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Resilience Evaluation for Water Distribution Networks

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Motivation and Background

- Water distribution systems face multiple challenges.
- Water utilities need to be able to predict how their system will perform during disruptive events and understand how to best absorb, recover from, and more successfully adapt.
- Simulation and analysis tools can help water utilities explore how their network will respond to expected, and unexpected, events.

Potential Hazards

Natural Disasters

- Drought
- Earthquakes
- Floods
- Hurricanes
- Tornados
- Tsunamis
- Wildfires
- Winter Storms

Terrorist Attacks

Cyber Attacks

Hazardous Materials Release

Climate Change

Potential Impacts

Pipe Break

Other Infrastructure Damage/Failure

Power Outage

Service Disruption (source water, treatment, distribution, or storage)

Loss of Access to Facilities/Supplies

Loss of Pressure/Leaks

Change in Water Quality

Environmental impacts

Financial impacts (e.g., loss of revenue, repair costs)

Social Impacts (e.g., loss of public confidence, reduced workforce)

Motivation and Background

- What is resilience?

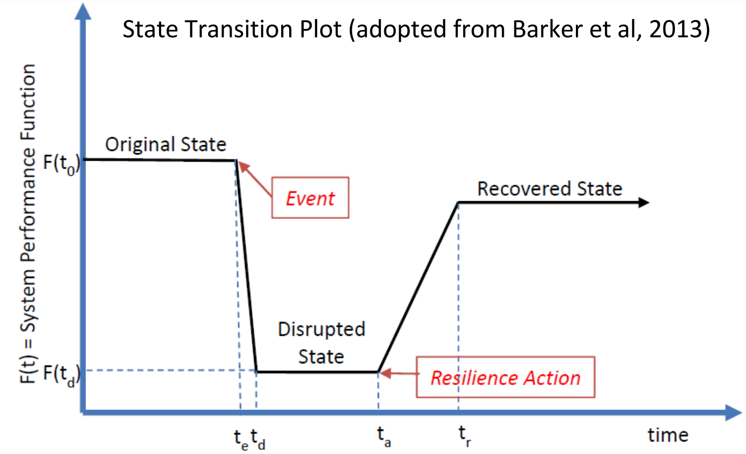
- PDD 21 "Critical Infrastructure Security and Resilience" establishes national policy to proactively increase infrastructure resilience.

- Resilience of the water sector is tightly linked to the resilience of other critical infrastructure such as energy, food and agriculture, health care and public health.

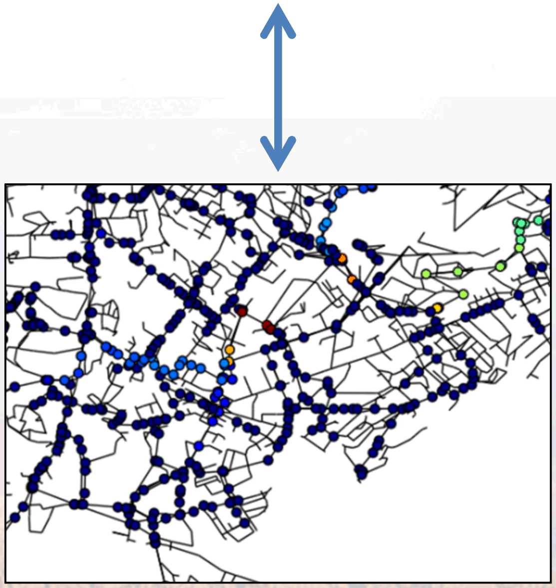
- Resilience of drinking water systems refers to the design, maintenance, and operations of water infrastructure that limits the effects of disasters and enables rapid return to normal delivery of safe water to customers.

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



- State transition plots graphically represents the meaning of resilience
  - System performance function, event, and resilience action must be clearly defined
  - Metrics used to define reliability, robustness, redundancy, and security might prove useful to measure resilience
  - Resilience is typically defined as a system measure, but could be measured for individual components of the network.



