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TEXAS
The University of Texas at Austin

WATER DISTRIBUTION SYSTEM DISASTER HARDENING IN THE US VIRGIN ISLANDS

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US Virgin Islands Overview

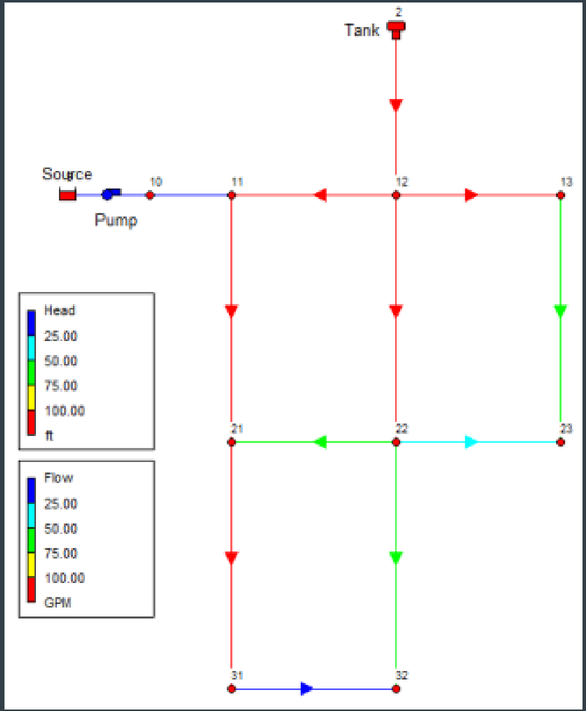
- 1917 US territory
- Population 100,000
- STX: 28 mi x 7 mi, STT: 13 mi x 4 mi
- Water Distribution
  - Only 70% of residents on utility water
  - Alternate water: water trucks + cisterns
  - STX separate from STT/STJ system
  - STX system losses: 40%
- Fun fact: Drive on the left!

*vulnerable to low pressure conditions from pumping outages

Motivation: Hurricanes in the USVI

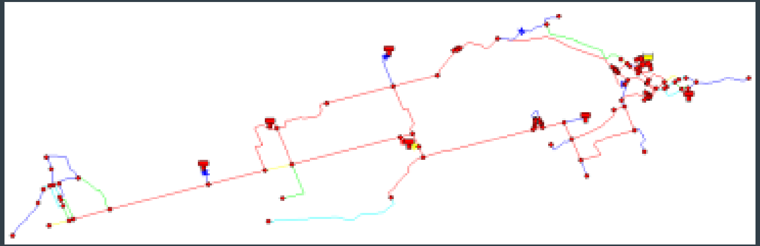
- 2017 Hurricanes Irma (Sept 6.) and Maria (Sept. 20)
- Emergency generators for pumping lasted 3 months
- 90% of power restored by Jan 1, 2018
- More Resilient: cisterns, buried power lines
- Less Resilient: power generation, power lines, pumping stations, pipes*

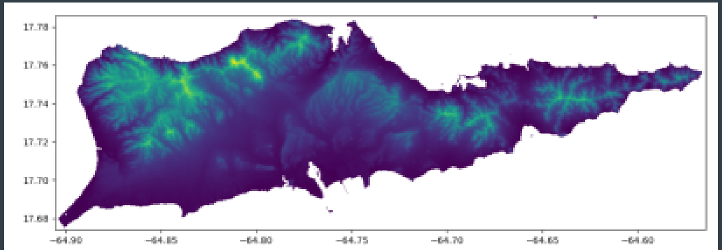
Water Network Tool for Resilience (WNTR)



- Open source Python package
- Compatible with EPANET
- Iteratively solves the constraint-satisfaction problem of resolving pipe pressures flows
- Some out-of-the box resilience analyses:
  - Water age analysis
  - Peak ground acceleration (earthquakes [2])
  - *Power Outages*
  - *Pipe Criticality*

