# Open Source Software to Analyze Water Distribution System Resilience

Erice Water Webinar

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# Funding Agency and Team

**Environmental Protection Agency**

Office of Research and Development

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**Sandia National Laboratories**

- Water Energy System Integration: Katherine Klise
- Geotechnology and Engineering: David Hart and Joseph Hogge
- Discrete Math and Optimization: Michael Bynum and Carl Laird

# Outline

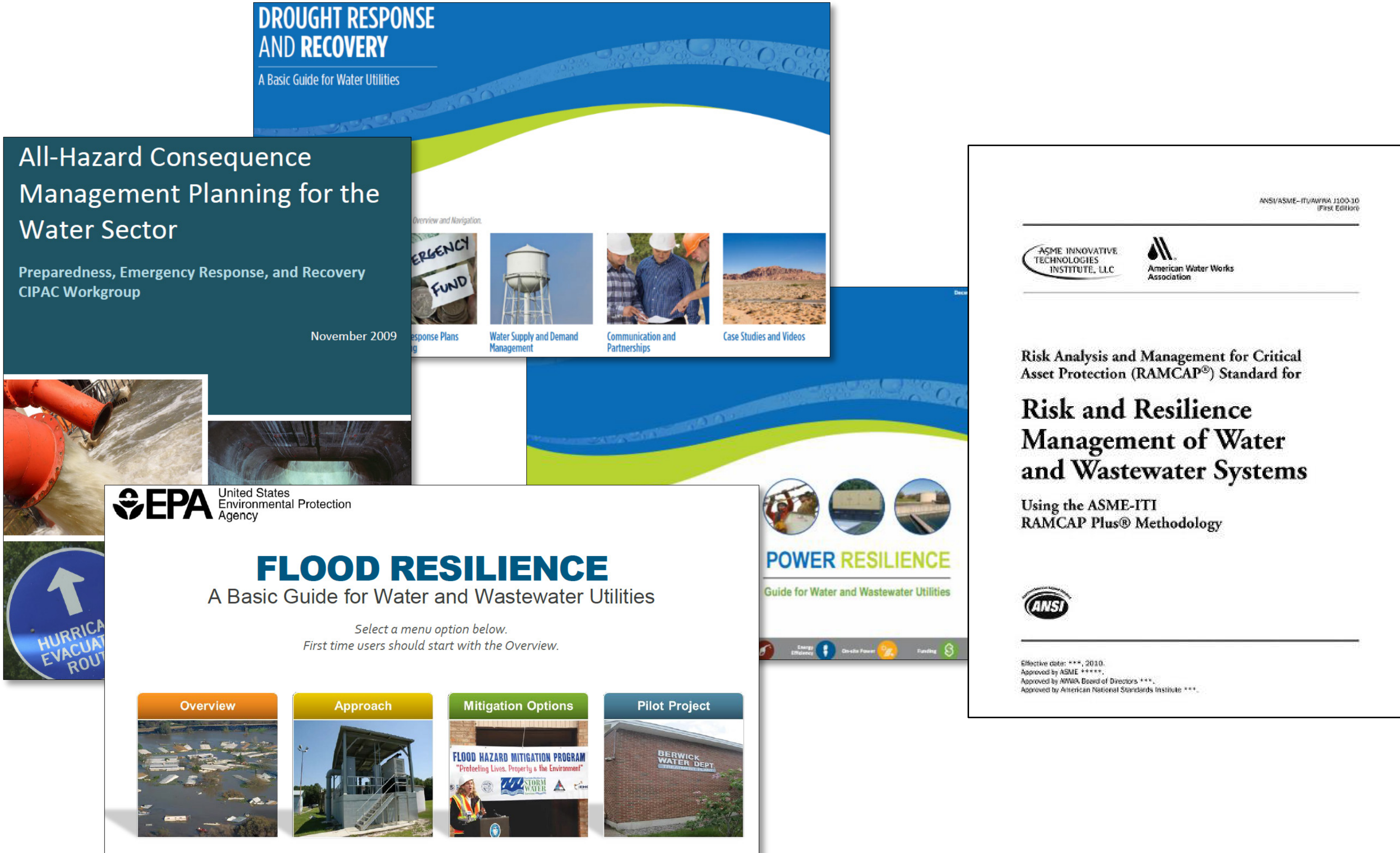
- Motivation and background
- Water sector resilience guidance and resilience policies
- Utility specific needs
- Water Network Tool for Resilience framework
  - Water network models
  - Hydraulic and water quality simulation
  - Modeling disruptive incidents and restoration actions
  - Quantifying resilience
- Examples
  - Earthquake analysis
  - Hurricane analysis
  - Compromised water source analysis
  - Pipe criticality analysis
  - Hydraulic connectivity analysis
  - Sensor placement optimization
- Conclusions

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

# Water Sector Resilience Guidance



# 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

# 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?

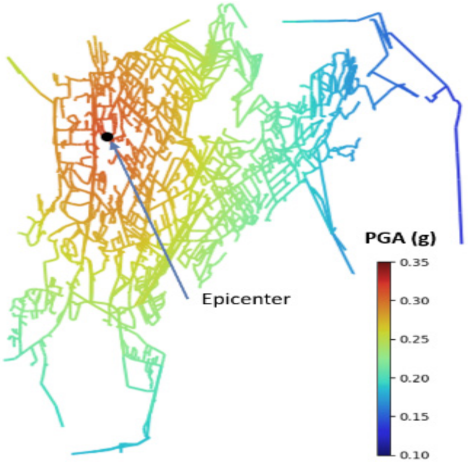
# Water Network Tool for Resilience

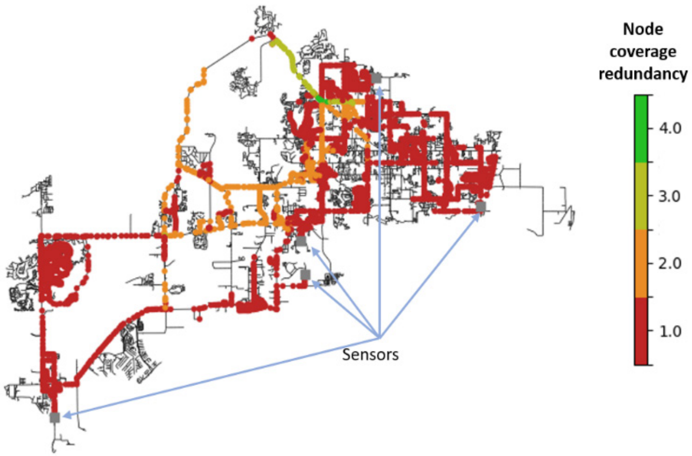
WNTR is designed to analyze water distribution system failure and recovery