Barker et al (2013) Resilience-based network component importance measures, Reliability Engineering and System Safety, 117(2013) 89–97
EPA (2014) Systems Measures of Water Distribution System Resilience, EPA 600/R-14/383

Hydraulic Simulation of Disruptive Events

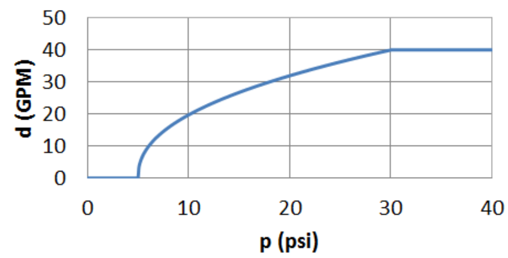
- Demand-driven simulation (such as with EPANET) might not be adequate to simulate hydraulic capacity during some disruptive events
- Pressure Dependent Demand Model (Wagner, 1988; Rossman whitepaper, 2015)
  - Demand at a node, *d*, depends on the pressure head *p* available at the node
  - Input parameters = minimum pressure (P_o) and nominal pressure (P_f)

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

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

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

Example
P_0 = 5 psi
P_f = 30 psi
D_f = 40 GPM



- PYOMO interface is used to solve non linear equations
  - Python interface
  - IPOPT nonlinear solver
  - Smoothing functions near the boundaries

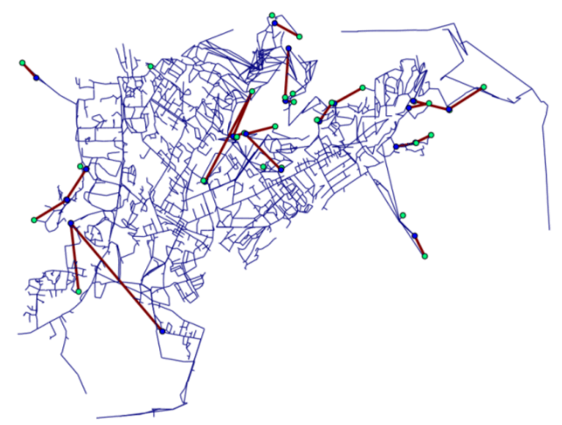
Wagner (1988) Water distribution reliability: simulation methods, J. Water Resour. Plan. and Manage., 114(3), 276-294.
Rossman (2015) Adding Pressure Dependent Demands to EPANET, EPA Memorandum

Power Outage Case Study

- Simulate network wide and isolated power outages by changing operations of the pumps
  - $P_o = 0$, P_f = 80% minimum pressure at each node when run under normal operations.
  - When power is off at a pump station, the pumps act as a by-pass. Water is not allowed to flow back into the reservoir. Pumps are closed if flow < 1e-9 m3/s
  - Tanks can fill be gravity when power is off. Tanks are allowed to empty completely.

- Track the ability to deliver expected volume of water as a function of time and location.

- Disruptive Events
  - 3000 node network contains 61 pumps at 22 pump stations
  - Power outage starts at 8 AM
  - Assume back-up generation has failed, or run its course



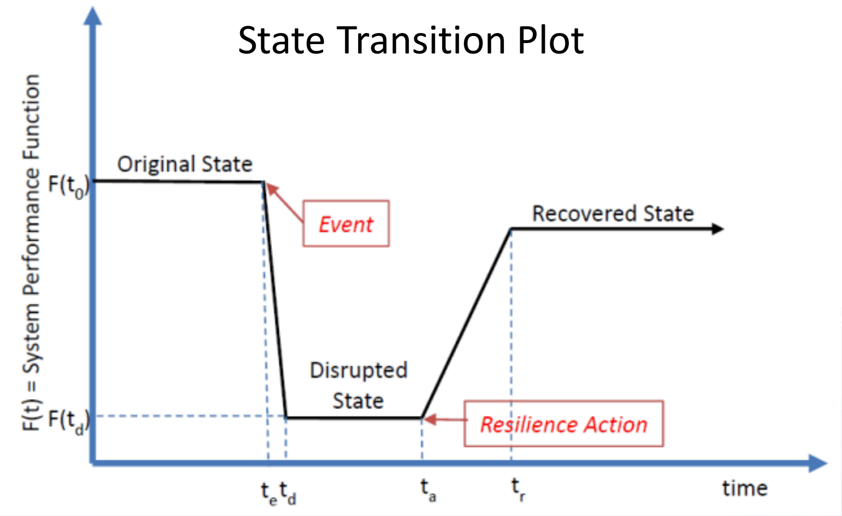
- Resilience Action
  - Restore power 5,10,15 hours after outage

