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Open Source Software for Water Distribution Resilience Analysis

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Sandia National Laboratories

EPA United States Environmental Protection Agency

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Background

- Recent natural disasters and environmental emergencies have highlighted the vulnerability of water infrastructure:
  - Hurricane Maria / Puerto Rico
  - Hurricane Harvey / Texas
  - Elk River Spill / Charleston, West Virginia
  - Lead contamination / Flint, Michigan
- General guidance on preparedness and resilience is available
- Utilities need quantitative site-specific analysis to justify capital investments that build resilience

Resilience Lifecycle

1. Understand your system
    - Who and where are your customers?
    - Where are your pipes, valves, pumps, etc.
    - What can you control? What can you not control?

1. Understand the threats to your system
    - Earthquakes? Hurricanes? Contamination?

- Consider possible resilience enhancing actions

1. Develop a model of your system

2. Evaluate the effect of threats to your system

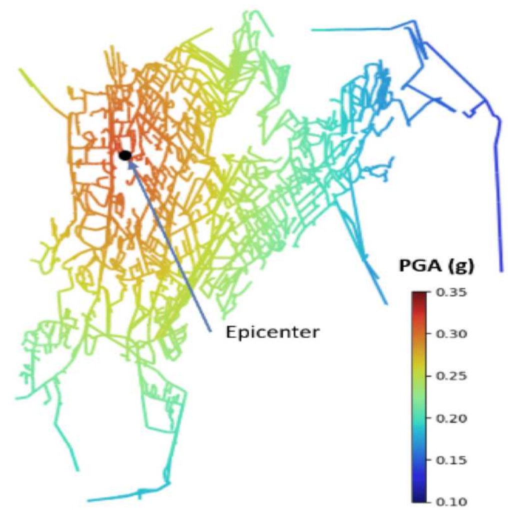
1. Prioritize resilience enhancing actions

WNTR

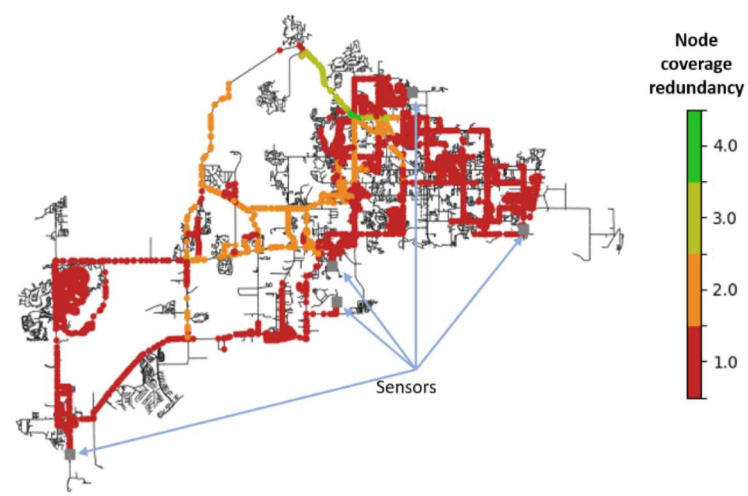
Water Network Tool for Resilience

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



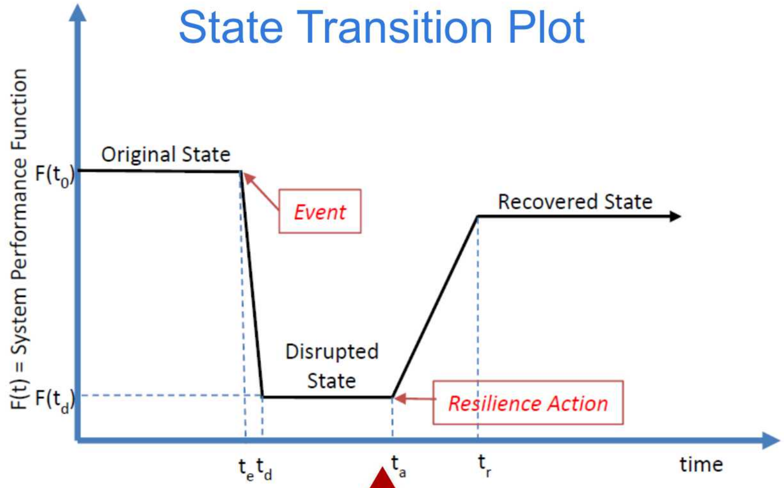
- Evaluate and prioritize resilience-enhancing actions
  - Isolate and repair pipe breaks
  - Change valve and tank operation to maintain water service
  - Install backup generation
  - Plan flushing or water conservation mandates
  - Evaluate sampling locations
  - Evaluate fire fighting capacity