- 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

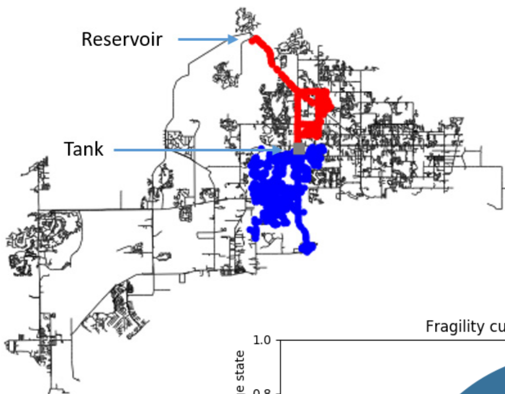
WNTR
Water Network Tool for Resilience

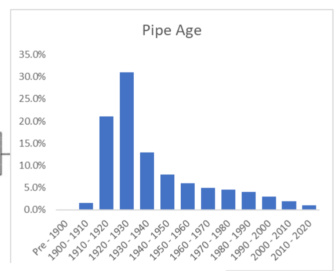


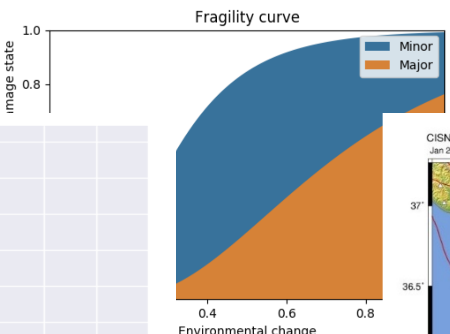



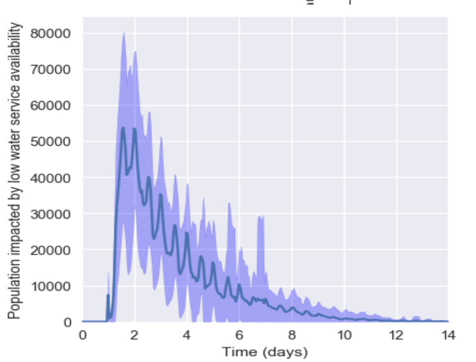
# WNTR Framework

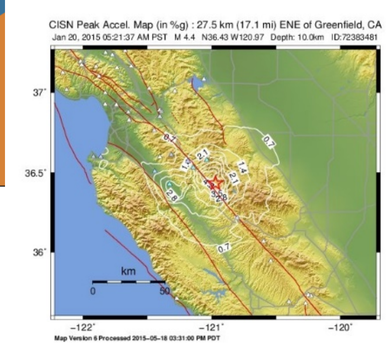
- EPANET is the industry standard for water distribution hydraulic and water quality modeling
- The Water Network Tool for Resilience, WNTR, builds on capabilities in EPANET to analyze water distribution resilience