Simulation and Analysis

- System performance function, F(t)
  - Fraction of delivered volume (FDV) (Ostfeld, 2002)
  - For a particular scenario, the fraction is computed over all nodes.

$$F(t) = FDV(i,t) = \frac{\sum_{n}^{N} RV_{i,n,t}}{\sum_{n}^{N} EV_{i,n,t}} \quad \forall\ i \text{ in I, t in T}$$

where:
RV = requested volume
EV = expected volume
I = set of scenarios
N = set of consumer nodes
T = set of simulation time steps



- Characteristics
  - Minimum state = $F(t_d)$ = min(F(t))
  - Time to disruption = $t_d - t_e$
  - Time to recover = $t_r - t_d$
  - Number and location of disrupted nodes

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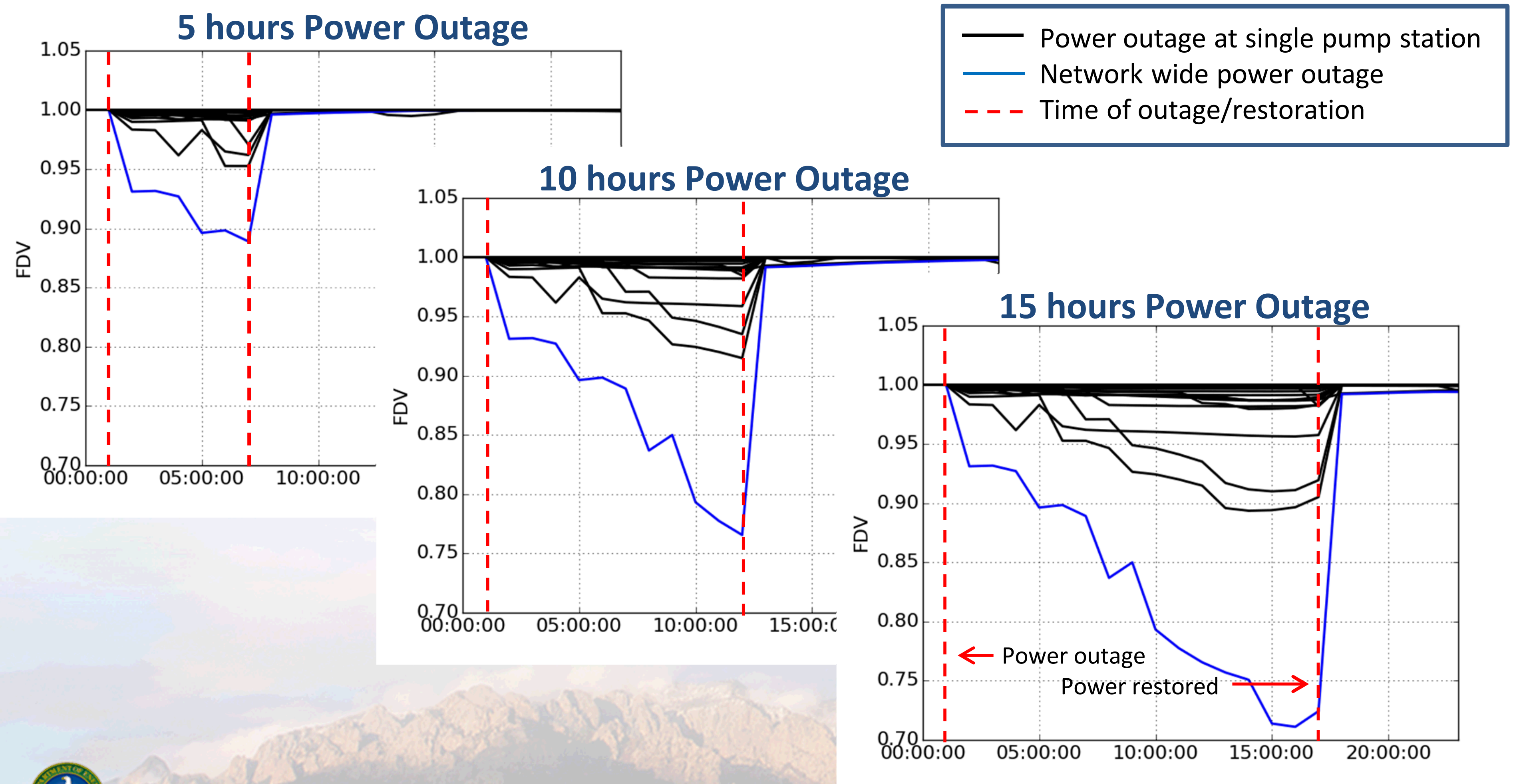
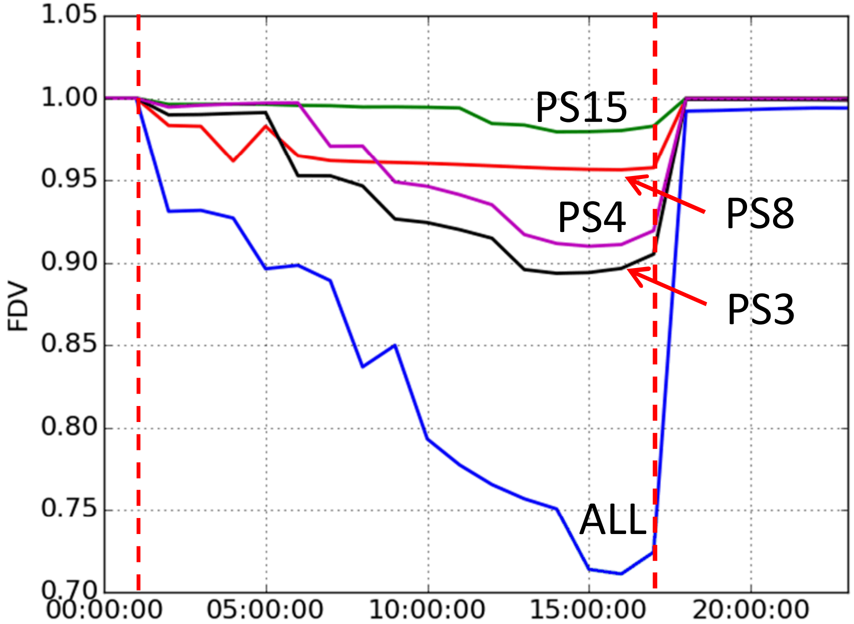
Results

