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Open Source Software to Analyze Water Distribution System Resilience

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Sandia National Laboratories

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Sandia National Laboratories

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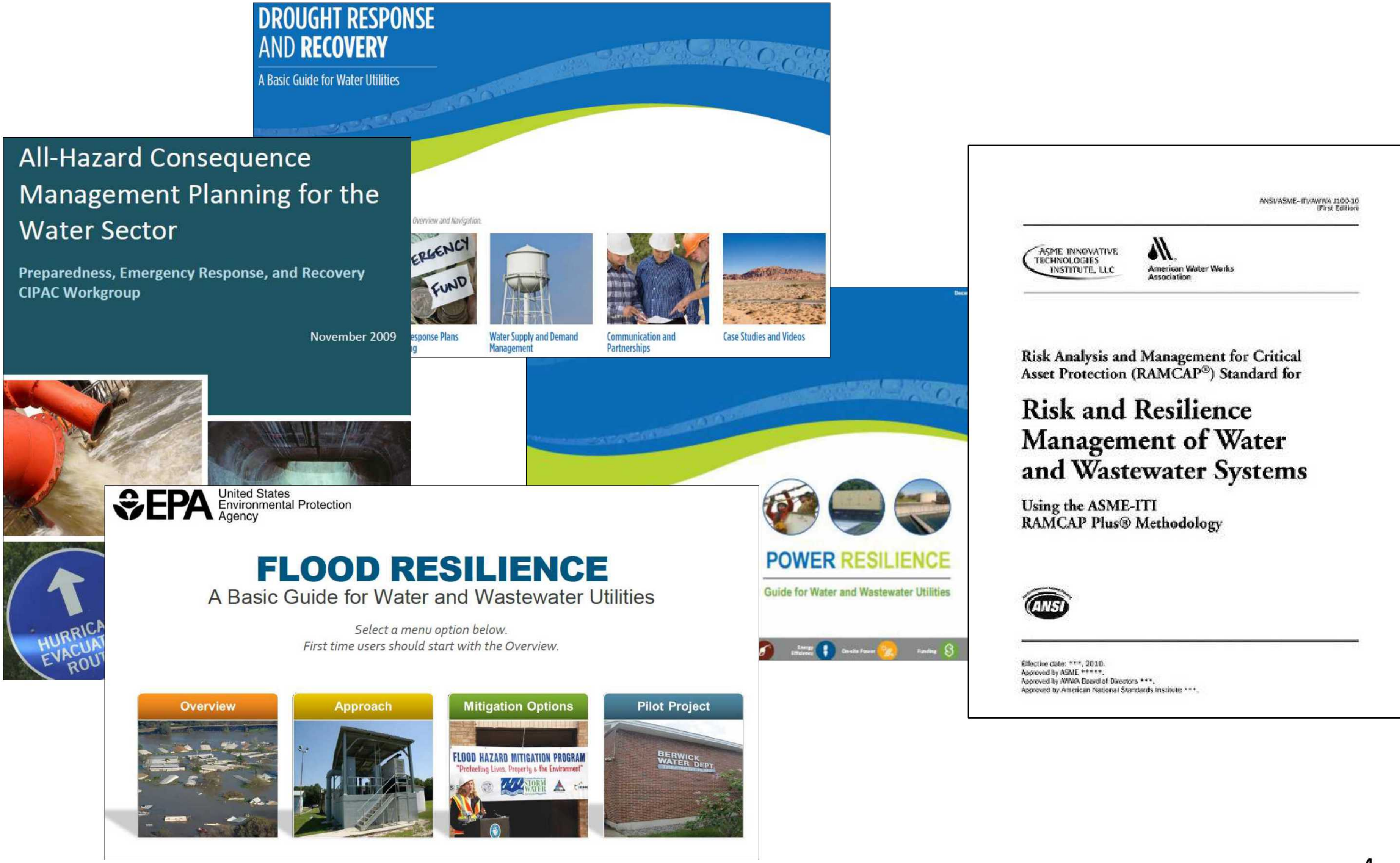
- Geotechnology and Engineering, David Hart
- Water Energy System Integration, Katherine Klise

Motivation and Background

- Water distribution systems face multiple challenges
- The goal of a resilient system is to minimize the magnitude and duration of disruption
- Resilience of drinking water systems is influenced by
  - Design
  - Maintenance
  - Operations
  - Dependence with other infrastructure

Potential Hazards	Potential Impacts
Natural disasters - Drought - Earthquake - Floods - Hurricanes - Tornados - Tsunamis - Wildfires - Winter storms Terrorist attacks Cyber attacks Hazardous material release Climate change	Infrastructure damage - Pipe breaks - Pump failure - Tank damage Service disruption Loss of access to facilities/supplies Loss of pressure or change in water quality Environmental impacts Financial impacts Social impacts

Water Sector Resilience Guidance



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?

Infrastructure Resilience Policy

Installation Energy and Water Security Policy (Army Directive 2017-07)

- Establish energy and water infrastructure requirements that ensure continuous availability, reliability and quality.
- Preparation for extended outages, providing necessary energy and water for a minimum of 14 days
- Microgrid/islandable capabilities

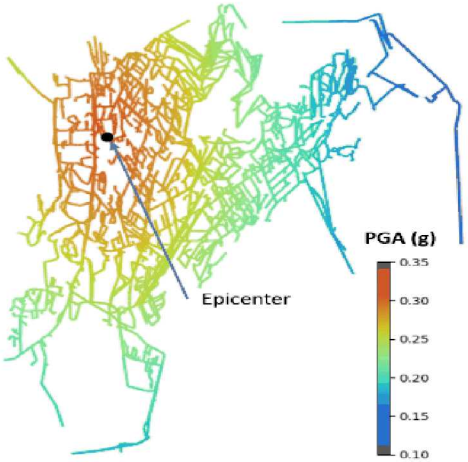
America's Water Infrastructure Act (AWIA, 2018)

- Requires drinking water systems serving more than 3,300 people to develop
  - Comprehensive water system risk and resilience assessment
  - Emergency response plans that address physical and cybersecurity threats
- Drinking Water Infrastructure Risk and Resilience Program: EPA may award grants to increase the resilience of community water systems