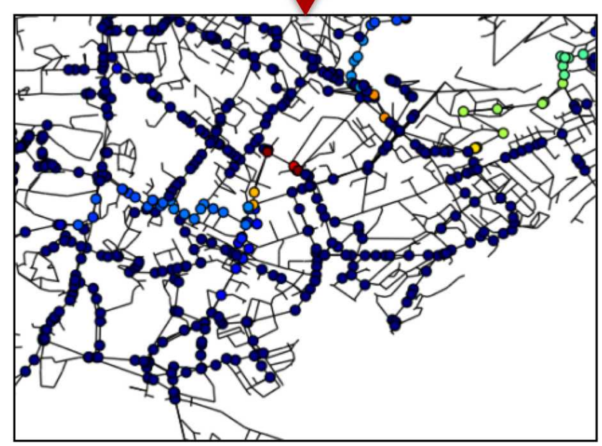


Quantifying Resilience

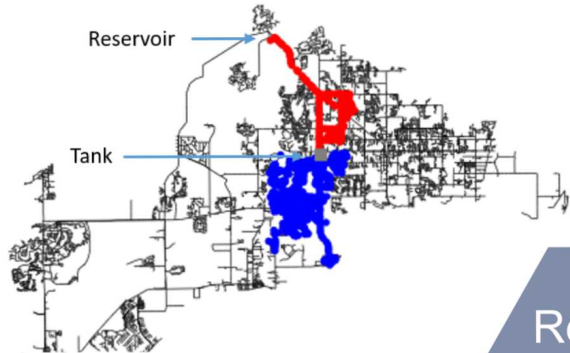
- Numerous metrics have been suggested to quantify reliability, robustness, redundancy, and security for water distribution networks
  - Topographic metrics
  - Hydraulic metrics
  - Water quality metrics
  - Economic metrics

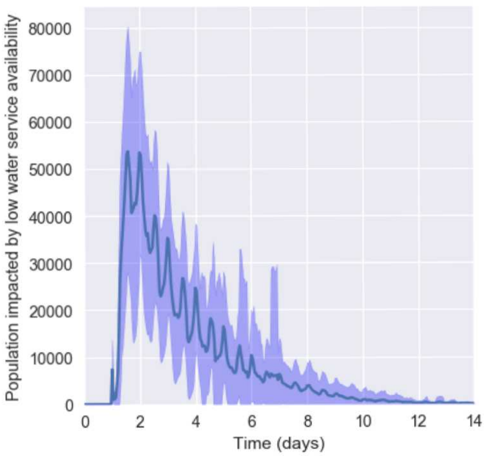
- State transition plots graphically represent the meaning of resilience
  - System performance function, event, and resilience action must be clearly defined
  - Resilience is typically defined as a system measure, but could be measured for individual components of the network