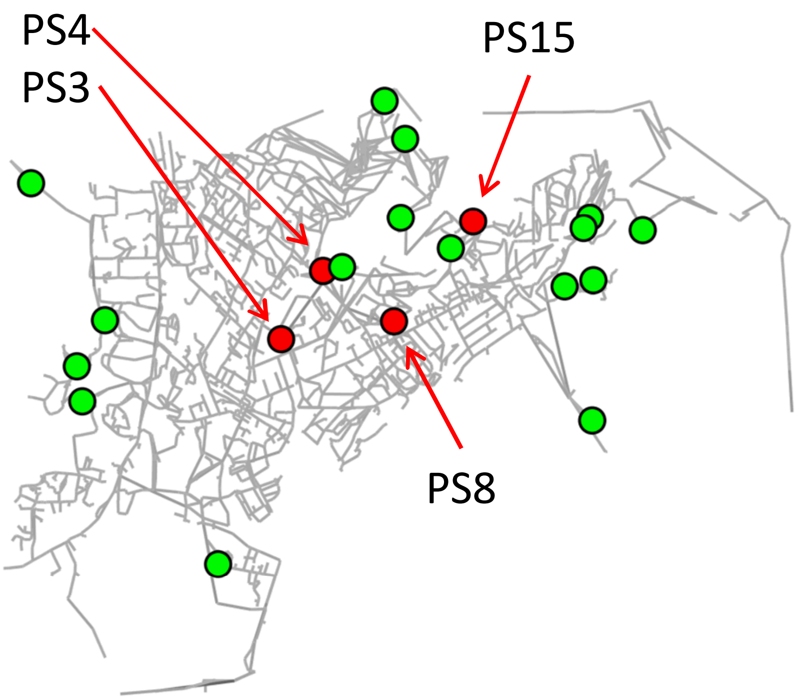
- State Transition Plot using Fraction of Delivered Volume per scenario