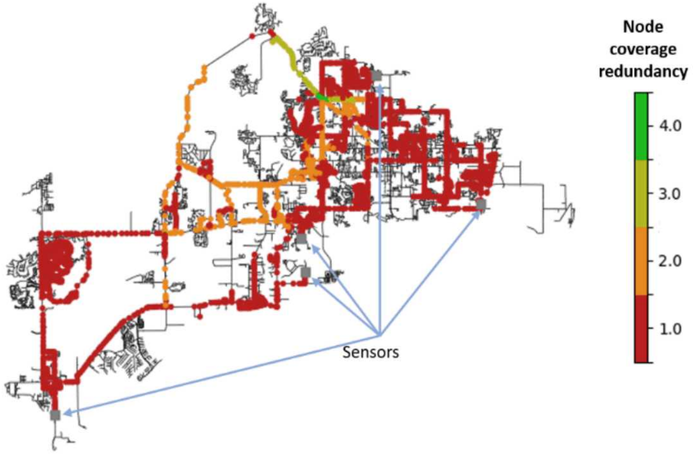
Water Network Tool for Resilience

WNTR is 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

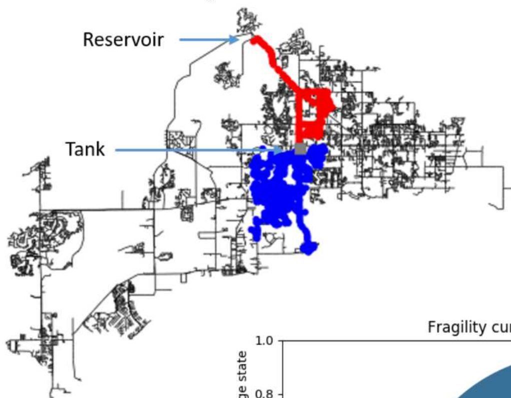


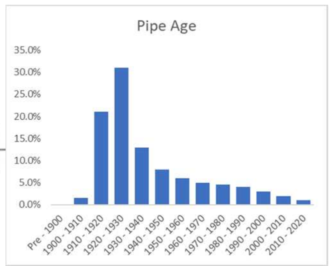
- Evaluate and prioritize resilience-enhancing actions
  - Isolate and repair pipe breaks
  - Change valve and tank operation to maintain water service
  - Install backup generation
  - Plan flushing or water conservation mandates
  - Evaluate sampling locations
  - Evaluate fire fighting capacity

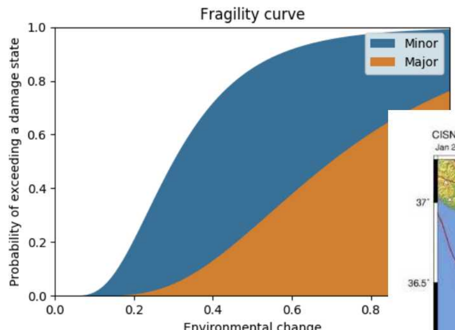


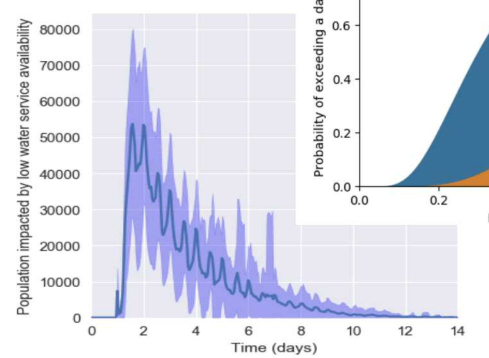
WNTR Framework

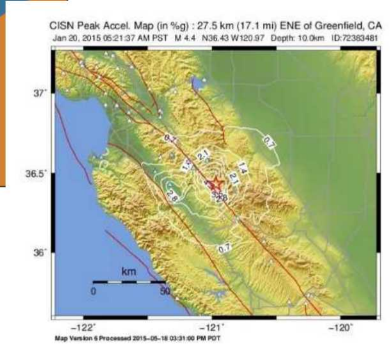
- EPANET is the industry standard for water distribution hydraulic and water quality modeling
- The Water Network Tool for Resilience, WNTR, builds on capabilities in EPANET to analyze water distribution resilience