St. Croix WDS Model Building



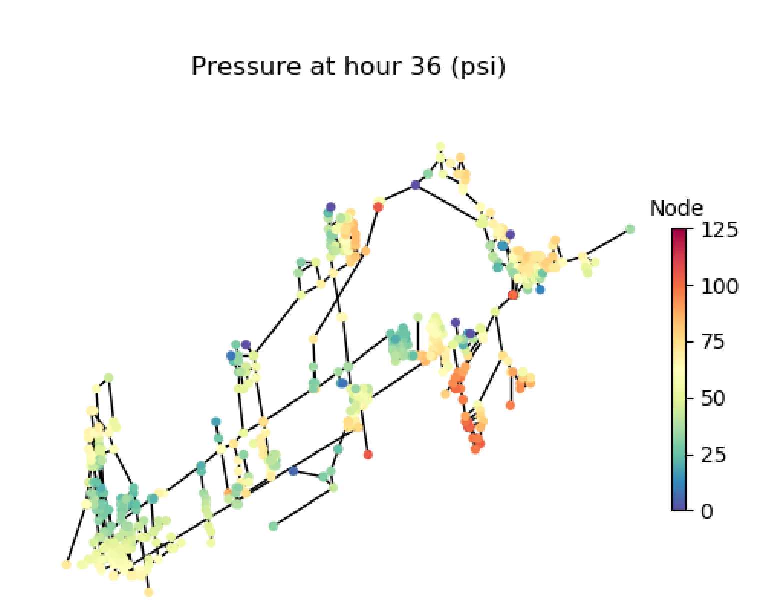


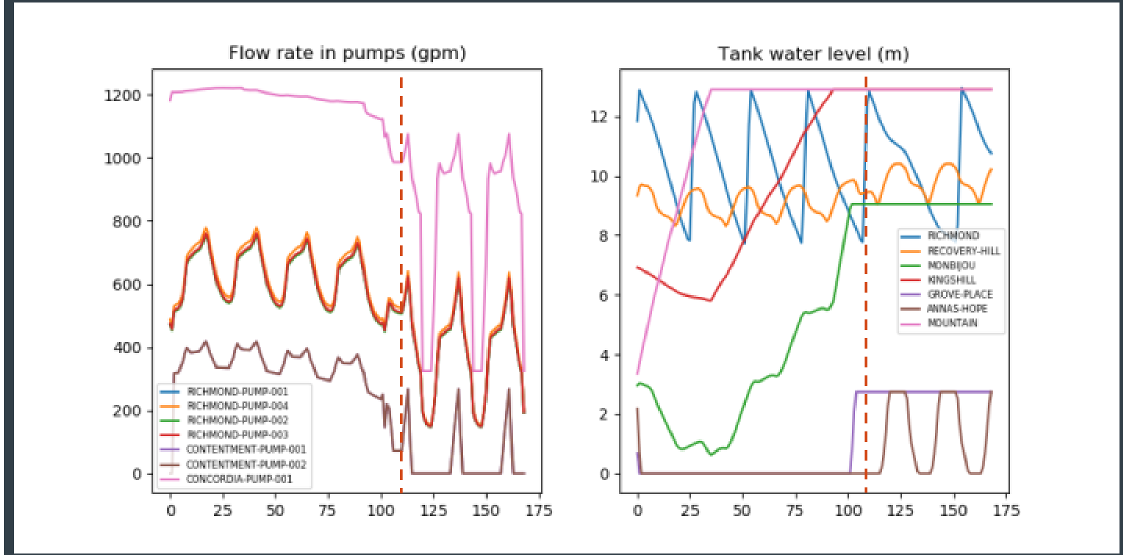
VIWAPA Data
- Node and Pipe configurations
- Demands
- Valves

December 2019 VIWAPA Master Plan
- Pump operation and curves
- Storage tanks
- Controls