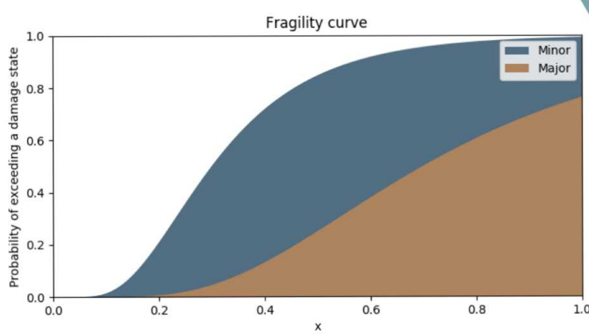


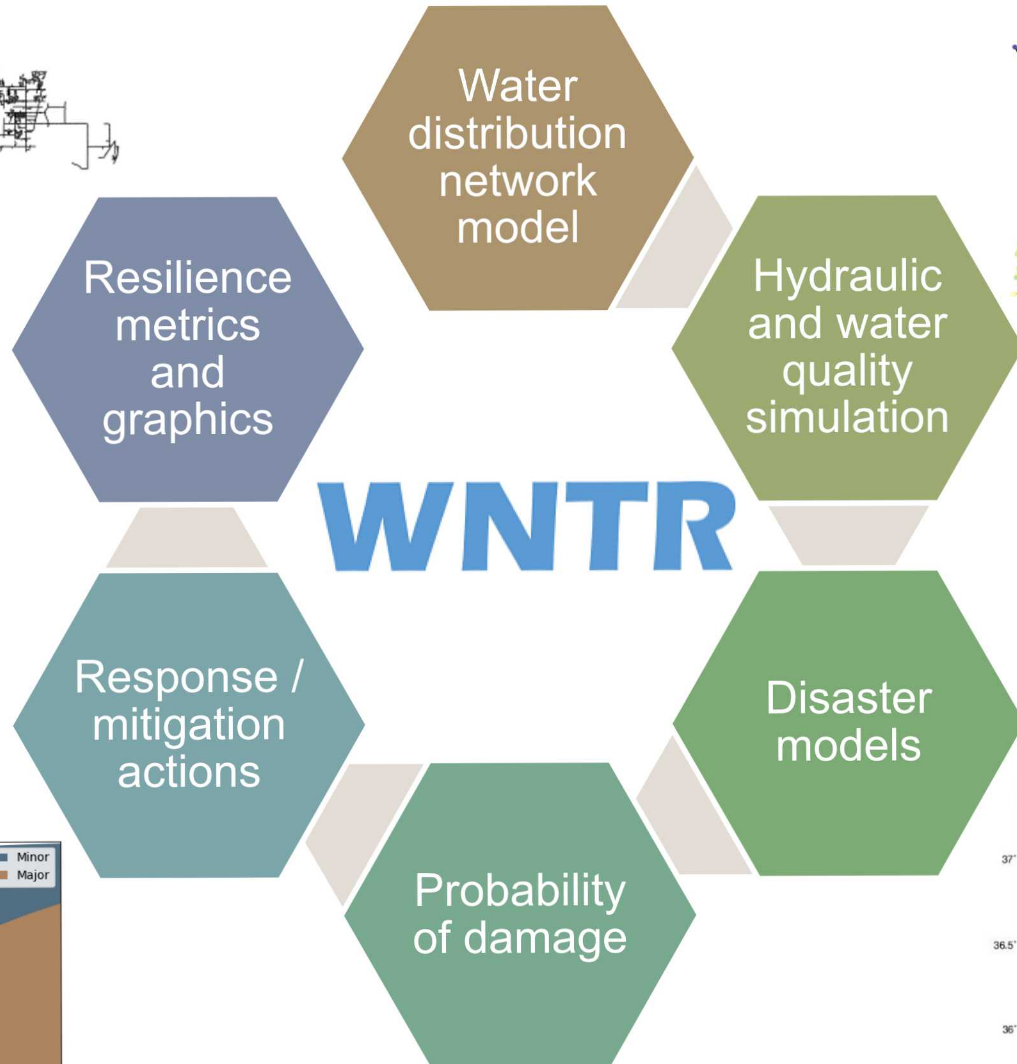


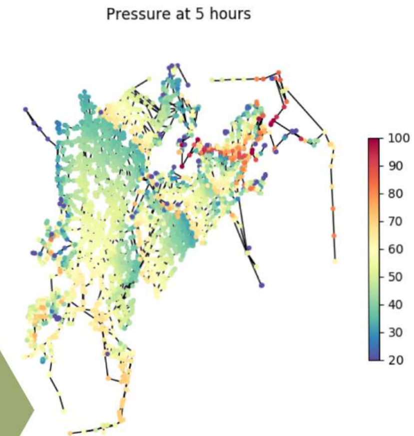
WNTR Framework

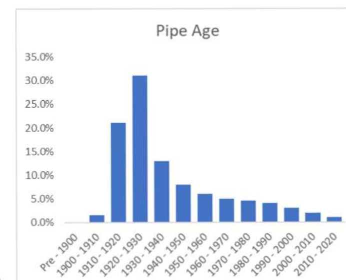




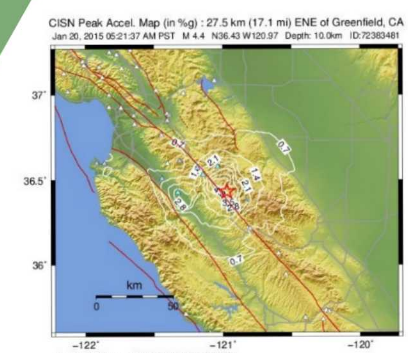








From Circle of Blue



From USGS Shakemap

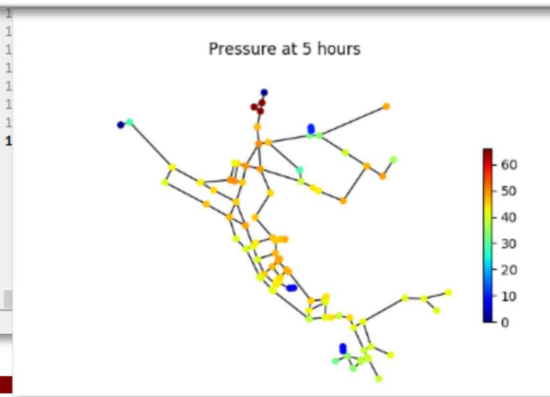
WNTR Framework

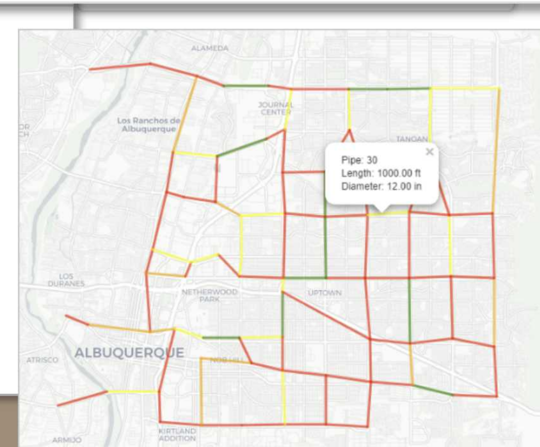
- Compatible with Python 2.7, 3.4, 3.5, and 3.6 and open source integrated development environments


```python
import wntr

# Create a water network model
inp_file = 'Net3.inp'
wn = wntr.network.WaterNetworkModel(inp_file)

# Simulate hydraulics
sim = wntr.sim.WNTRSimulator(wn, mode='PDD')
results = sim.run_sim()

# Plot results on the network
pressure_5hr = results.node['pressure'].loc[5*3600, :]
wntr.graphics.plot_network(wn, node_attribute=pressure_5hr, title='Pressure at 5 hours')
```