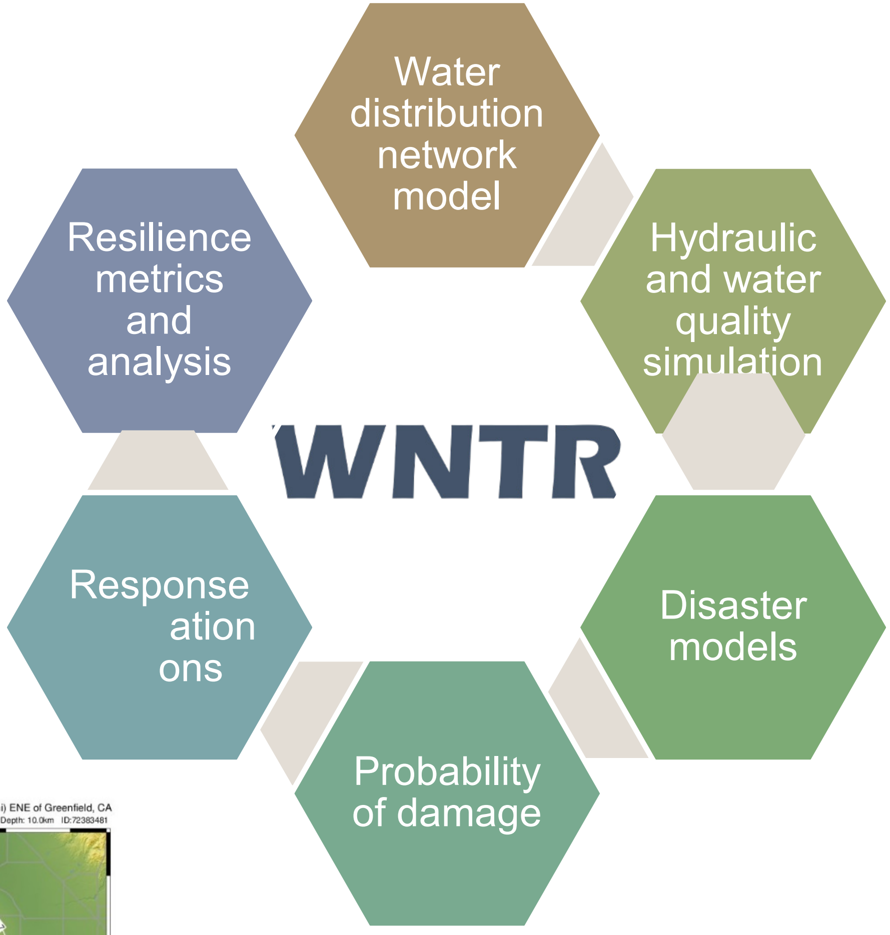


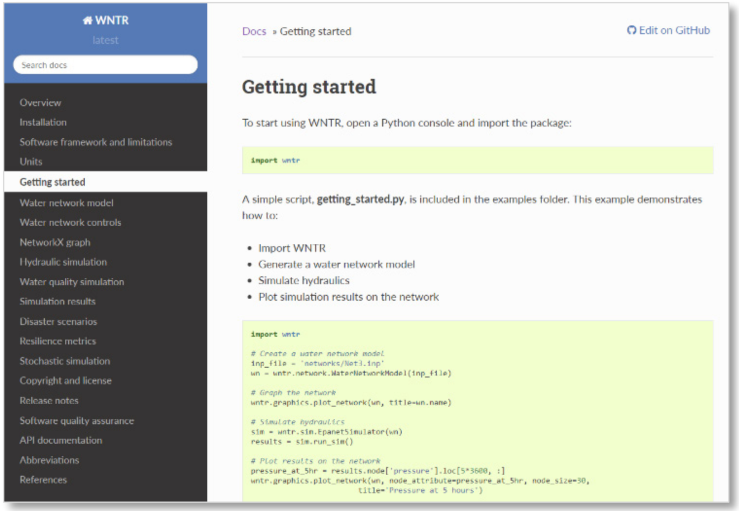



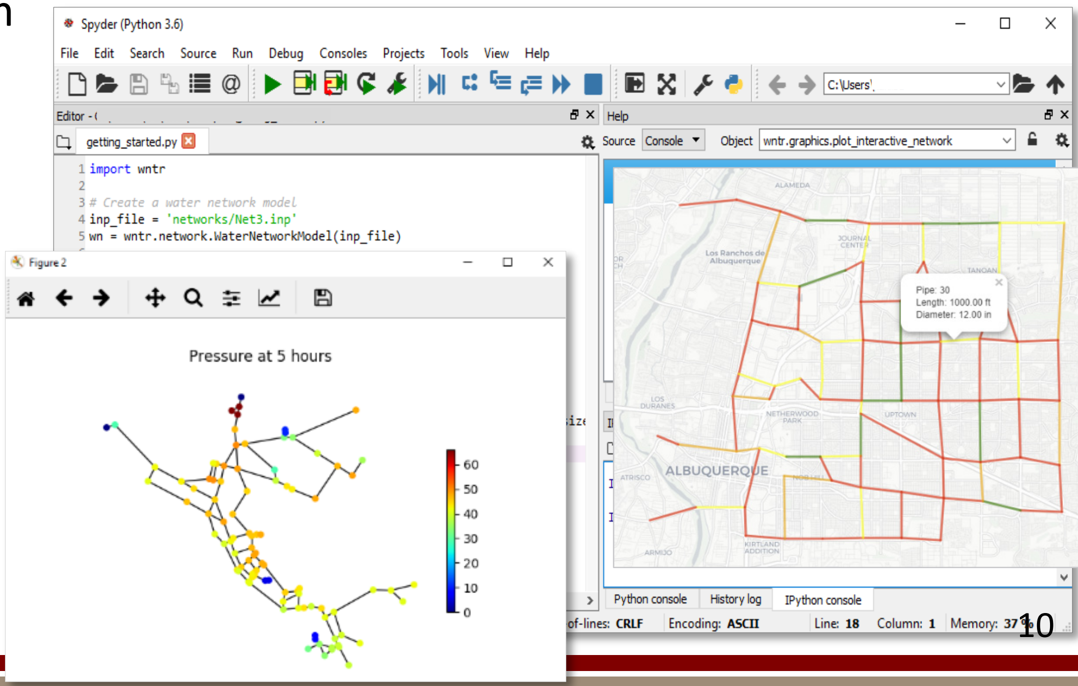




https://github.com/usepa/wntr

# WNTR Framework

- Open source Python package
- 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



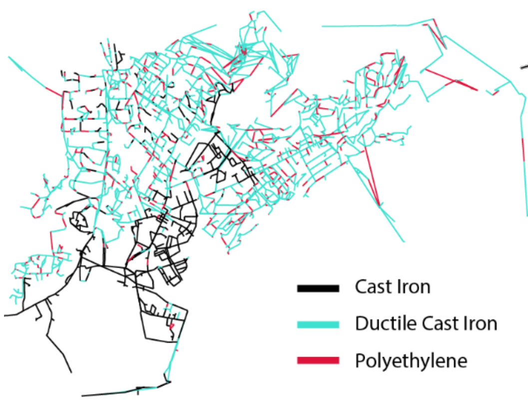



# Water Network Models

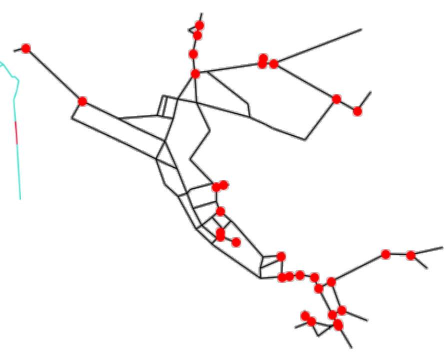
- Generate network models from EPANET INP files or from scratch
- Model contains physical layout and system operations
  - Nodes: Junctions, Tanks, Reservoirs
  - Link: Pipes, Valves, Pumps
  - Demands
  - Controls
  - Simulation options
- Add/remove/modify components
- Query node/link attributes
- Skeletonize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