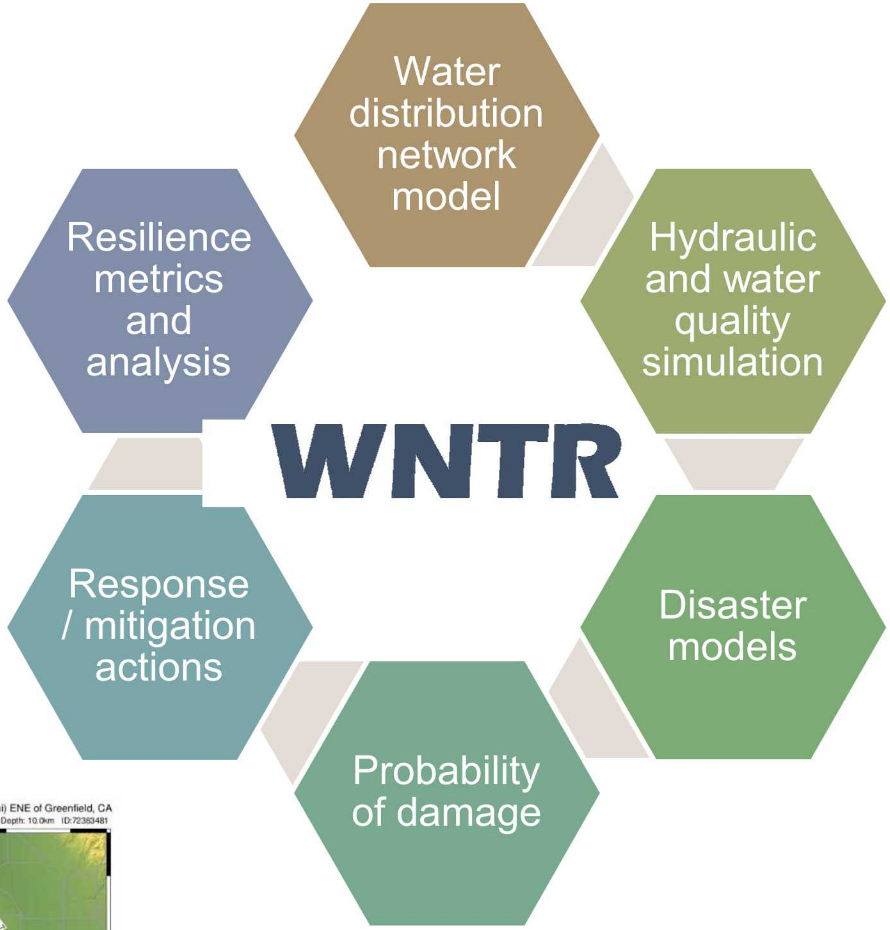








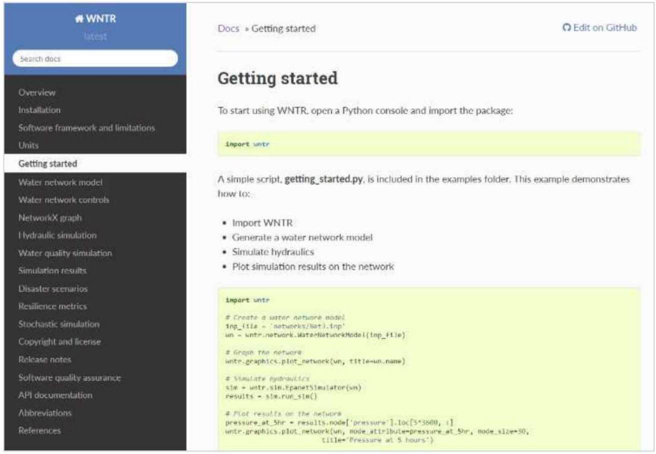


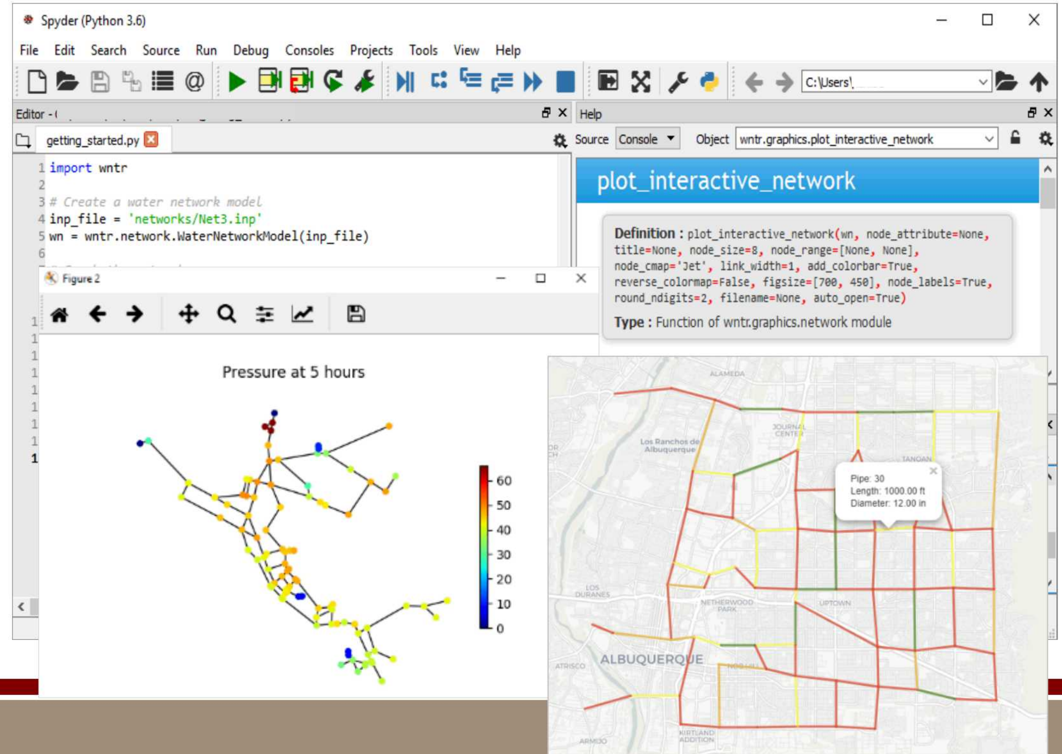


https://github.com/usepa/wntr

WNTR Framework

- Open source Python package
  - Python 2/3 compatible
  - Integrated development environments
- Integrates commonly used efficient Python packages
  - Numpy and Scipy
  - Pandas
  - NetworkX
  - Matplotlib, Plotly, and Folium
- Git repository, extensive online testing and documentation
  - GitHub
  - TravisCI
  - ReadtheDocs





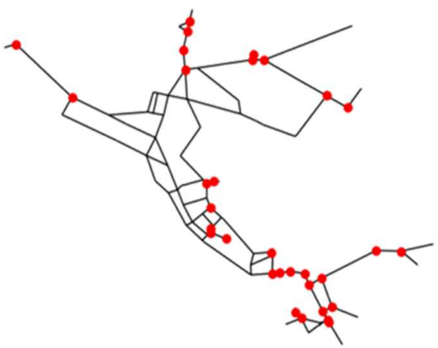
Water Network Models

- Model contains physical layout and system operations
  - Nodes: Junctions, Tanks, Reservoirs
  - Link: Pipes, Valves, Pumps
  - Demands
  - Controls
  - Simulation options
- Generate network models from EPANET INP files or from scratch
- Add/remove/modify components
- Query node/link attributes
- Skeletonize network models
- Plot network attributes
- Analyze network structure