Results

- 15 hour power outage
- State transition plots with minimum disruption < 98%

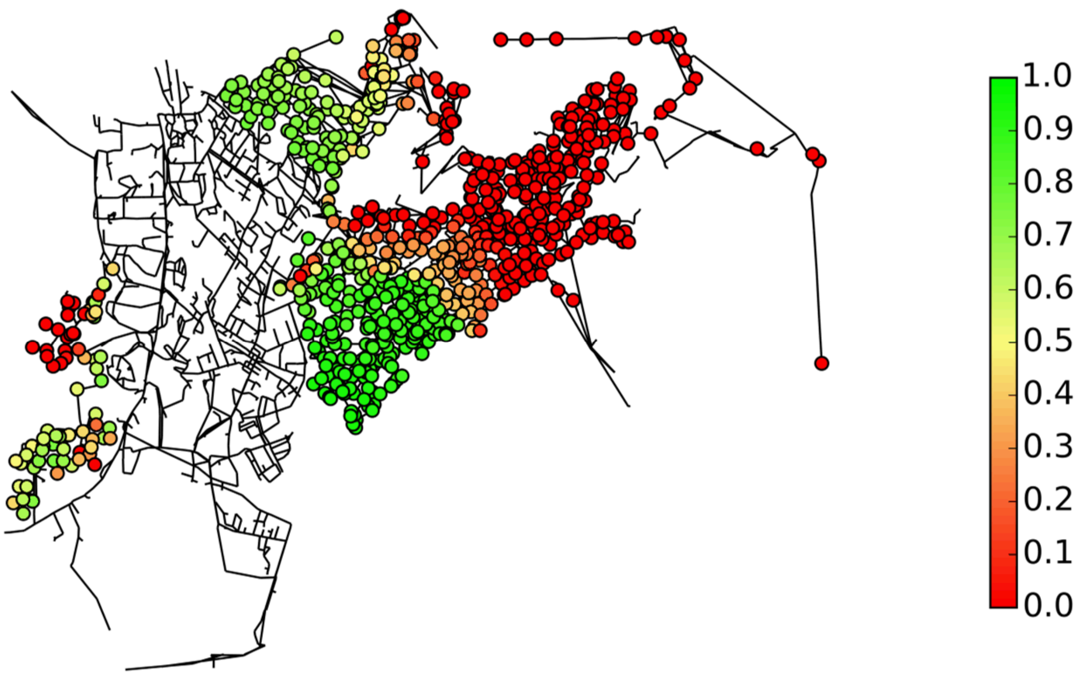




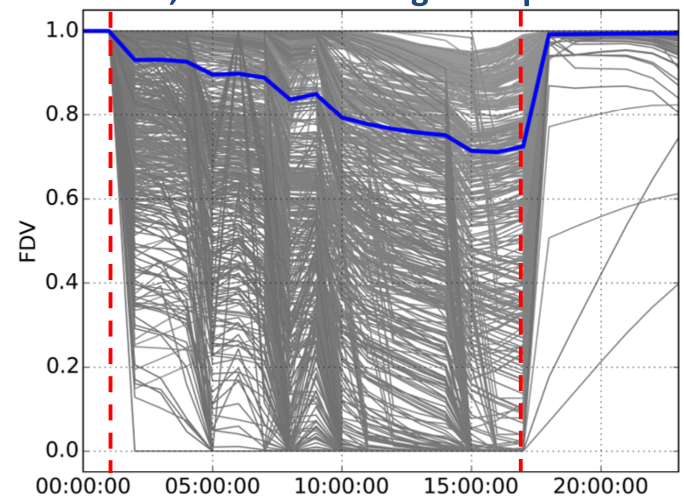
Results

- 15 hour network wide power outage
  - 24 tanks fall below 2m
  - 53% of consumer nodes deliver less than 98% expected volume