extensive online testing and documentation

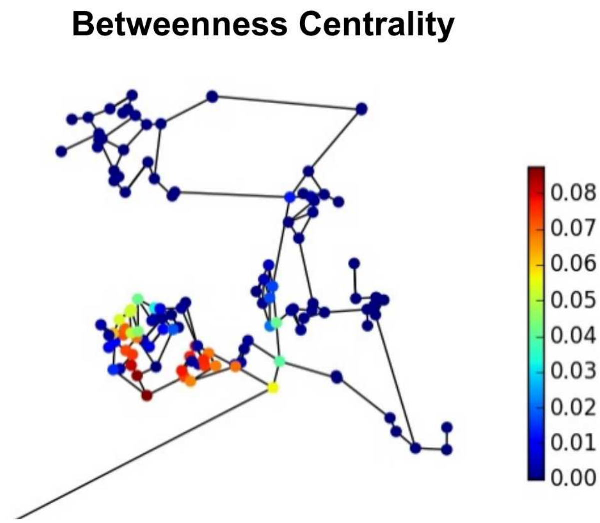
  - GitHub
  - TravisCI
  - ReadtheDocs

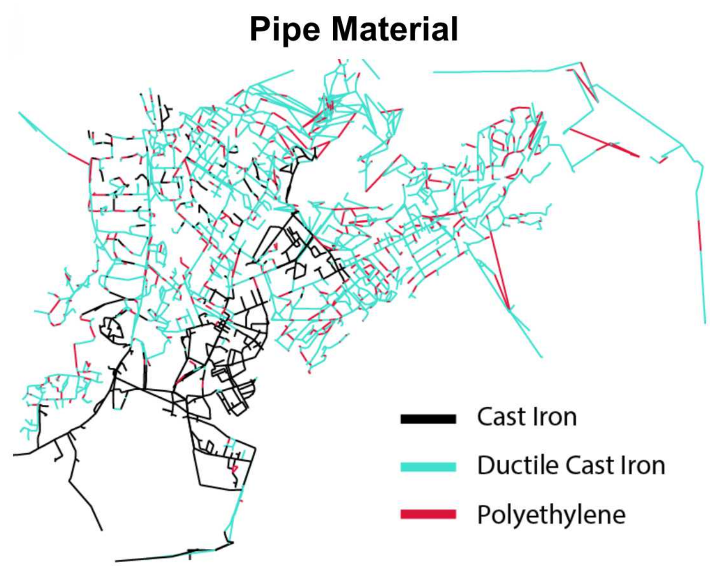




Network Models

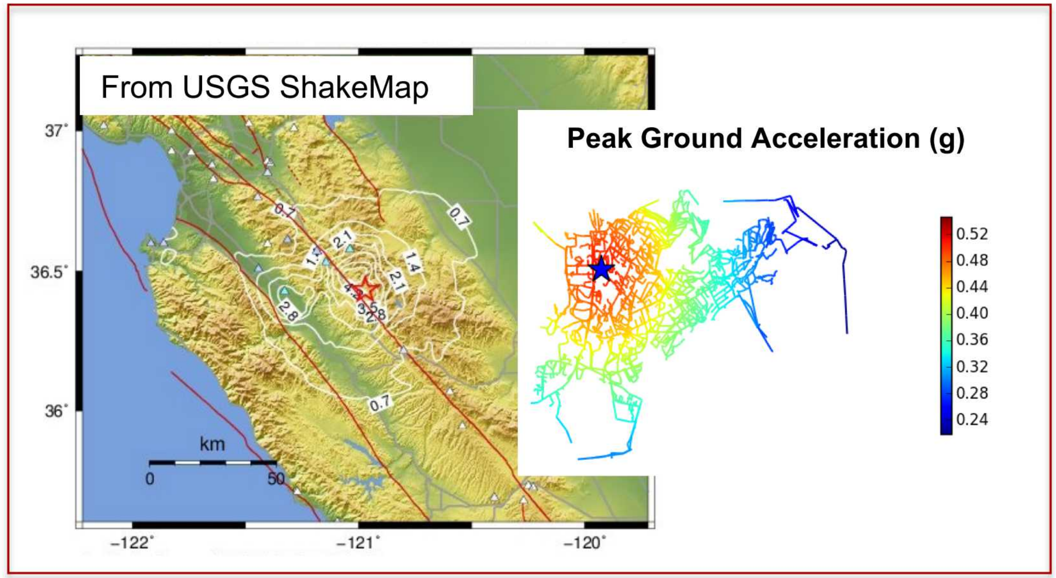
- WNTR is EPANET compatible
  - Generate network models from EPANET INP files
  - Complete unit converter and read/write functionality
- Generate network models from scratch
- Add/remove network components and controls
- Modify and query node/link attributes
- Plot node/link attributes on the network
- Analyze network structure using NetworkX