**Original network**

**Skeletonized network**

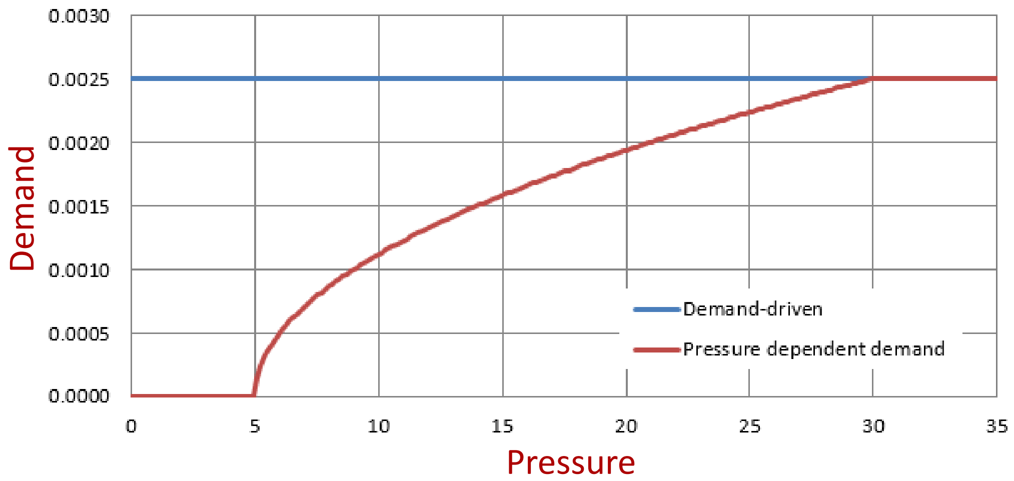



**Articulation points**



# 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




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

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

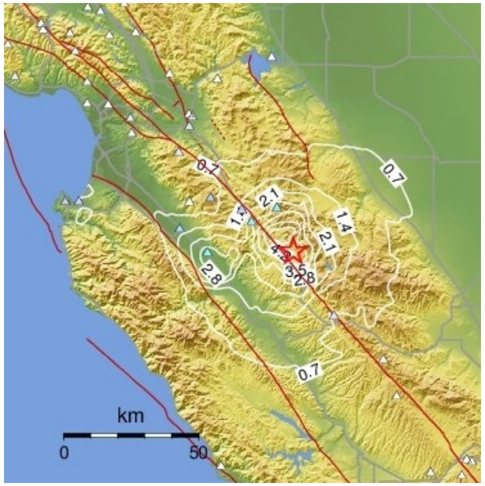
$$d = 0 \quad \text{for } p \leq P_o$$

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

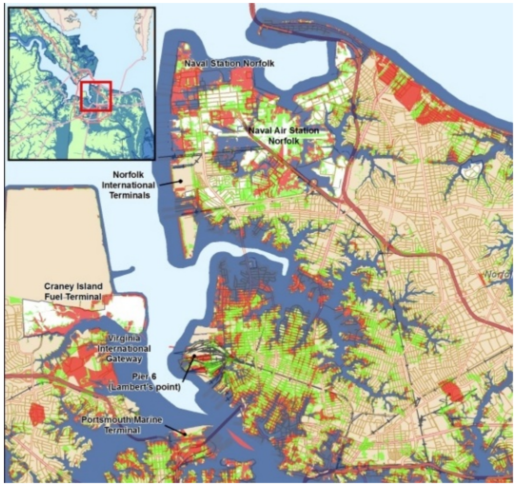
# Modeling Disruptive Incidents

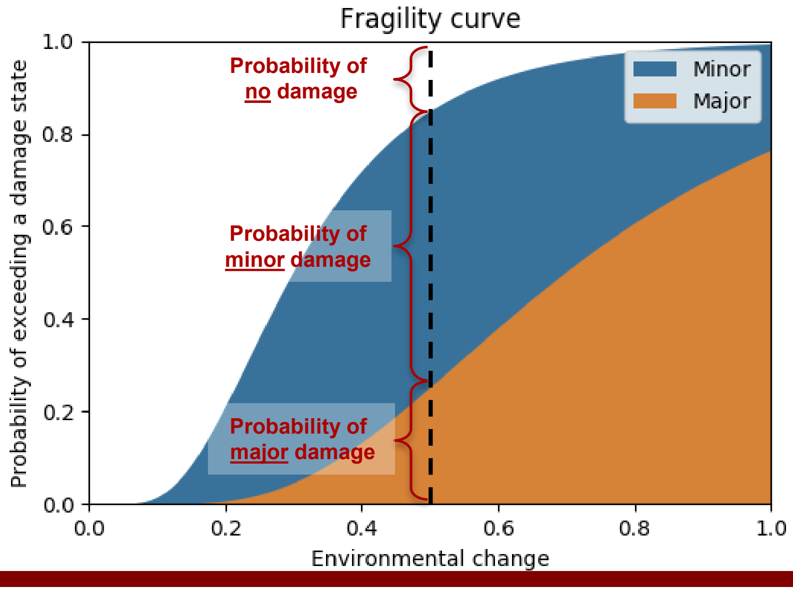
- Define disruptive incident
  - Informed by data or a model
- Define probability of damage
  - Fragility and survival curves
- Modify the model
  - Controls, demands, components, attributes to match each scenario

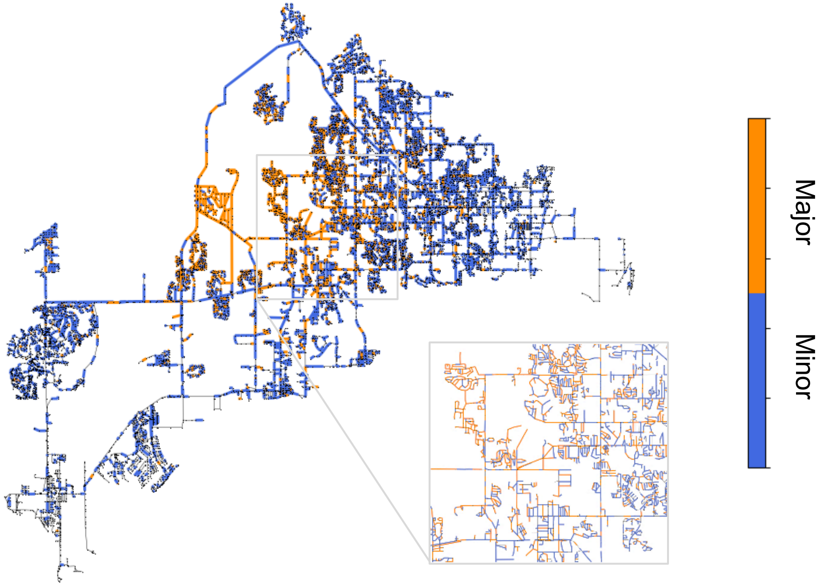
PGA after an earthquake in California (USGS)