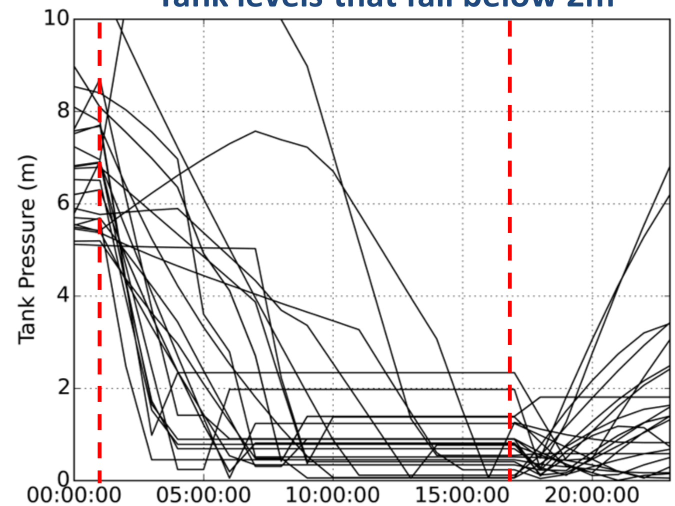
Minimum State (FDV per node)



FDV, network average and per node



Tank levels that fall below 2m

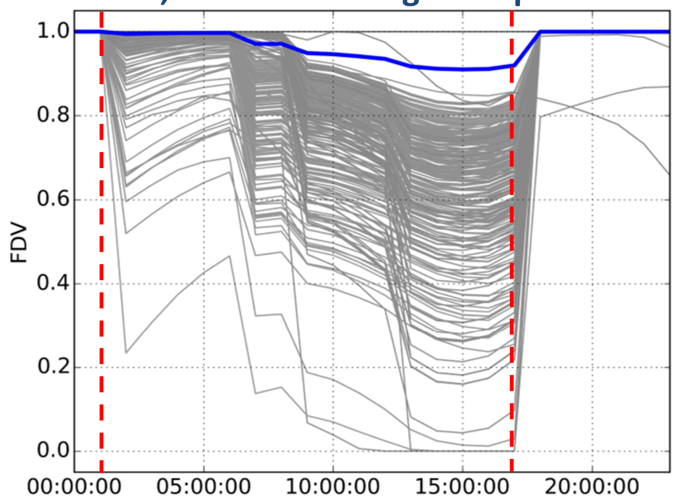


Results

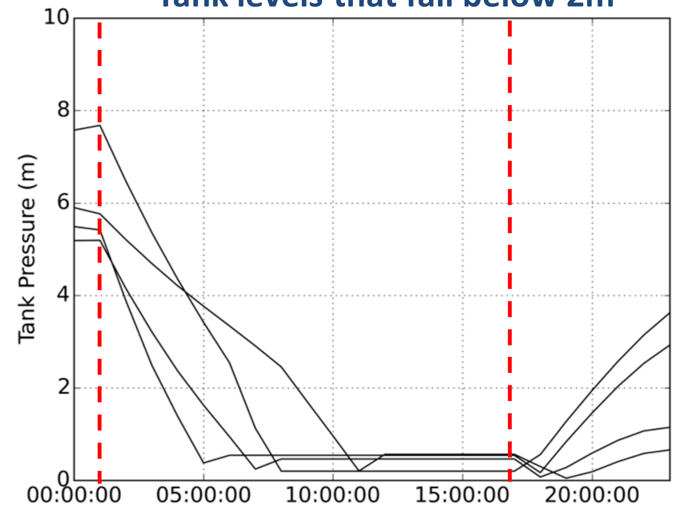
- 15 hour power outage at pump station 4
  - 4 tanks fall below 2m
  - 24% consumer nodes deliver less than 98% expected volume
  - Pump station 3 and 4 have similar response