USGS Elevation raster
- Asset Elevations

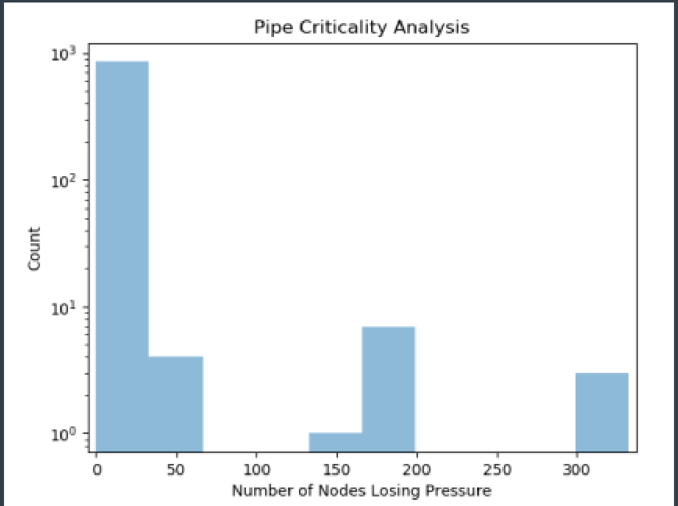
St. Croix Standard Operating Conditions

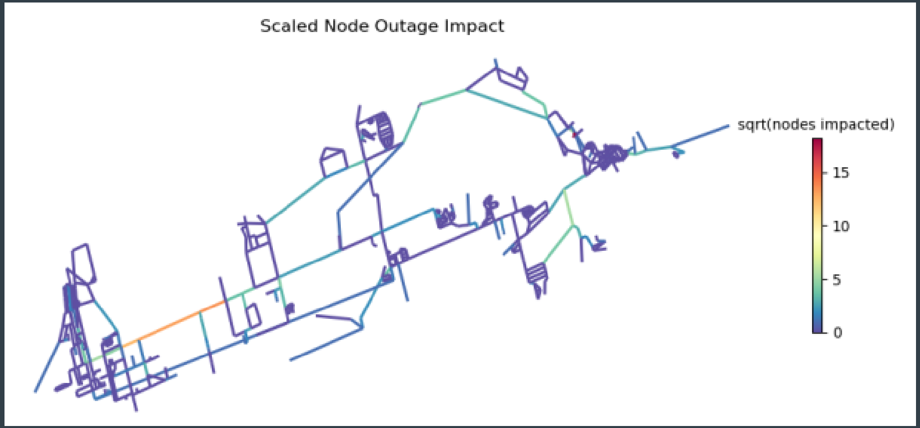




St. Croix WDS Pipe Criticality

Are some pipes more important to preserving pressure than others?

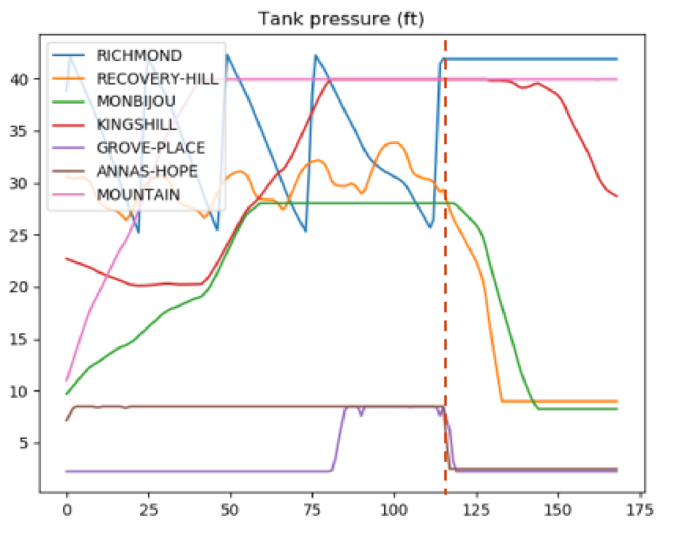




Do some geographic regions have less pipe redundancy?

St. Croix WDS Pump Outage Vulnerability

After reaching steady state, how well does the system maintain pressure with no pumping?



Pumping Station Outage	Junctions Losing Pressure
Richmond	35.5%
Concordia	0%
Contentment	0.8%
All	36.7%

Which pumps are most critical for maintaining system pressure?

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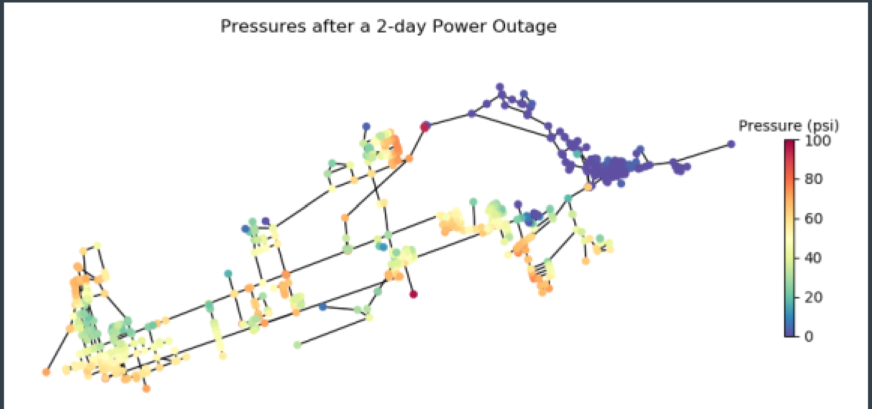

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Conclusions and Future Work

- Challenges in the USVI: threats and mitigation logistics
- Model building in WNTR
- Resilience Analyses:
  - Pipe criticality
  - Pump Outage
  - *Hurricane hardening*

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Which system components should be fortified to optimally protect against hurricanes?

The centralized (WDS) or decentralized (Water Trucks) system?

