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An Overview of the Water Network Tool for Resilience (WNTR)

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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
 - Earthquake / Napa, California
 - 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

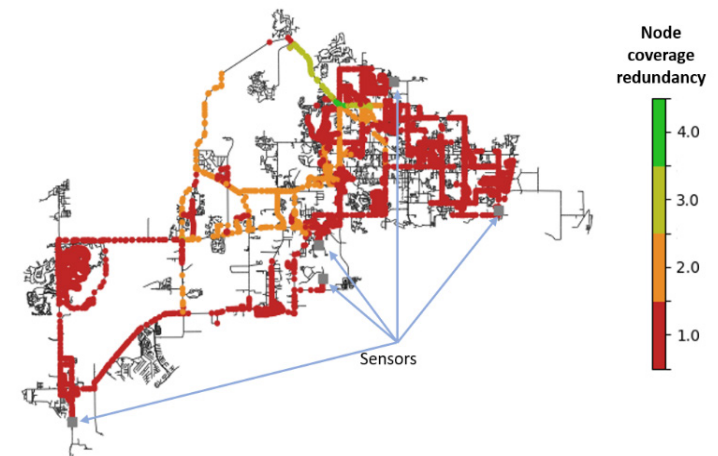
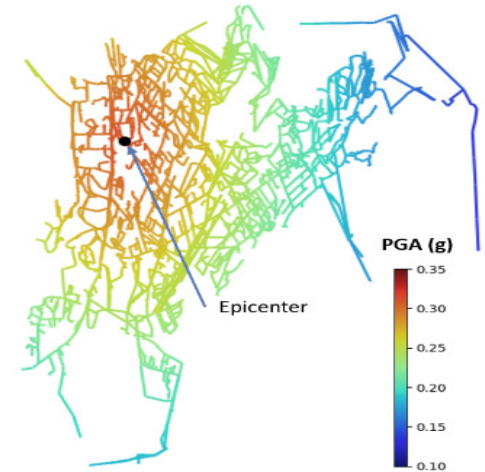




Water Network Tool for Resilience

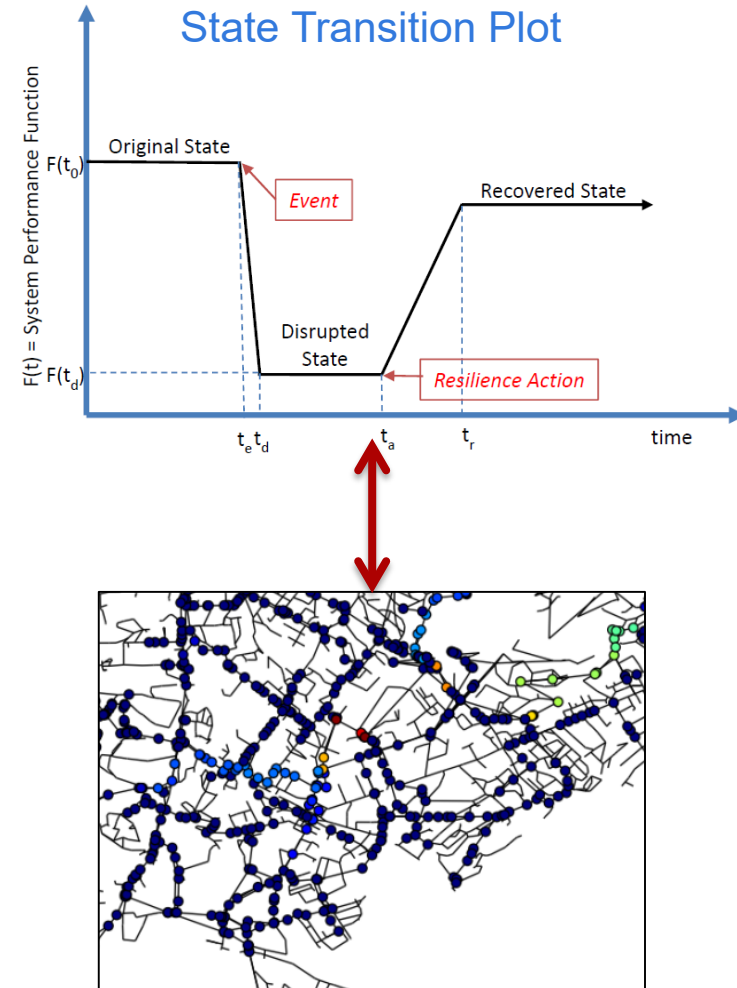
WNTR is a Python package designed to analyze water distribution network failure and recovery