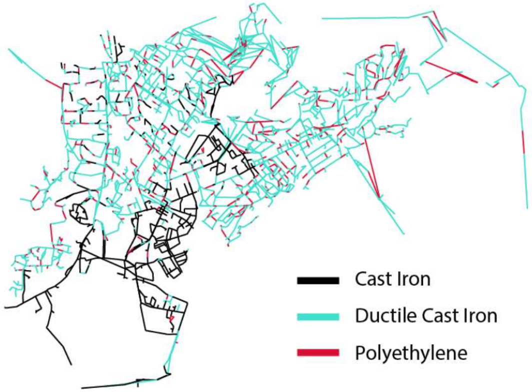
Original network

Skeletonized network

Articulation points

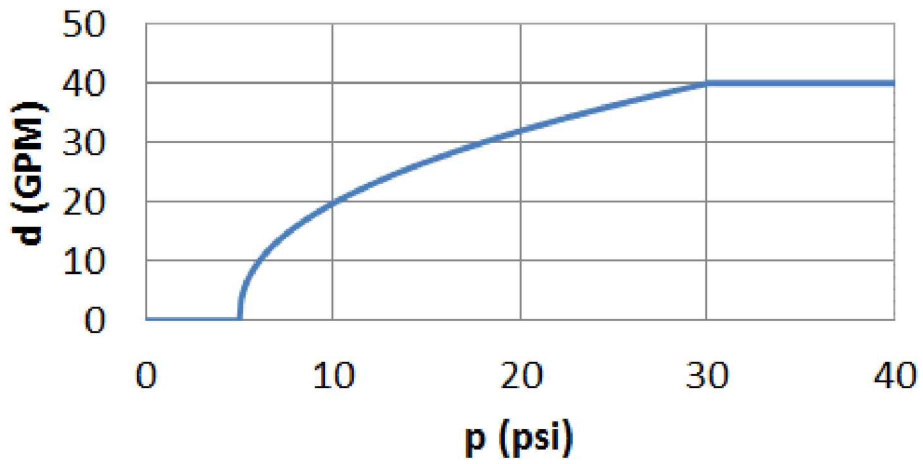


Pipe Material



Hydraulic and Water Quality Simulation

- Demand-driven hydraulic simulation
- Pressure dependent demand hydraulic simulation
  - Demand at a node depends on the pressure that is available at the node



$$d = D_f \quad \text{for } p \geq P_f$$

$$d = D_f \left(\frac{p - P_o}{P_f - P_o} \right)^{1/e} \quad \text{for } P_o < p < P_f$$

$$d = 0 \quad \text{for } p \leq P_o$$

- Water quality simulations that compute water age or concentration
- Simulation start/stop capabilities
- Feedback loops, cascading failure
- Monte Carlo simulation
- Parallelization

Modeling Disruptive Incidents

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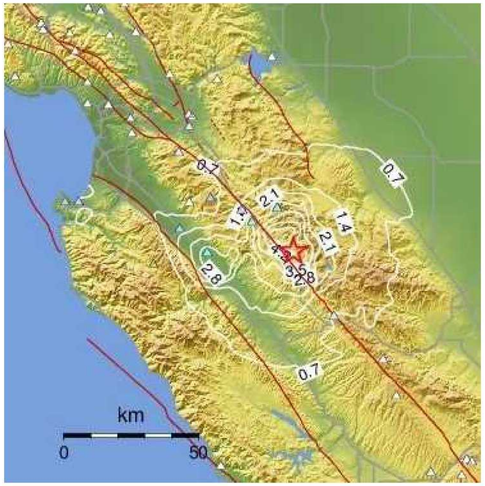
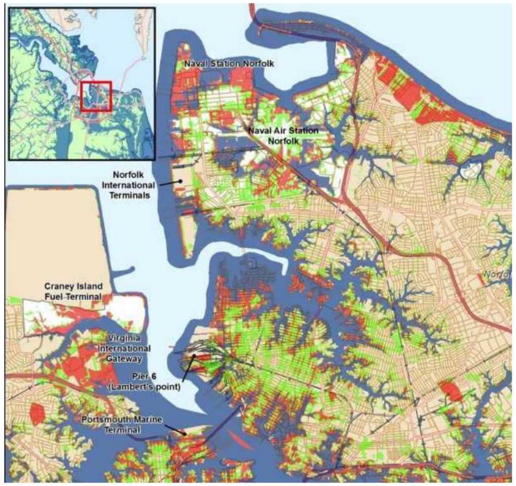
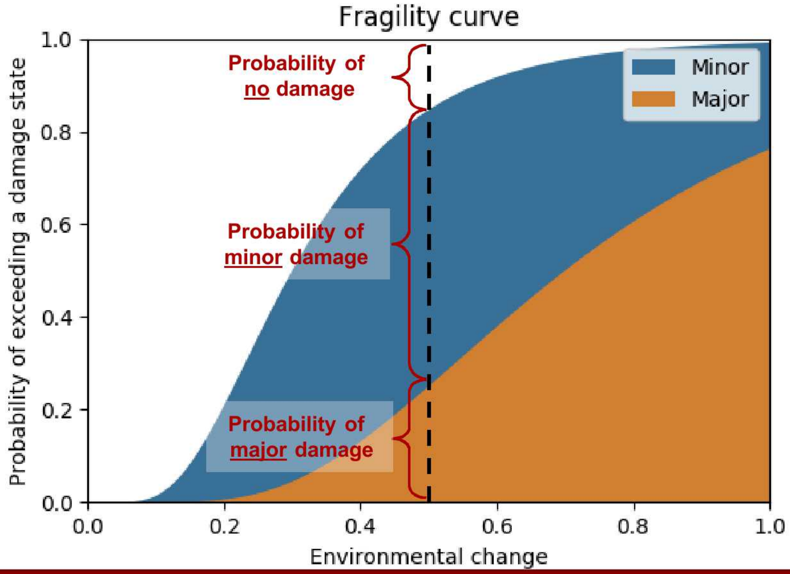
- Define disruptive incident
  - Informed by data or a model
- Define probability of damage
  - Fragility and survival curves
- Modify the model
  - Controls, demands, components, attributes to match each scenario

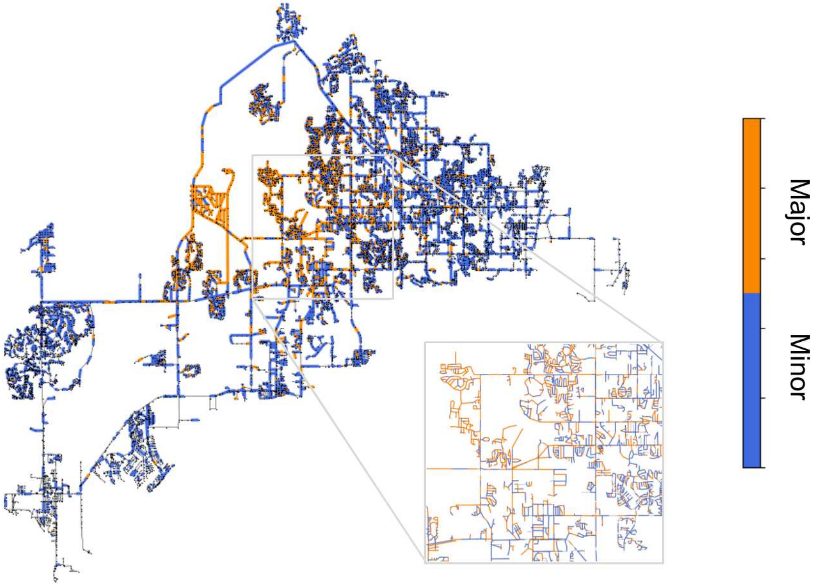
PGA after an earthquake in California (USGS)