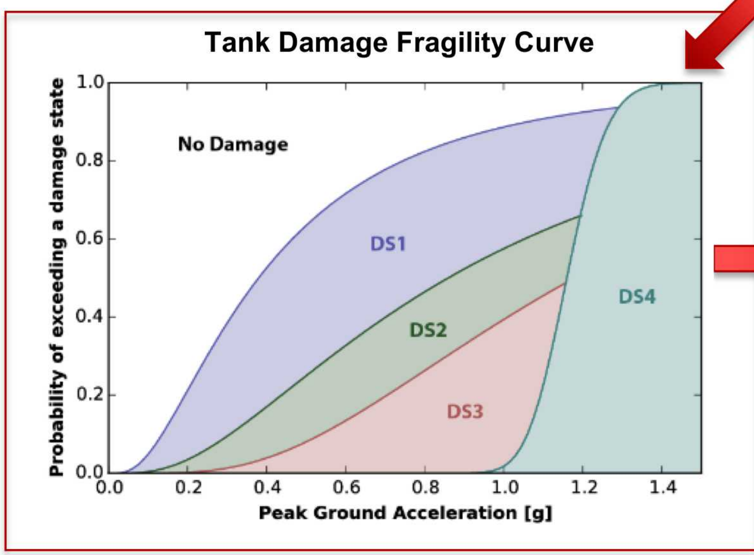


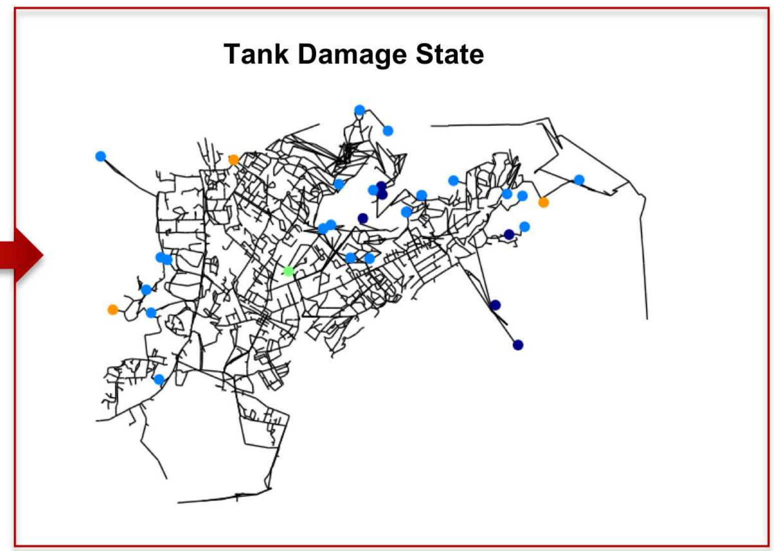


Disruptive Incidents

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



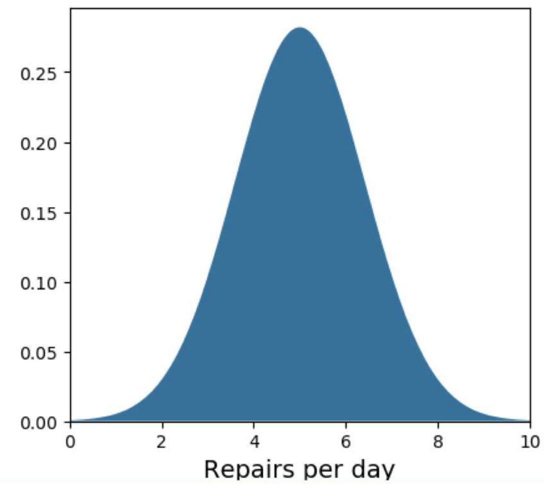




Restoration Actions

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

Repair Strategy Following 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



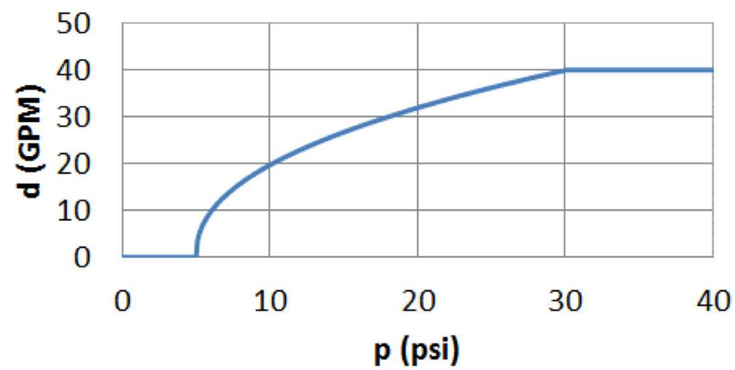
Hydraulic and Water Quality Simulation

- Demand-driven hydraulic simulation and water quality simulation using EPANET
- Pressure dependent demand hydraulic simulation
  - Demand at a node, *d*, depends on the pressure, *p*, available at the node
  - Input parameters = nominal pressure (P_f) and minimum pressure (P_o)