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



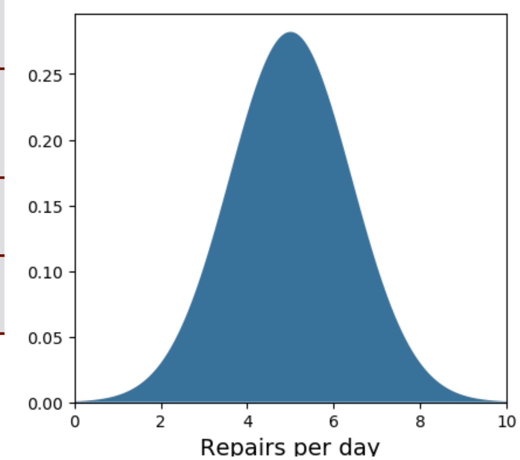


# Modeling Restoration Actions

- Define the restoration action
  - Type of repair actions
  - Number of crews
  - Time to repair
  - Supply chain
- Define priorities
  - Distance from the reservoir or maintenance yard
  - 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 |

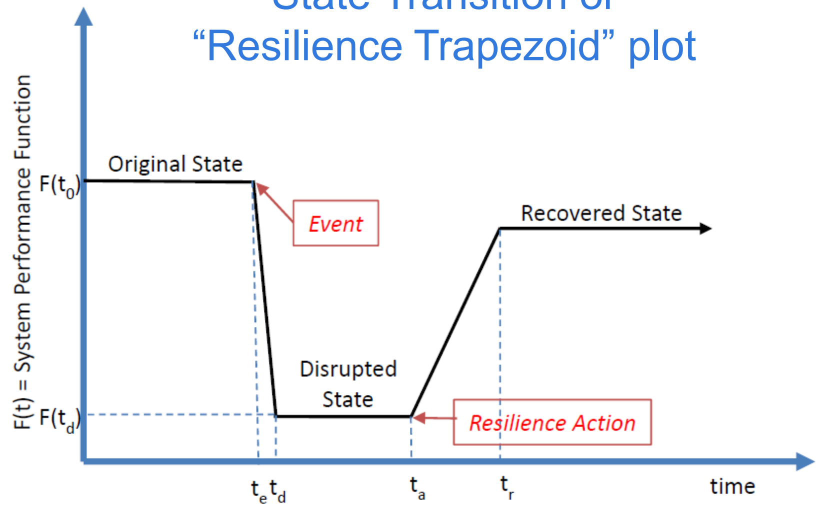


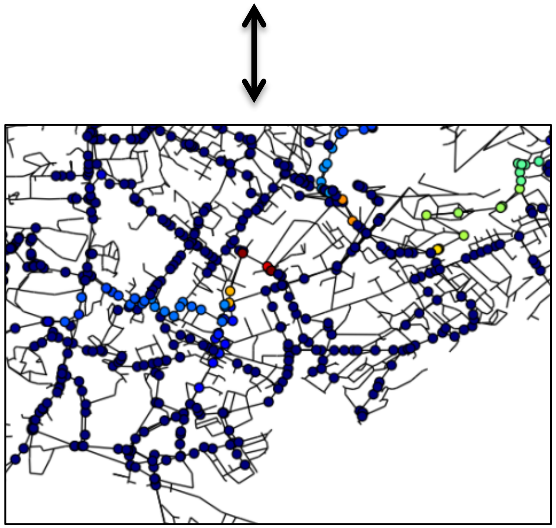
# Quantifying Resilience

- 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

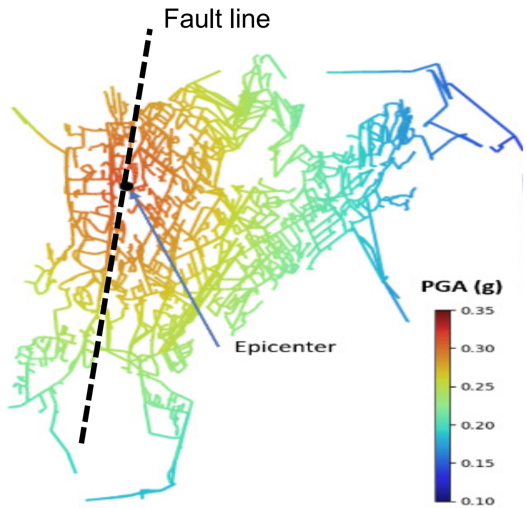


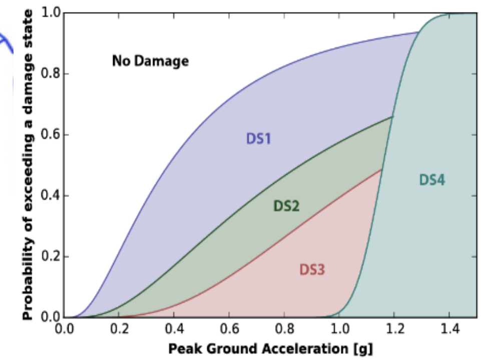



# Earthquake Analysis

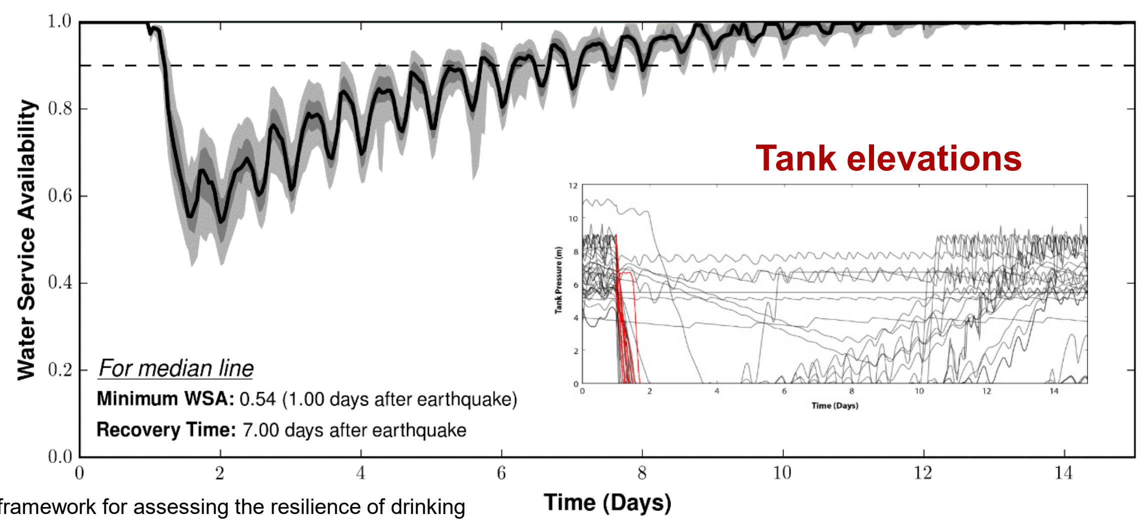
Sandia National Laboratories

- 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



