Water-Power Systems in the US Virgin Islands, M.S. Thesis in Operations Research, Naval Postgraduate School, Monterey, CA.

Student Opportunities

High school through post-doc positions

Summer and year-round schedules

Multi-disciplinary teams

- Engineering, math, operations research, data science, economics, sociology, computer science

Basic and applied research

UT-Austin is one of our academic alliance partners

Campus recruiting

We recruit at the some of the best colleges and universities, looking for talented individuals to join our diverse workforce.

https://www.sandia.gov/careers/students_postdocs/index.html

Q&A

Always welcome to contact us!

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Thushara: tgunda@sandia.gov