- 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



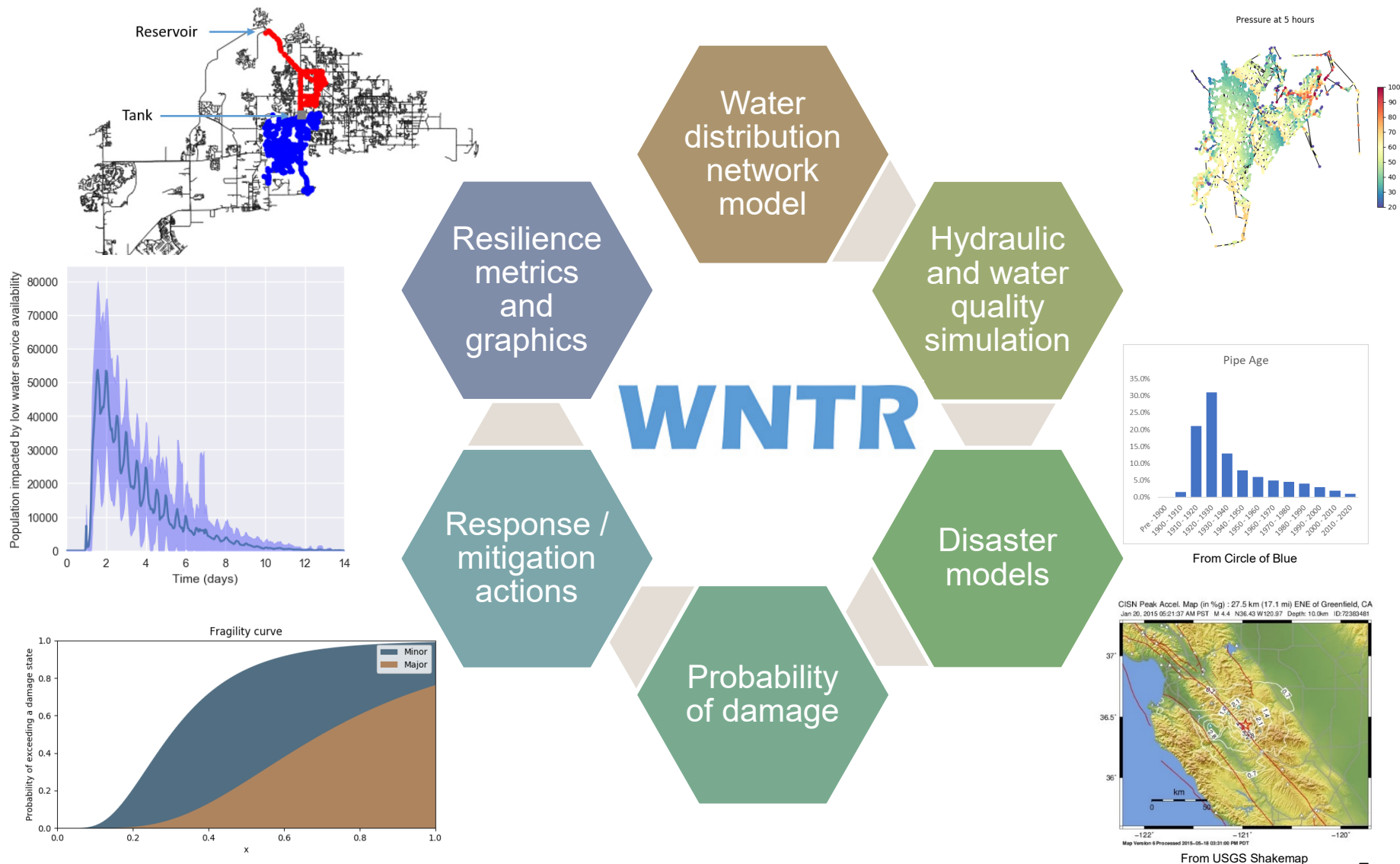
Quantifying Resilience

- 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





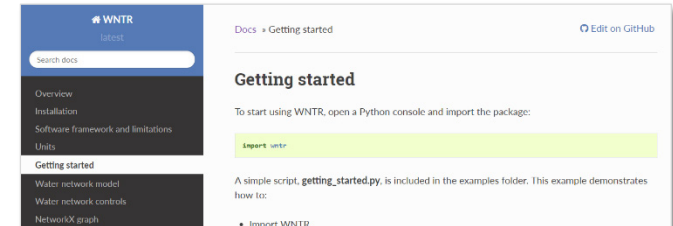
WNTR Framework





WNTR Framework

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



```
1 import wntr
2
3 # Create a water network model
4 inp_file = 'Net3.inp'
5 wn = wntr.network.WaterNetworkModel(inp_file)
6
7 # Simulate hydraulics
8 sim = wntr.sim.WNTRSimulator(wn, mode='PDD')
9 results = sim.run_sim()
10
11 # Plot results on the network
12 pressure_5hr = results.node['pressure'].loc[5*3600, :]
13 wntr.graphics.plot_network(wn, node_attribute=pressure_5hr, title='Pressure at 5 hours')
```

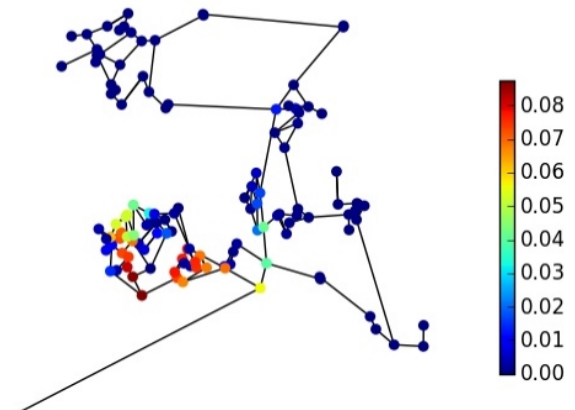
extensive online testing
and documentation