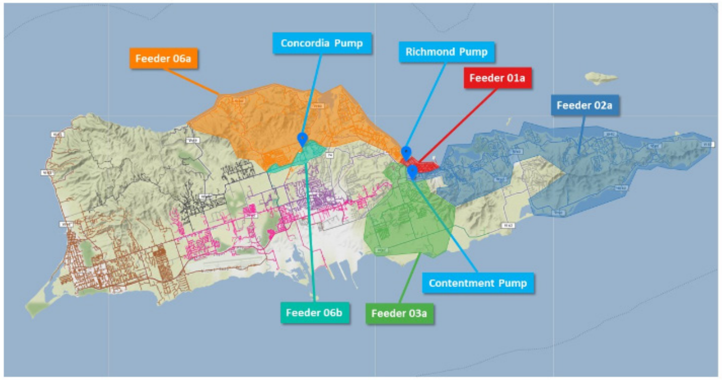

Klise, K.A., Bynum, M., Moriarty, D. and Murray, R., 2017. A software framework for assessing the resilience of drinking water systems to disasters with an example earthquake case study. *Environmental Modelling & Software*, *95*, pp.420-431.

# Hurricane Analysis

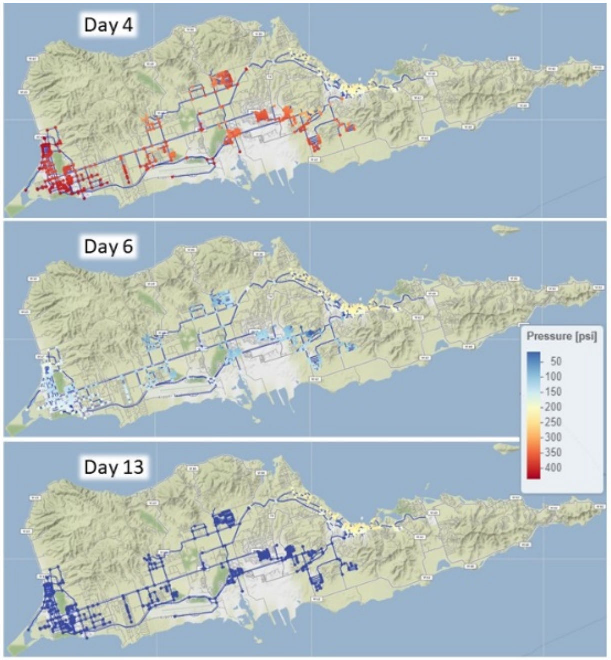


- Water-power resilience analysis in response to Category 5 hurricanes (Irma and Maria) that hit the US Virgin Islands
- Partnership with Naval Post Graduate School and Virgin Islands Water and Power Authority
- Couple detailed water and power infrastructure models with key dependencies
- Monte Carlo simulations track the 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**