100-yr flood stage with sea level rise in Virginia (100RC)



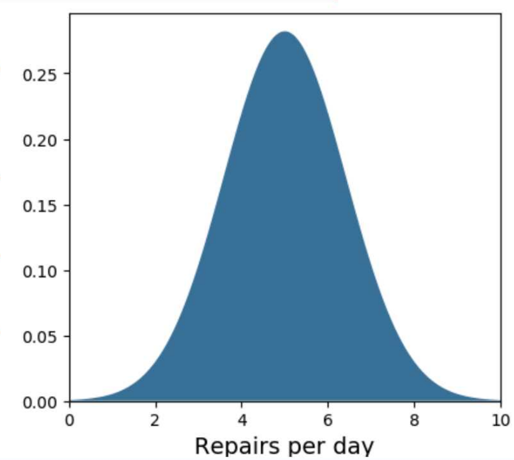




Modeling Restoration Actions

- Define the restoration action
  - Type of repair actions
  - Number of crews
  - Time to repair
  - Supply chain
- Define priorities
  - Distance from the reservoir
  - Magnitude of leak
  - Number of people affected
- Modify the model
  - Controls, demands, components, attributes to match each scenario

Repair Strategy Following 2014 Napa Valley Earthquake
Number of repair crews – 5
Repairs per day – 5 *(120 breaks fixed in 5 days)*
Repairs started 24 hours after earthquake
Separate team repaired tank
Prioritized repairs by proximity to limit travel time
Production maximized to feed leaks
Boil water order for affected regions

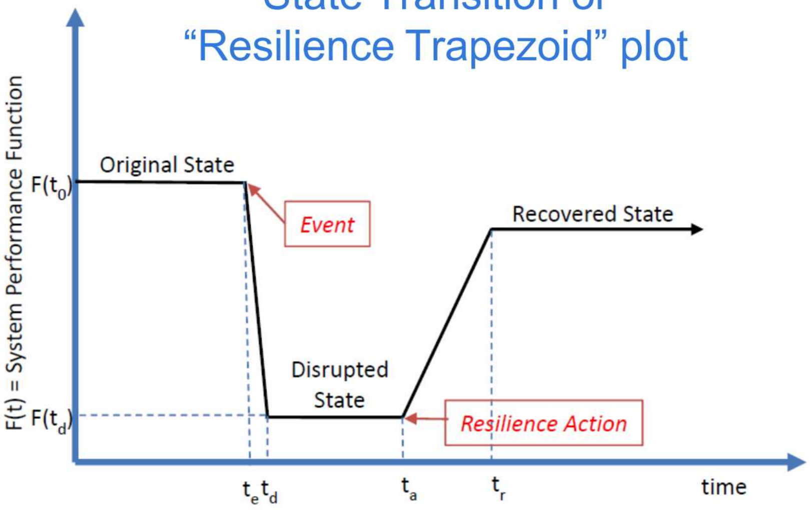


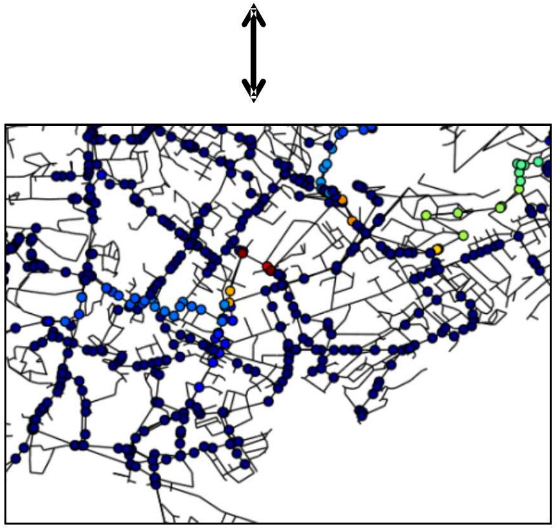
Quantifying Resilience

- Numerous metrics have been suggested to quantify reliability, robustness, redundancy, and security for water distribution networks
  - Topographic metrics
  - Hydraulic metrics
  - Water quality metrics
  - Economic metrics

- Commonly used metrics include
  - Water service availability
  - Population impacted by service disruption or low pressure conditions
  - Water age and chlorine residual
  - Cost associated with repair and lost service

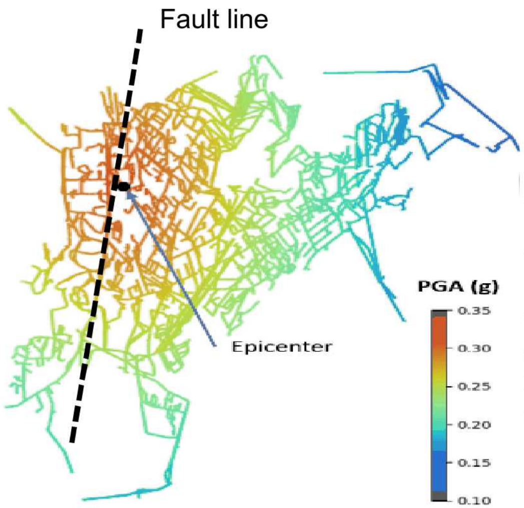
State Transition or
"Resilience Trapezoid" plot