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

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

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

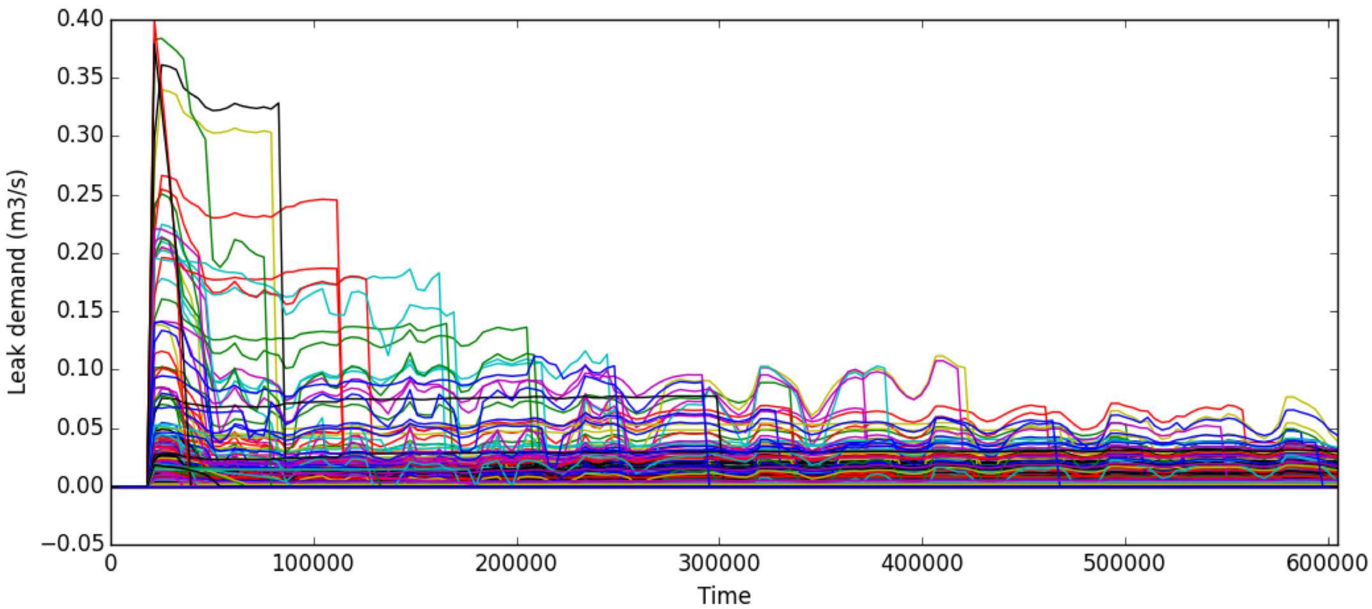


- Simulation start/stop capabilities
- Feedback loops
- Monte Carlo simulation
- Parallelization

Leak Model

- Explicitly model water lost between the time when the leak starts and the time when crews can isolate/repair the leak
  - Leak demand, d_{leak}, depends on pressure, p, at that node
  - Input parameters: discharge coefficient (C_d) and area (A), α set to 0.5

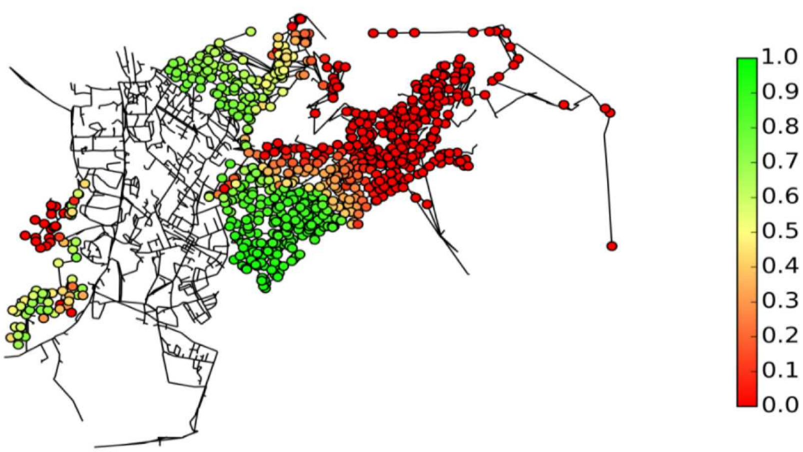
$$d_{leak} = C_d A \sqrt{2\rho} p^{\alpha}$$



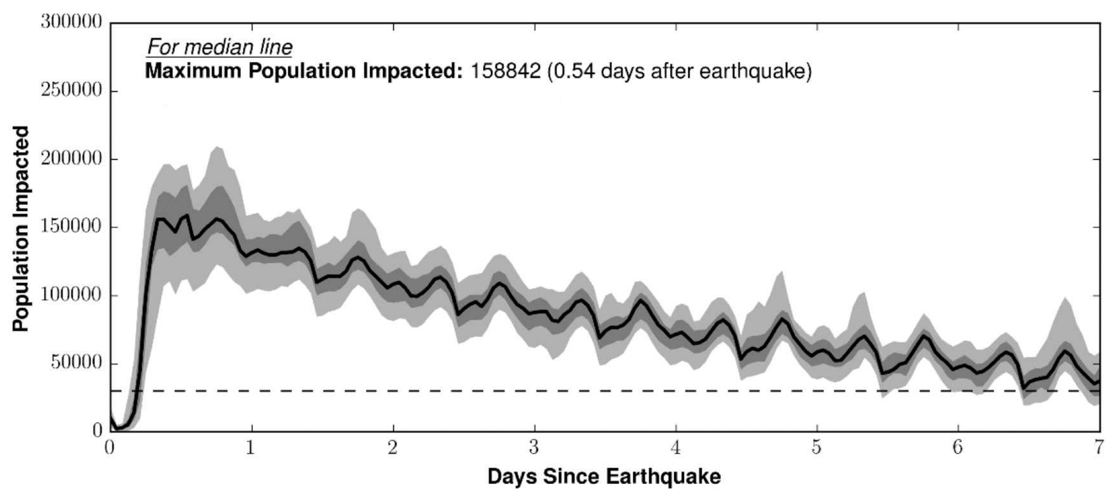
Resilience Metrics

Topographic	Shortest path lengths, bridges, articulation points, betweenness centrality
Hydraulic	Pressure above/below threshold, Todini index, entropy, water service availability, population impacted by hydraulic metrics
Water quality/security	Concentration above/below threshold, water age, mass consumed, extent of contamination, population impacted by water quality/security metrics
Economic	Network cost, greenhouse gas emissions