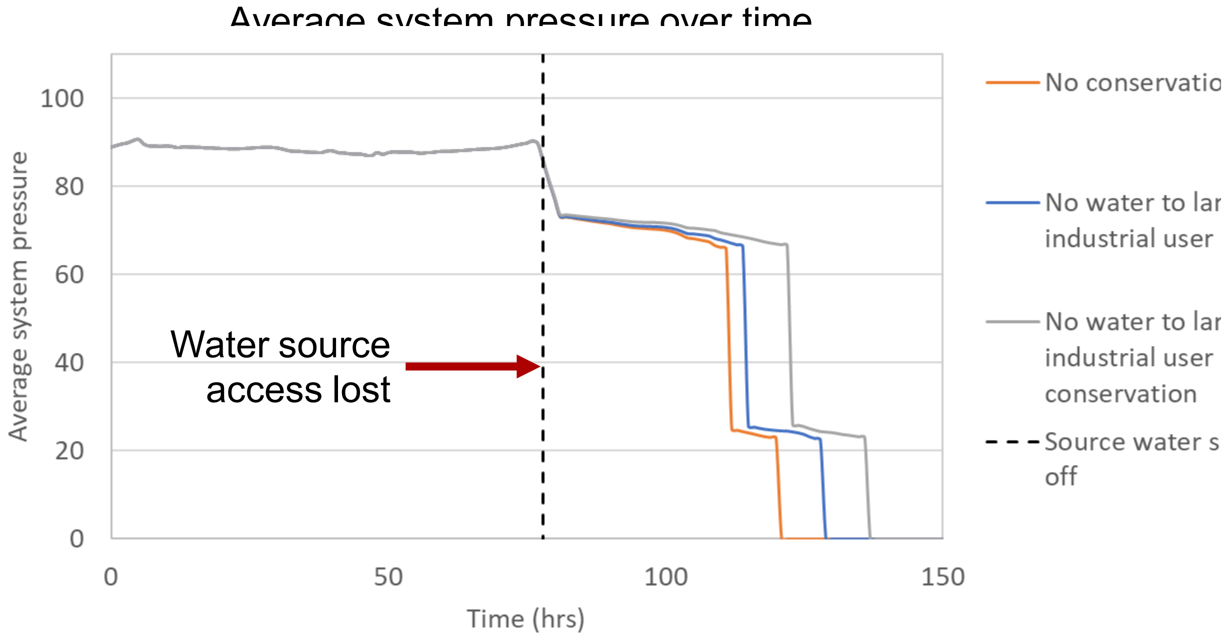

**Water pressure after power outage at a single pump station**

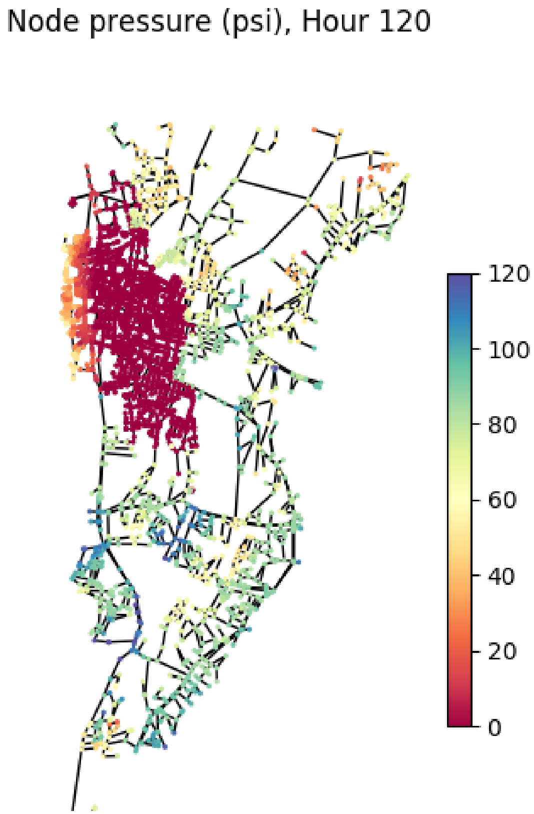



Wille, D, 2019, Simulation Optimization for Operational Resilience of Interdependent Water-Power Systems in the US Virgin Islands, M.S. Thesis in Operations Research, Naval Postgraduate School, Monterey, CA.

# 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

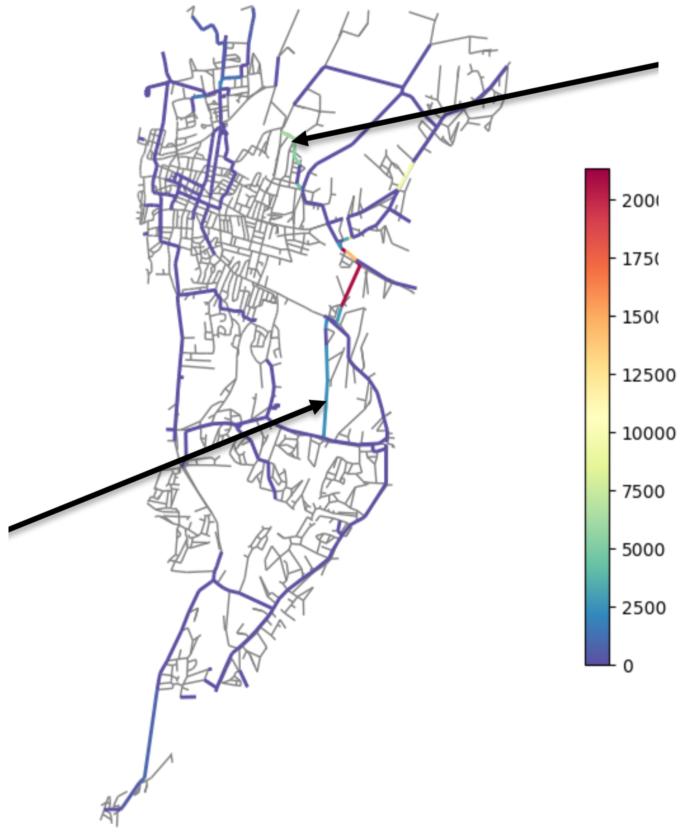


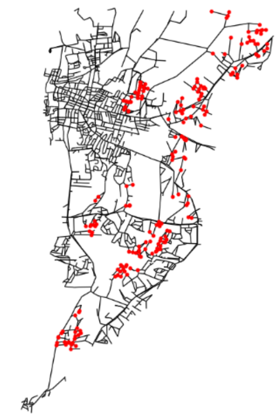



# Pipe Criticality Analysis

- 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
- Currently extending the analysis to include valve segments