Minimum State (FDV per node)

FDV, network average and per node



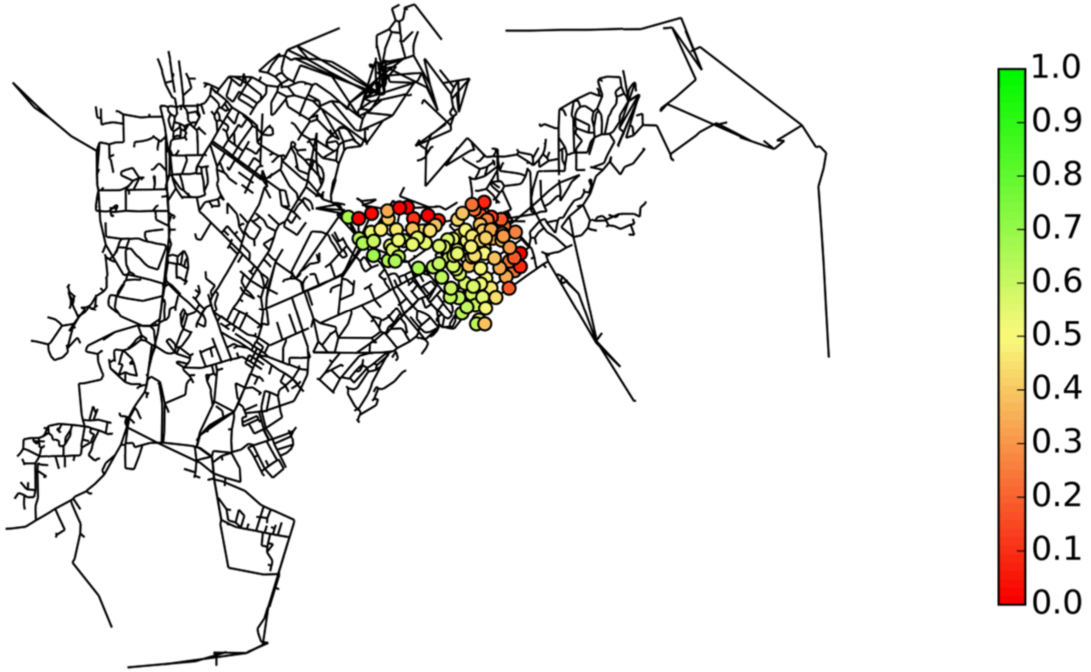
Tank levels that fall below 2m



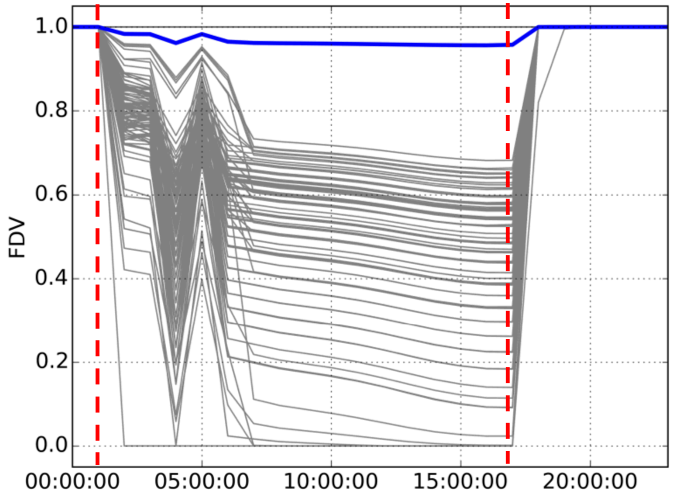
Results

- 15 hour power outage at pump station 8
  - 2 tanks fall below 2m
  - 8% consumer nodes deliver less than 98% expected volume