Water service availability after a power outage



Population impacted after an earthquake



WNTR Applications

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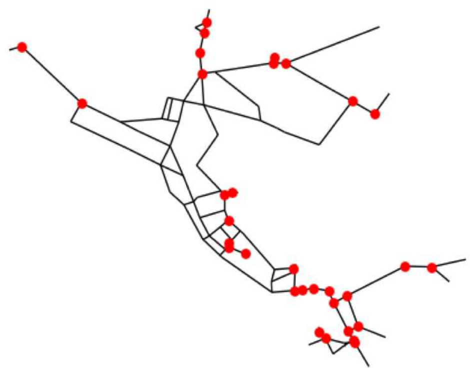
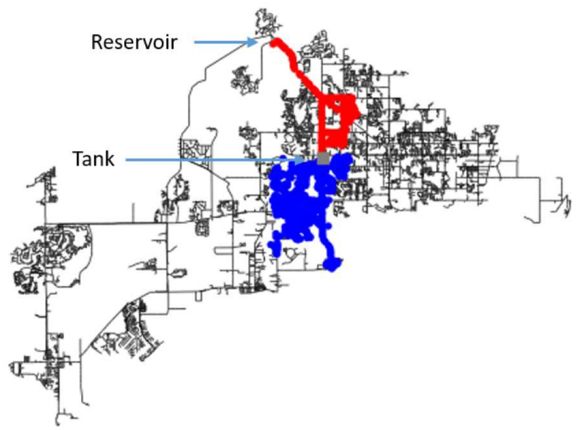
Topographic analysis

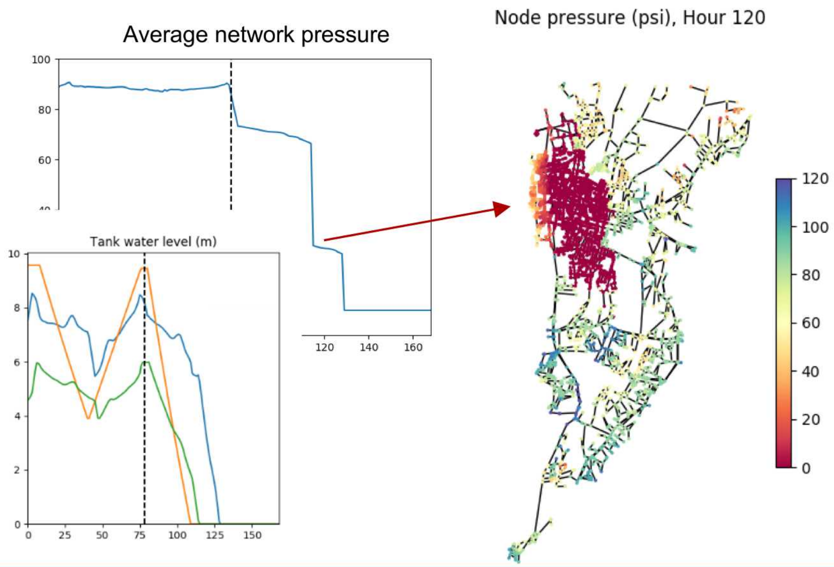


Hydraulic connectivity analysis

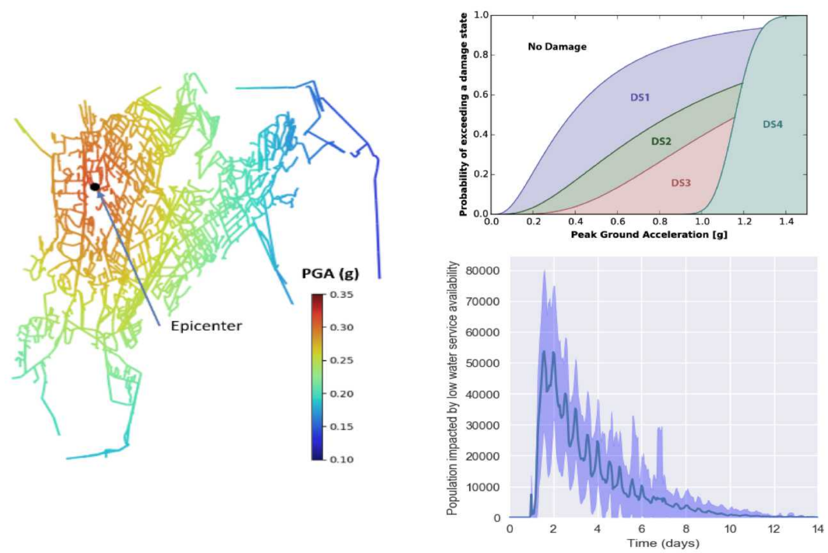


Pipe criticality analysis

Power outage or compromised source water analysis



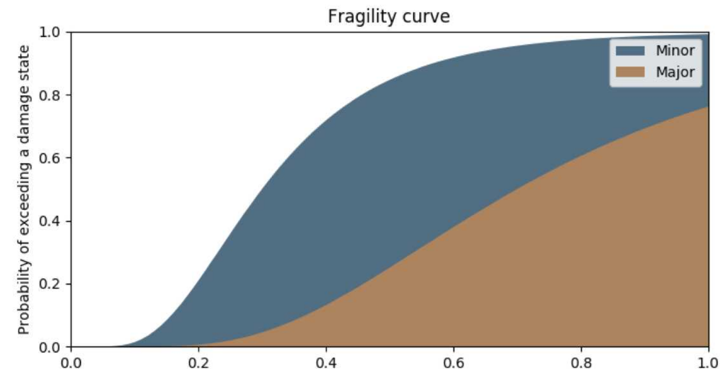
Earthquake disaster and recovery analysis