- GitHub
- TravisCI
- ReadtheDocs

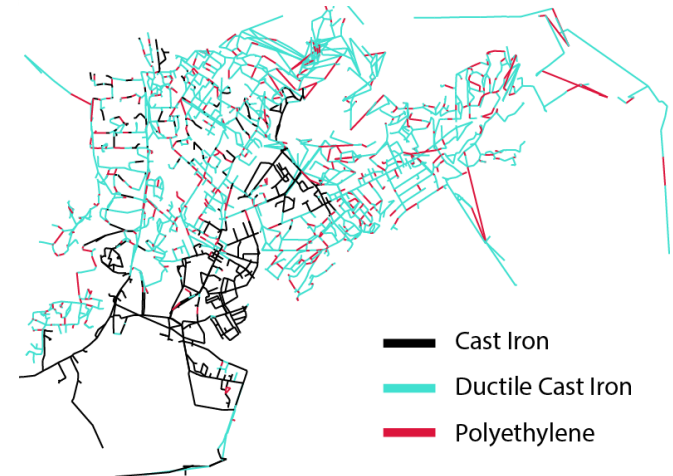
Network Models

- 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

Betweenness Centrality



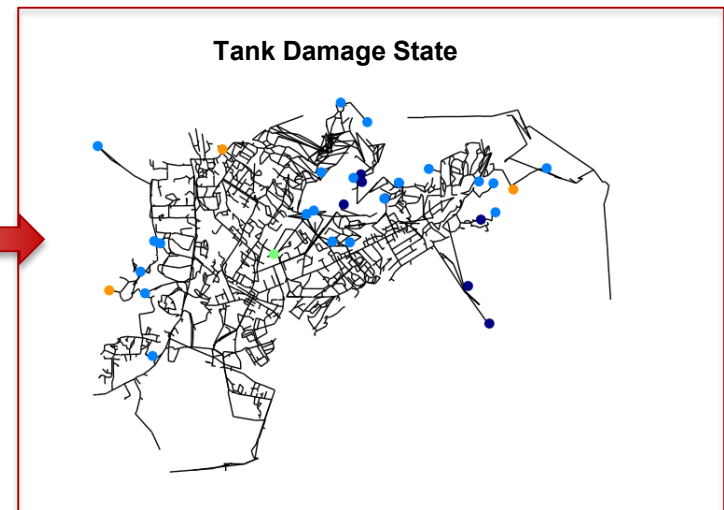