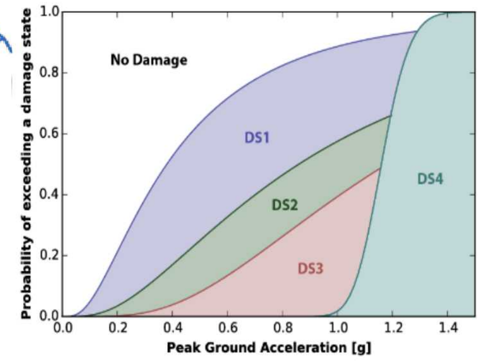




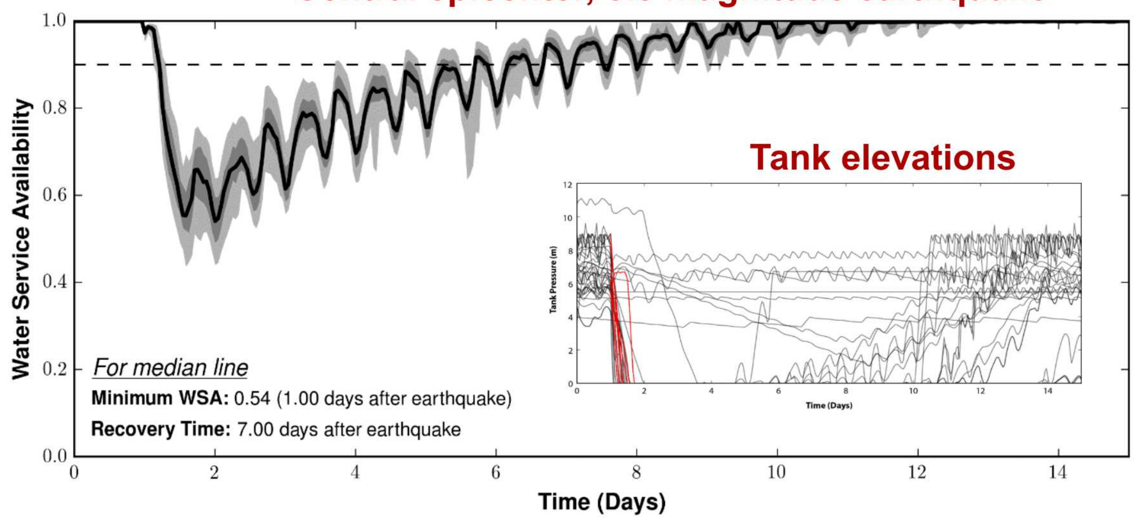
Earthquake Analysis

- 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
  - Separate pipe, tank, and pump repair crews
  - Prioritization for largest leak and pumps closest to the reservoir



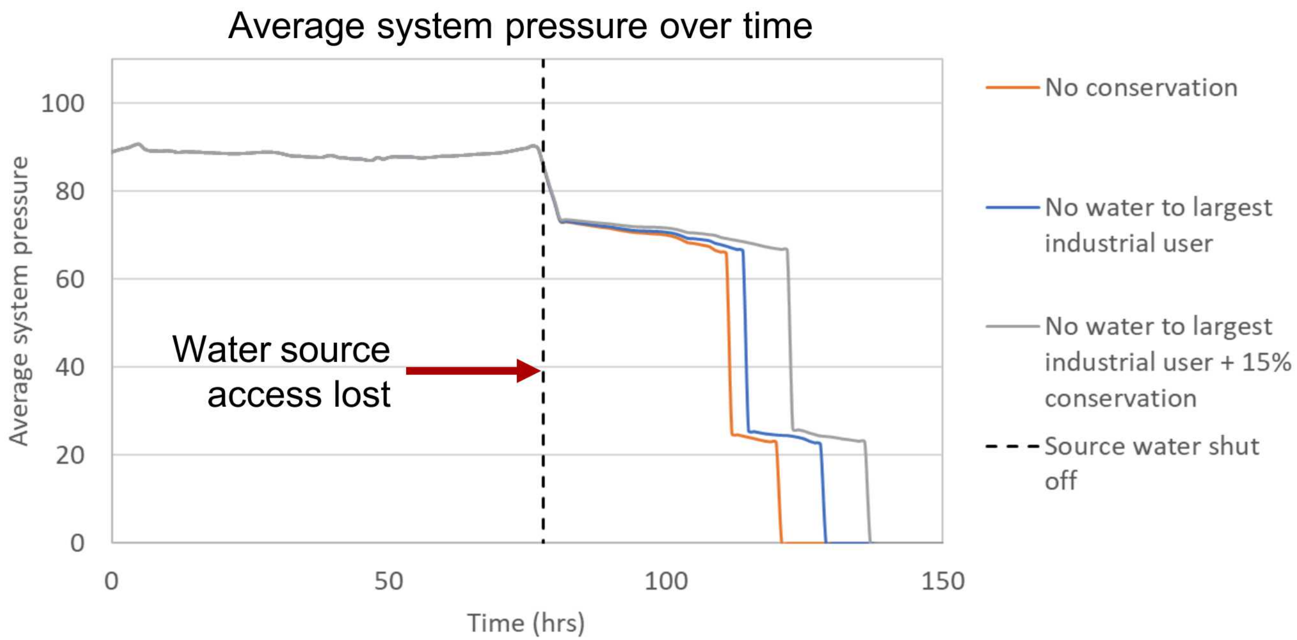


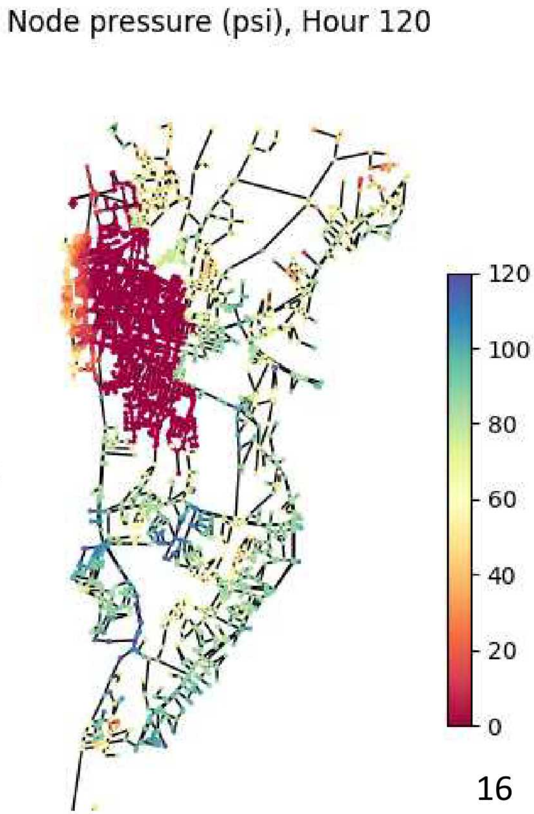
Central epicenter, 6.5 magnitude earthquake