Formulation: Variables

- Time Horizon T

Nodes

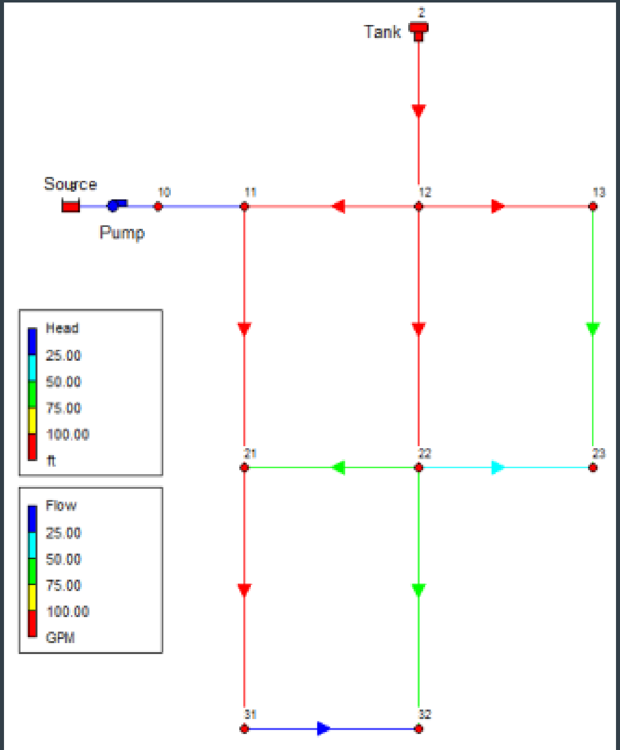
- Tanks $\mathcal{T}$
- Reservoirs $\mathcal{R}$
- Junctions $\mathcal{J}$
- Nodes $\mathcal{N} = \mathcal{T} \cup \mathcal{R} \cup \mathcal{J}$

- Pressure head p_{it} for $i \in \mathcal{N}, t \in T$
- Water truck supply w_{it} for $i \in \mathcal{N}, t \in T$

Links

- Pumps $\mathcal{P}$
- Valves $\mathcal{V}$
- Pipes $\mathcal{L}$
- Edges $\mathcal{E} = \mathcal{P} \cup \mathcal{V} \cup \mathcal{L}$

- Head change h_{kt} for $k \in \mathcal{E}, t \in T$
- Flowrate q_{kt} for $k \in \mathcal{E}, t \in T$
- Pump power m_k for $k \in \mathcal{P}$



Formulation: WDS constraints [3]

$$\frac{\delta}{A_i}\left(\sum_{k\in\mathcal{E}} a^{+}(i) q_{kt} - \sum_{k\in\mathcal{E}} a^{-}(i) q_{kt}\right) + p_{i(t-1)} = p_{it} \quad \forall i \in \mathcal{T}, t \in T$$

(2: tank head)

$$h_{kt} \leq C_k^0 (q_{kt})^2 + C_k^1 (q_{kt}) + C_k^2 \quad \forall k \in \mathcal{P}, t \in T$$

(3: pump operation: pump curve)

$$R_k = (p_{it} + \bar{e}_{it}) - (p_{jt} + \bar{e}_{jt}) \quad \forall (i,j) = k \in, \mathcal{V}\ t \in T$$

(4: valve setting)

$$h_{kt} = F_k (q_{kt})^2 \quad \forall k \in \mathcal{L}, t \in T$$

(5: friction losses)

Formulation: WDS constraints [3]

$$h_{kt} = (p_{it} + \bar{e}_{it}) - (p_{jt} + \bar{e}_{jt}) \quad \forall (i,j) = k \in \mathcal{E}, t \in T$$

(6: head change along edge)

$$m_k = \frac{\rho g}{\eta_k} h_{kt} q_{kt} \quad \forall k \in \mathcal{P}, t \in T$$

(7: pump power consumption)

$$p_{it} \geq p_i^{min} \quad \forall i \in \mathcal{J}, t \in T$$

(8: pressure minimum)

$$h_{kt} \geq 0, p_{it} \geq 0, q_{kt} \geq 0,$$
$$w_{it} \geq 0, m_k \geq 0 \quad \forall i \in \mathcal{N}, k \in \mathcal{E}, t \in T$$

(9: nonnegativity)

Formulation: WDS and Water Trucks

Max *Water Service Availability (WSA)*

$$=\sum_{t\in T}\sum_{i\in\mathcal{J}}[\sum_{k\in\mathcal{E}} a^{+}(i)q_{kt} - \sum_{k\in\mathcal{E}} a^{-}(i)q_{kt} + w_{it}]/d_{it}$$

s.t.

$$\sum_{k\in\mathcal{E}} a^{+}(i)q_{kt} - \sum_{k\in\mathcal{E}} a^{-}(i)q_{kt} + w_{it} \le d_{it} \qquad \forall i \in \mathcal{J}, t \in T$$

(1: conservation of flow)

(2-9: previous constraints)

$$\sum_{k\in\mathcal{P}} C_k^{p} m_k + \sum_{i\in\mathcal{J}}\sum_{t\in T} C_i^{w} w_{it} \le b$$

(10: budget constraint)

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