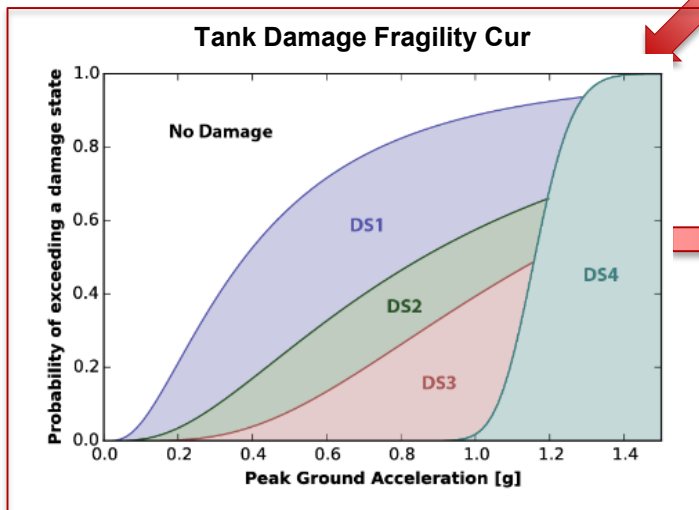
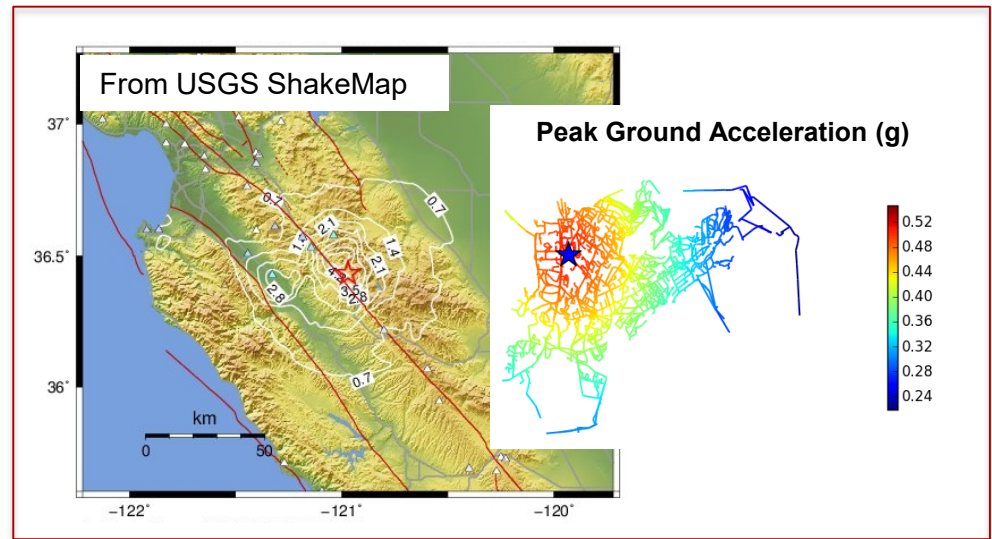
Pipe Material





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*)

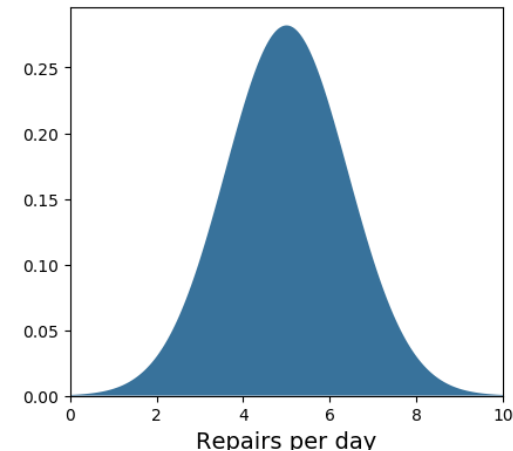
Repairs started 24 hours after earthquake