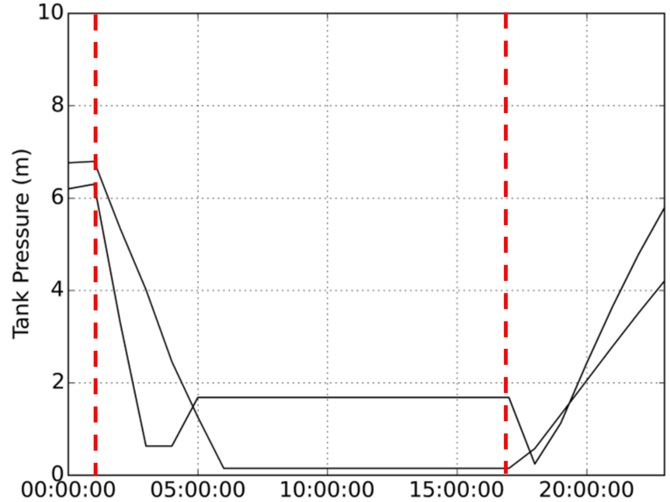
Minimum State (FDV per node)



FDV, network average and per node



Tank levels that fall below 2m

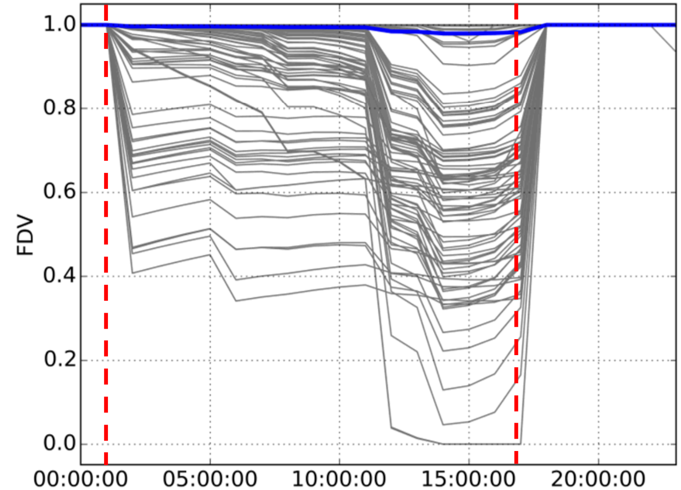


Results

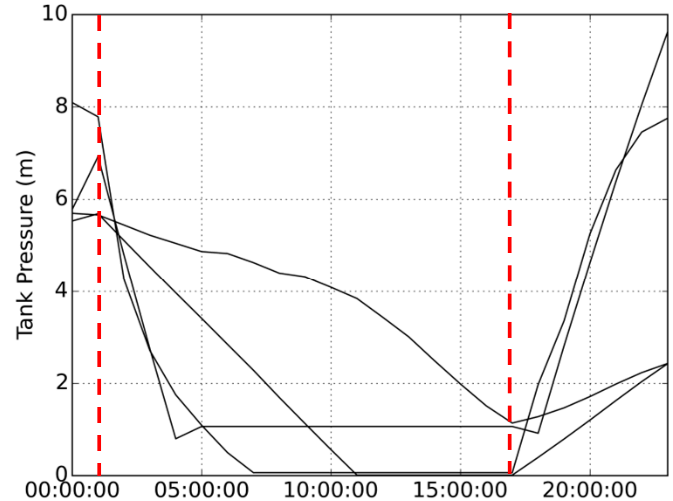
- Power outage at pump station 15
  - 4 tanks fall below 2m
  - 6% consumer nodes deliver less than 98% expected volume

Minimum State (FDV per node)

FDV, network average and per node



Tank levels that fall below 2m



Summary

- What does it mean to be resilient in face of a power outage?
  - Reduce the magnitude and duration of disrupted service
  - Identify critical pumps and other infrastructure for backup generation
  - Understand where and when customers will be impacted
  - Identify worst case scenarios
  - Simulate response and adaptation strategies
  - Modify network operations to be better prepared for future events

- Future steps
  - Test other resilience metrics as the system performance function
  - Model other types of disruptive events
  - Expand case studies to include a wide range of expected and unexpected events
  - Include information about critical infrastructure into the analysis

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