Infrastructure Dependency

- Resilience of the water system is dependent on other sectors, including
  - Electricity grid
  - Natural gas
  - Transportation network
  - Cyber, communication
- WNTR can integrate data from other sectors in several ways
  - Controls (IF/THEN/ELSE statements that depend on status of other sectors)
  - Fragility curves (where the probability of damage to a component depends on status of other sectors)
  - Additional networked infrastructure models could be generated within the WNTR framework

```
IF substation A fails
     THEN pump B looses power
```



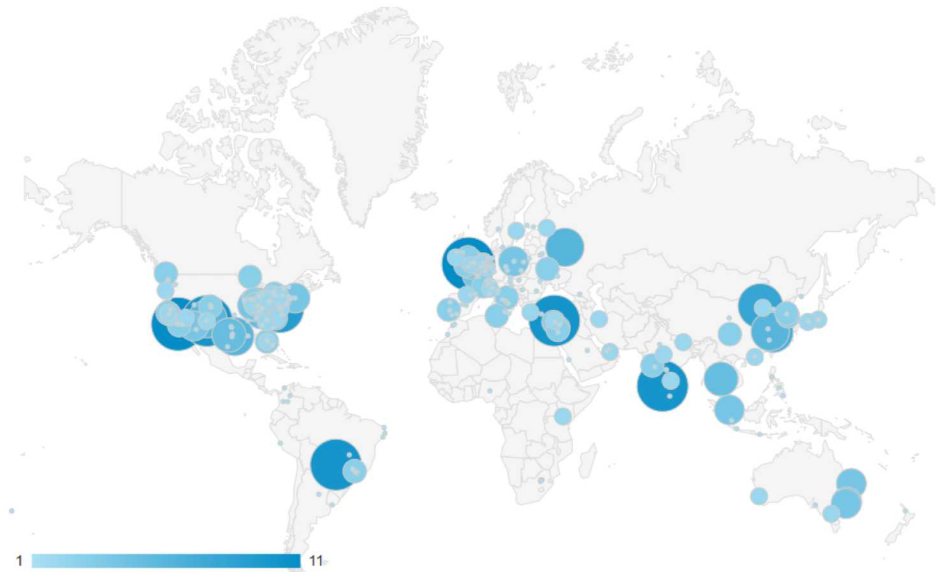
Who Is Using WNTR?

- WNTR users
  - Arcadis
  - Los Alamos National Laboratory
  - National Energy Renewable Laboratory
  - National Institute of Standards and Technology
  - University of California, Los Angeles
  - University of South Florida

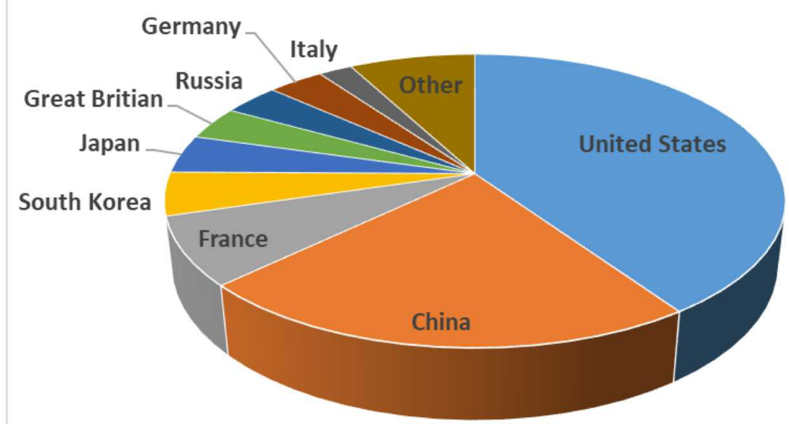
- Example use cases
  - Sampling analysis for Flint, MI
  - Hurricane preparedness for the US Virgin Islands
  - Earthquake preparedness for Seattle, WA
  - Power outage analysis for Poughkeepsie, NY

- WNTR has been downloaded over 7000 times
- Approximately 150 visitors to the online documentation each month

Number of WNTR users, per city



Downloads, per country



Future Directions

- Utilization – We are helping several utilities and researchers to use WNTR effectively
  - How do you think about and evaluate resilience?
  - How do you prioritize resilience enhancements?
  - How do you use the software? Roadblocks, missing features, etc?
- Integration with other infrastructure
  - E.g., electric grid resilience affects water distribution system resilience
- Robustness
- Extensibility - We are trying to make it significantly easier to extend WNTR
  - Custom models
  - Custom controls
  - Integration with other infrastructure modeling tools

Conclusions

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- WNTR is a Python package designed to evaluate water distribution system resilience considering a wide range of disruptive incidents, including earthquakes, power outages, water quality concerns

- WNTR extends the capabilities of basic hydraulic modeling to help water utilities do a “deeper dive” into understanding the resilience of their drinking water system

- Water utilities and researchers are invited to work with the US EPA and Sandia on case studies, feature development, and resilience education

WNTR
Water Network Tool for Resilience

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