Separate team repaired tank

Prioritized repairs by proximity to limit travel time

Production maximized to feed leaks

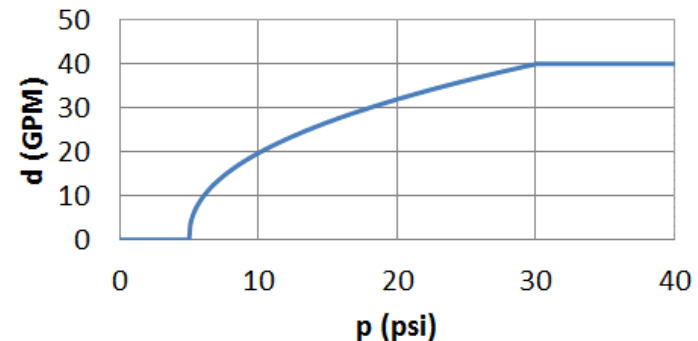
Boil water order for affected regions



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)

$$\begin{aligned} d &= D_f && \text{for } p \geq P_f \\ d &= D_f \left(\frac{p - P_o}{P_f - P_o} \right)^{1/e} && \text{for } P_o < p < P_f \\ d &= 0 && \text{for } p \leq P_o \end{aligned}$$



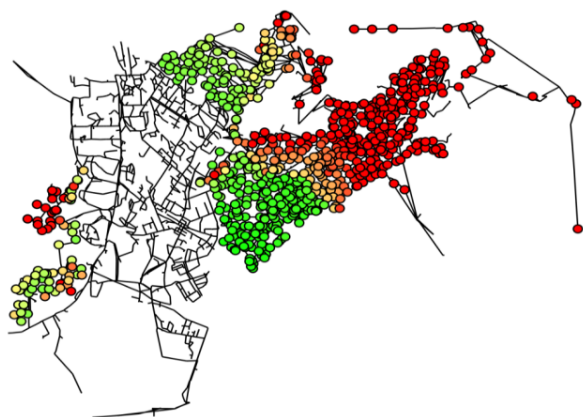
- Simulation start/stop capabilities
- Feedback loops
- Monte Carlo simulation
- Parallelization