Compromised Source Water Analysis

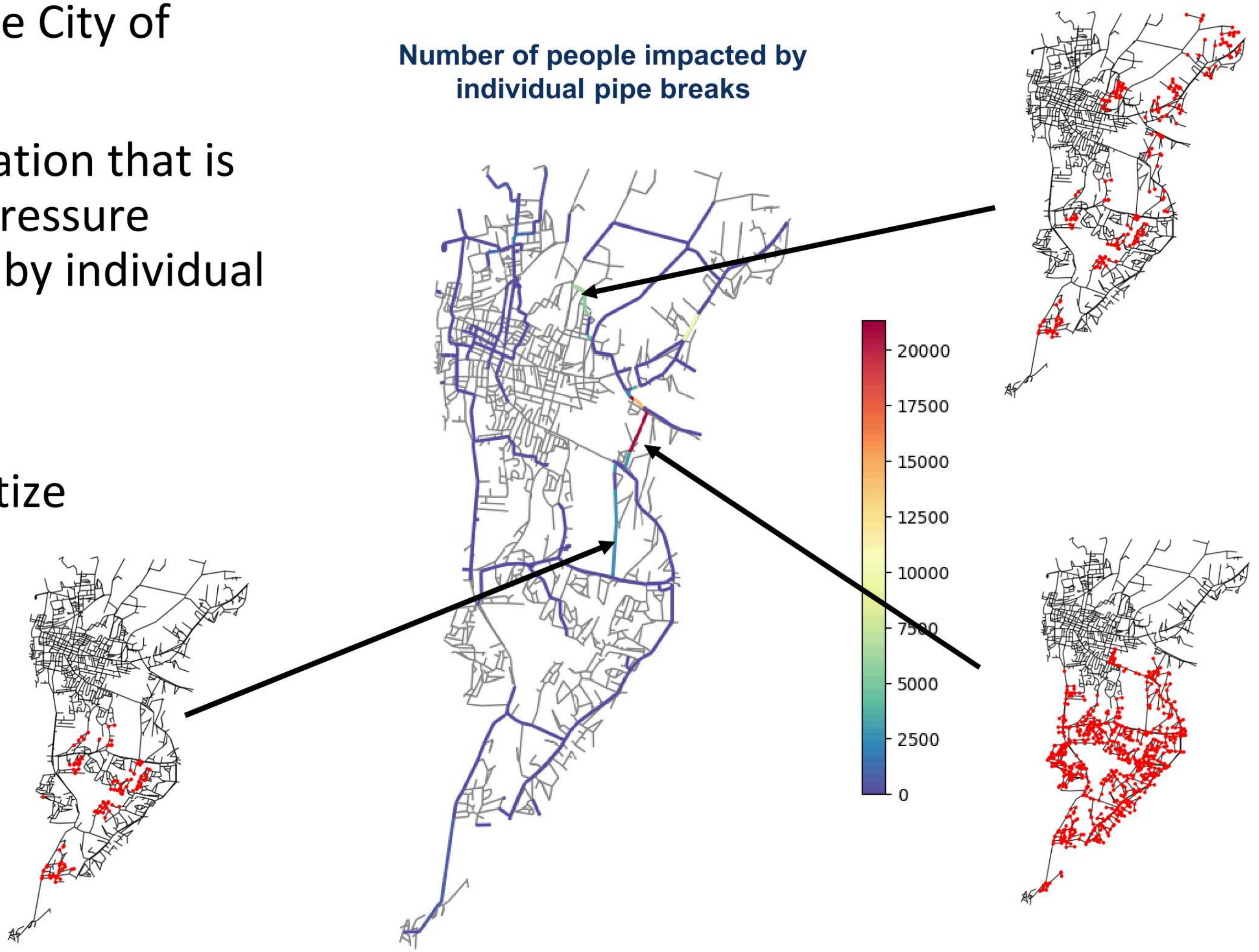
- Case study with the City of Poughkeepsie, NY
- Loss of source due to river contamination, treatment plant failure, winter storm freezing intake, or power outage.
- Track water pressure and water service availability over time
- Test mitigation strategies