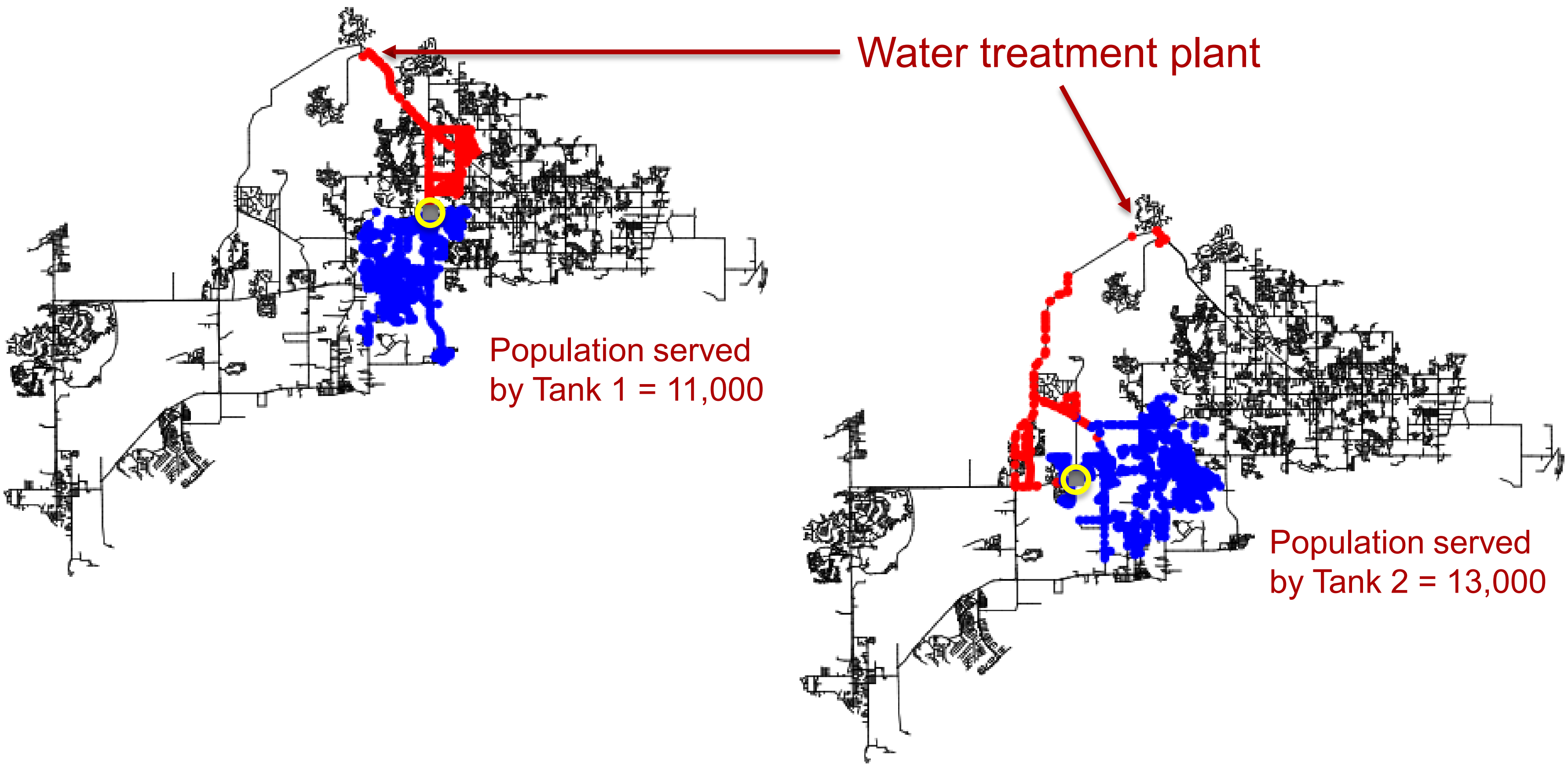
**Number of people impacted by individual pipe breaks**



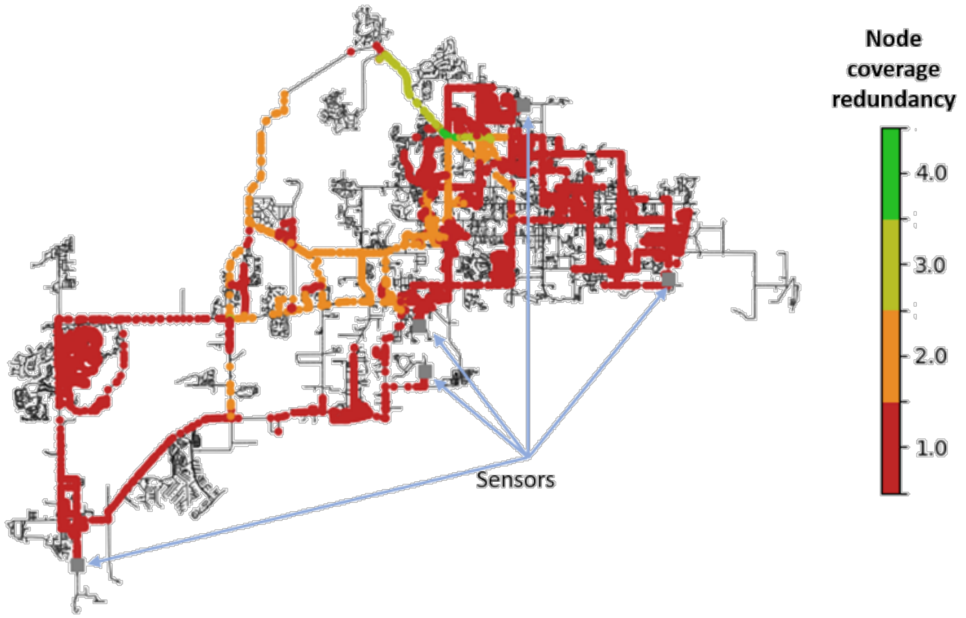
# Hydraulic Connectivity Analysis

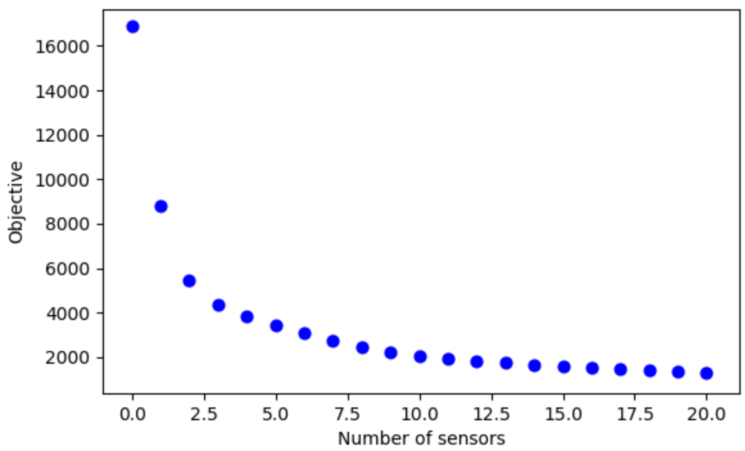
- Evaluate critical paths between water treatment plant and customers
- Compute upstream and downstream nodes from tanks, valves, pumps



# Sensor Placement Optimization

- 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

Klise, K.A., Nicholson, B. and Laird, C.D., 2017. Sensor Placement Optimization using Chama, SAND-2017-11472, Sandia National Laboratories, Albuquerque, NM

# 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, research groups, and government organizations 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