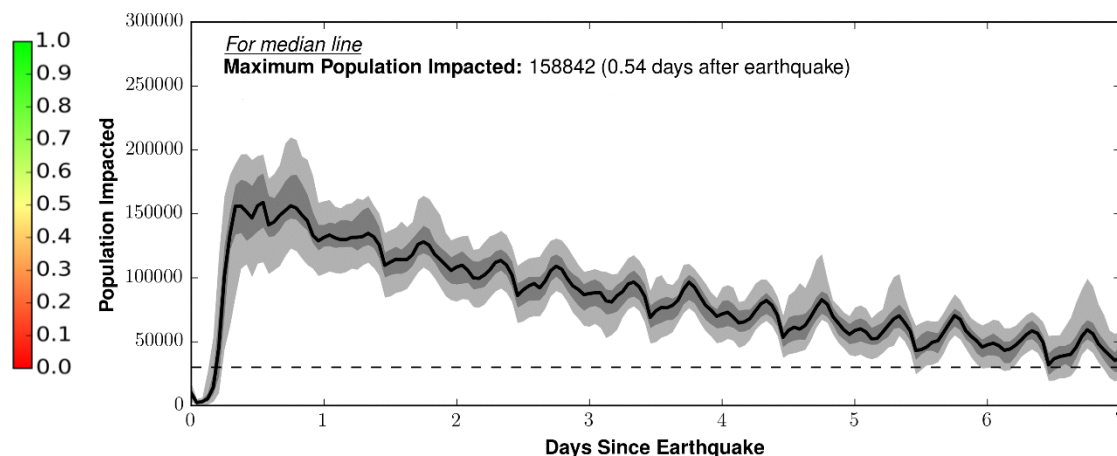
Resilience Metrics

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



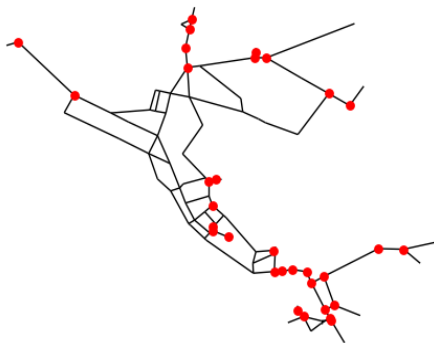
Population impacted after an earthquake



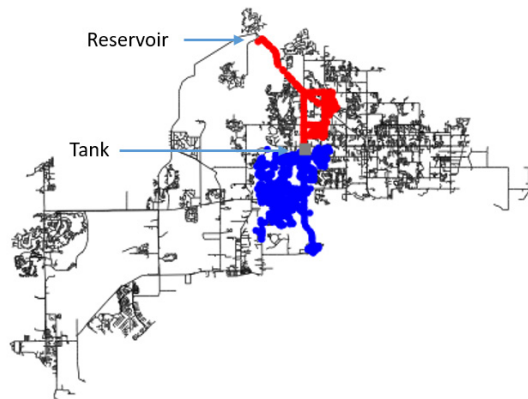


WNTR Applications

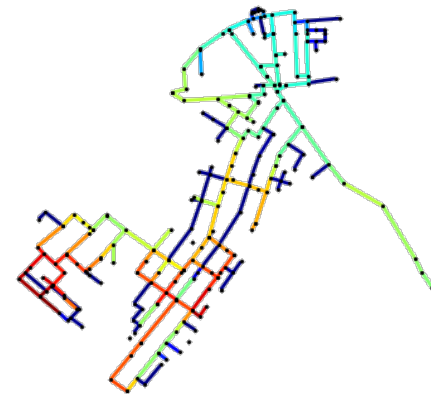
Topographic analysis



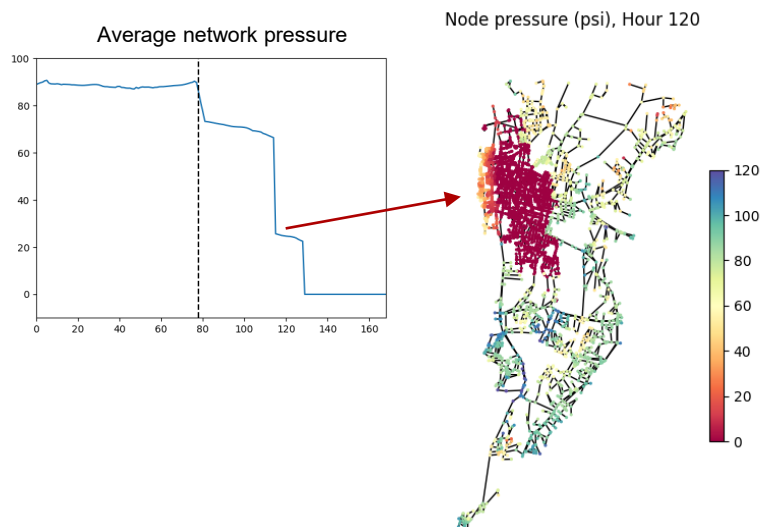
Hydraulic connectivity analysis



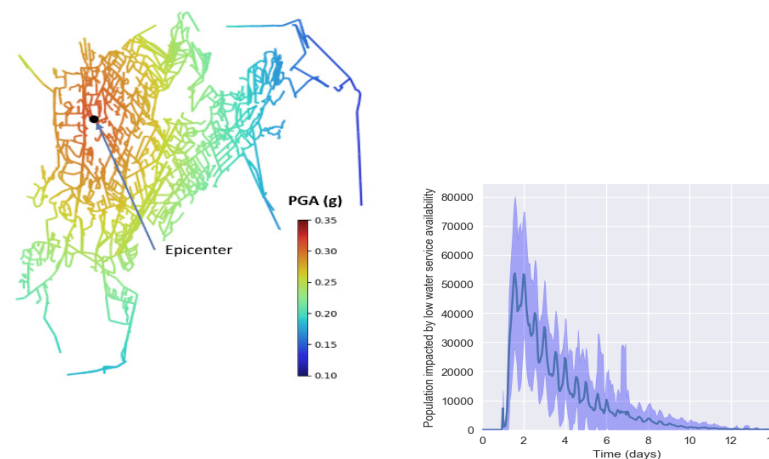
Pipe criticality analysis



Power outage or compromised source water analysis



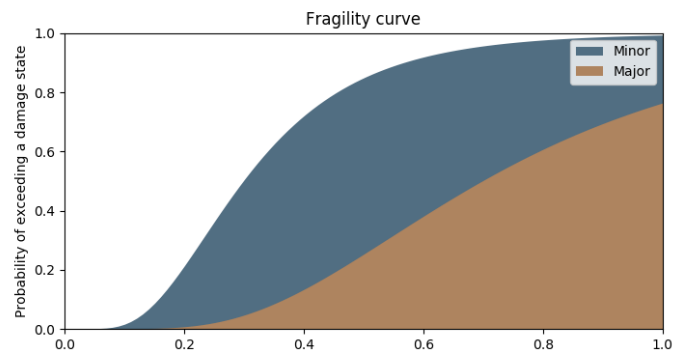
Earthquake disaster and recovery analysis