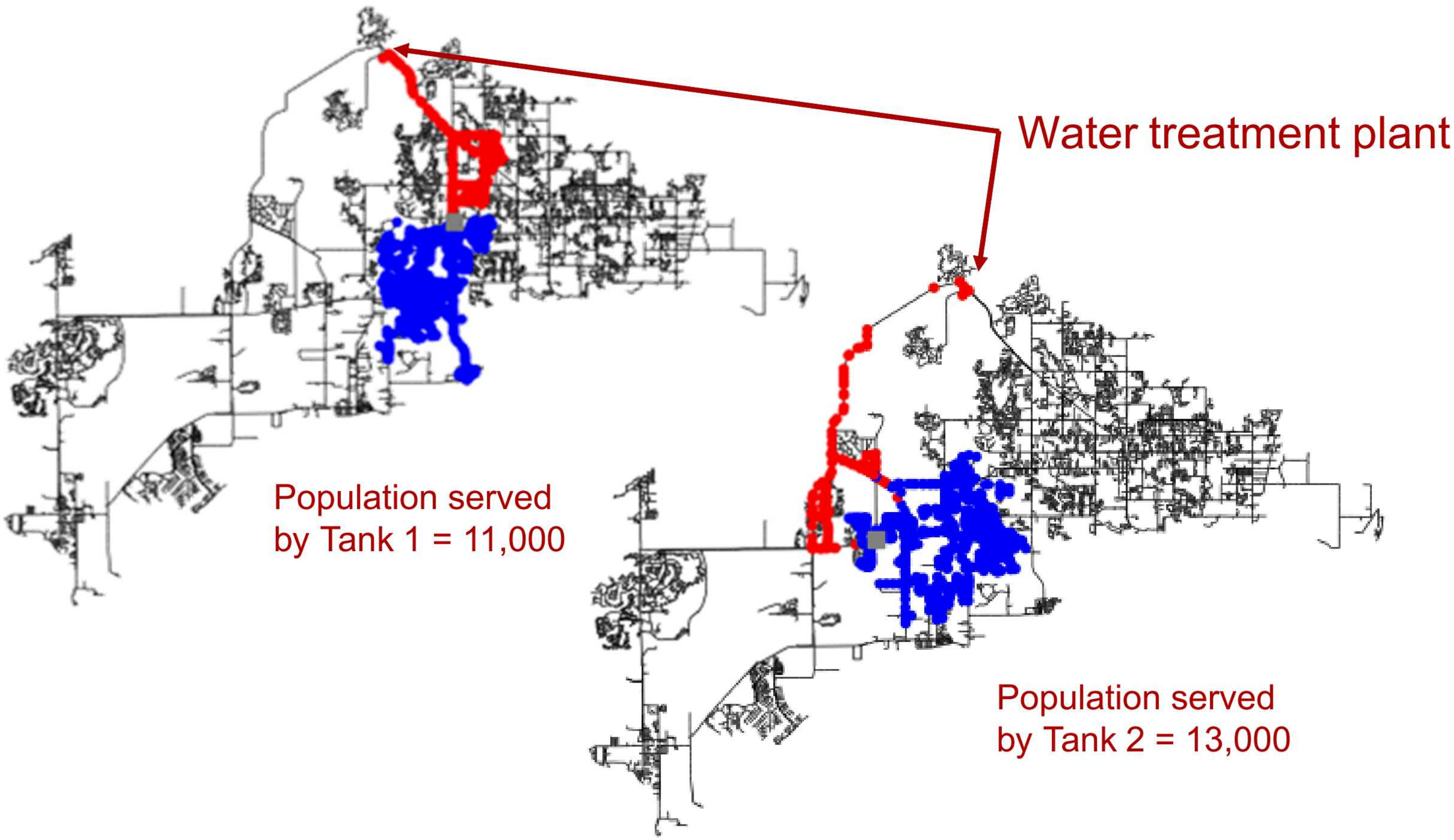
Pipe Criticality Analysis

- Case study with the City of Poughkeepsie, NY
- Identify the population that is impacted by low pressure conditions caused by individual pipe breaks
- N-1 analysis
- Results help prioritize investment



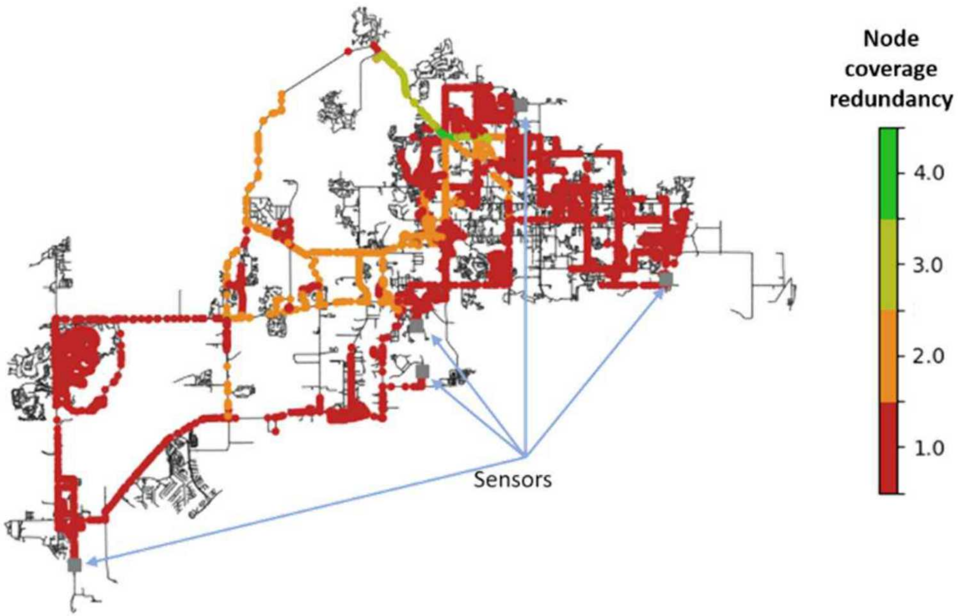
Hydraulic Connectivity Analysis

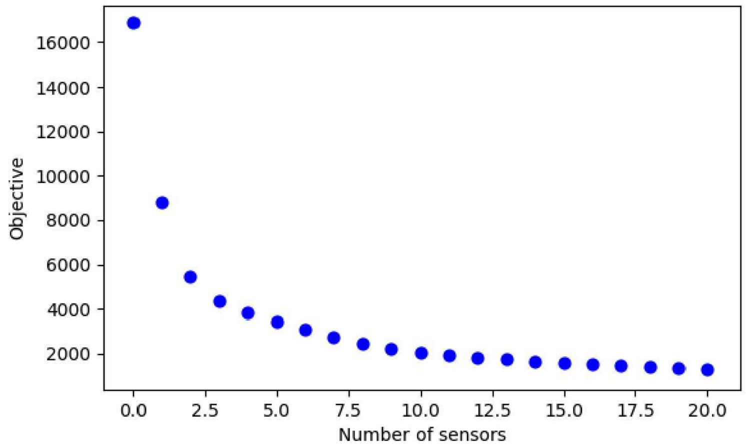
- Compute location of all upstream and downstream nodes
- Evaluate critical paths between water treatment plant and customers



Sensor Placement Optimization

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



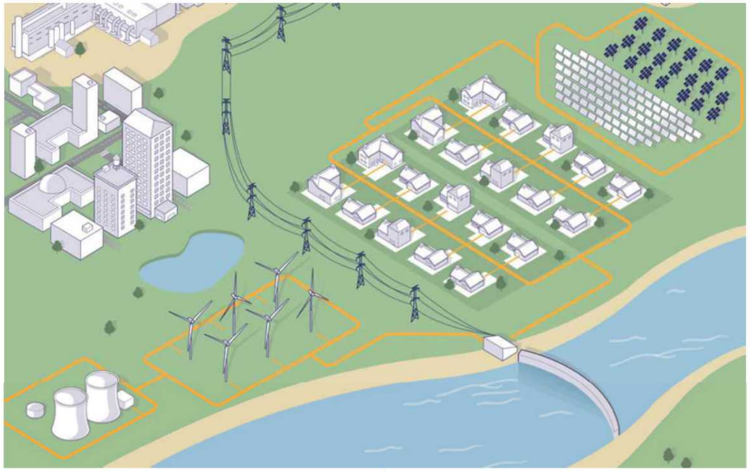


https://github.com/Pyomo
https://github.com/sandialabs/chama

Infrastructure Dependency

- Resilience of the water system is highly dependent on other sectors, including
  - Electricity grid
  - Natural gas
  - Transportation network
  - Cyber, communication

- Resilience analysis applied across multiple infrastructures
  - Data analytics
  - Sensor placement
  - Simulation and optimization
  - Resilience and risk assessment
  - Microgrid/islanding capabilities
  - Capacity expansion
  - Emergency response plans



Conclusions

- Sandia and the EPA are developing a wide range of capabilities to help water utilities do a “deeper dive” into understanding the resilience of their drinking water system
- By integrating hydraulic models and resilience metrics, water utilities can quantify the benefit of response actions and long-term mitigation strategies
- Open-source software makes these methods available to a wide audience
- Water utilities are invited to work with Sandia and the EPA on case studies

WNTR

Water Network Tool for Resilience

https://github.com/usepa/WNTR
http://wntr.readthedocs.io