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 loses 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

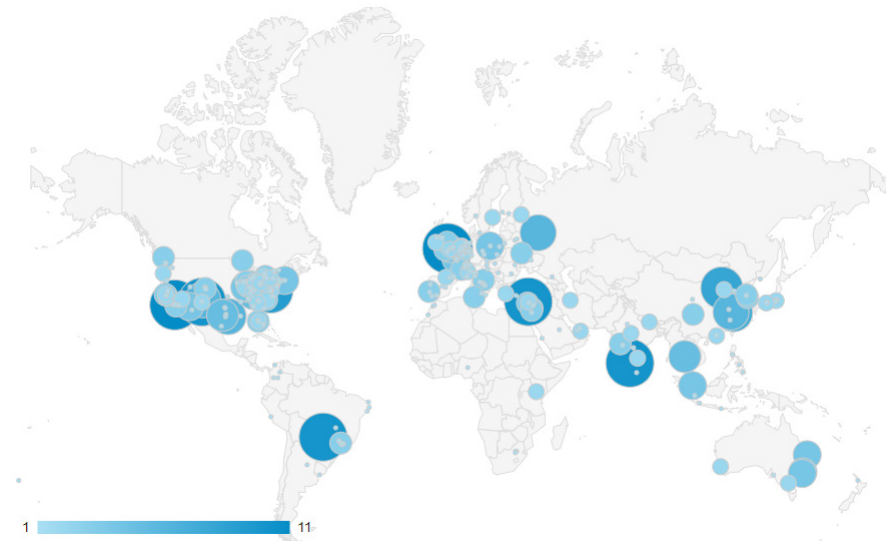
■ Example use cases

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

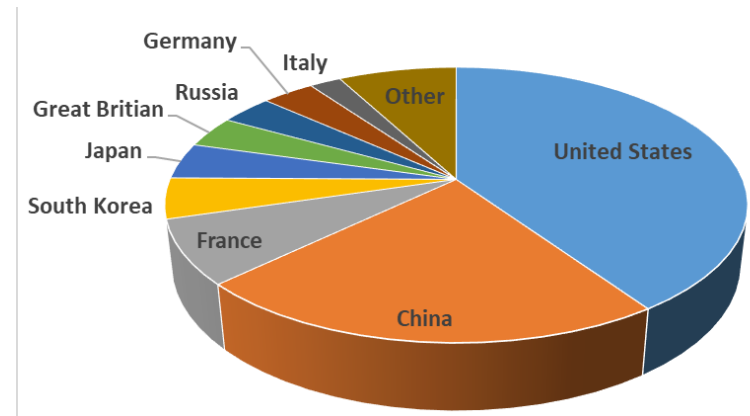
- WNTR has been downloaded over 7000 times

- Approximately 150 visitors to the online documentation each month

Number of WNTR users, per city



Downloads, per country



Conclusions

- 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, industry, and researchers are invited to work with the US EPA and Sandia on case studies and feature development



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