AquaSCALE: Exploring Resilience of Community Water Systems

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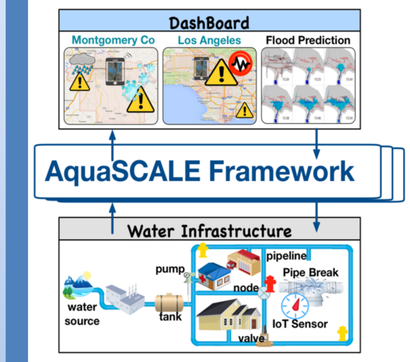
"A framework to improve the outcomes of water related emergencies"

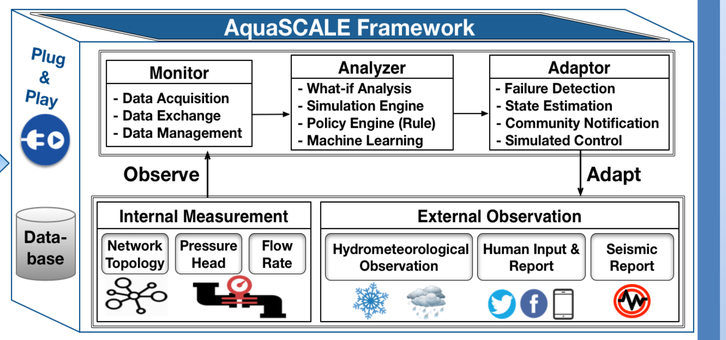
Goals and Overview

- Water is a precious resource and lifeline to worldwide communities.
- The critical infrastructure has been developed over decades (sometimes centuries) and has become complex and vulnerable to failures.
- Pipe breakage, one of the most frequent types of failures, often causes community disruptions.

- Develop methodologies to understand operational performance and resilience issues for real-world community water infrastructure.
- Explore solutions to problems in cyberspace before instantiating them in physical infrastructure.

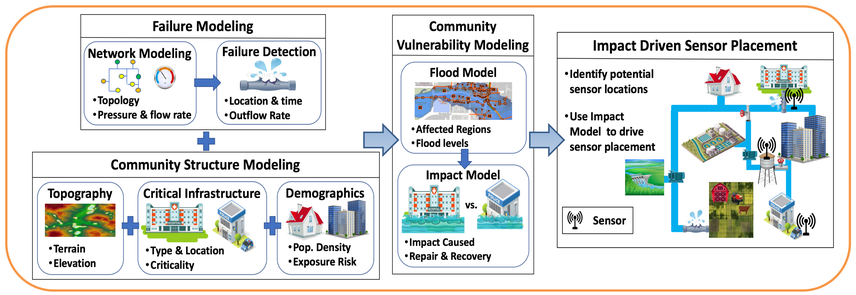
- Prevent water service failures by identifying operational degradation in aging infrastructure.
- Improve speed and accuracy of damage estimation in natural disasters and human-made hazards.
- Reduce service restoration time in the event of large hazards.

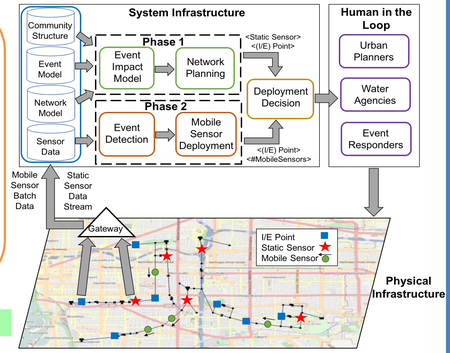




Impact-driven Sensor Placement (In-situ + Mobile)

IEEE ICCPS 2018, 2019





Goal: Sensor Placement Methods for Rapid and cost effective identification of leaks

Objective: Detect all leaks + minimize total impact of leaks on the community.

Intuition: Not all leaks are equally impactful, e.g. leak at hospital vs. open field
- **Community Vulnerability**: varies based on location, structure, demographics
- **Varied leak severity** results in varied outflows

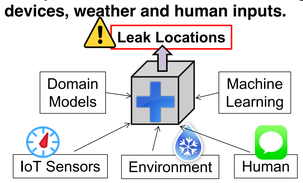
Challenges:
- **Buried assets**: Much of the network is below ground.
- **Movement of mobile sensors** constrained by direction and velocity of water flow.
- **Wireless networks have attenuation**; wired incurs high costs.

Contributions:
- **Novel In-situ sensor placement** algorithms to model event impact, i.e. vulnerability of communities to failure events. Notion of event impact drives sensor placement.
- **Low-cost hybrid monitoring framework**: Leveraged in-situ sensors (continuous monitoring, larger sensing ranges, high accuracy) and mobile sensors (adaptive sensing, on-demand monitoring, low cost).
  - **Network Planning Phase**: uses a greedy impact driven heuristic to determine locations for in-situ sensor placement and mobile sensor insertion infrastructure.
  - **Deployment phase**: dynamically leverages current network information to determine locations from which to deploy mobile sensors for rapid localization of high impact events.
- **Validation using real-world networks**: Impact driven hybrid placement (in-situ and mobile sensor) achieves a **79% reduction in impact** while being **68% more cost efficient** compared to existing approaches.

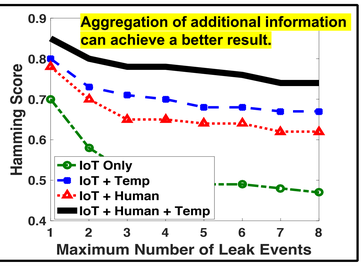
Failure Localization – Operational Degradation & Extreme Events

IEEE ICDCS 2017, SRDS 2018 (best paper)

- An integrated approach to incorporate multiple information sources including IoT devices, weather and human inputs.



- A two-phase approach enables an accurate and timely leak event identification.
- Proposed a hybrid algorithm HybridRSL, a combination of Random Forest (RF) and Support Vector Machine (SVM) via Logistic Regression (LogisticR).
- The profile model is trained using 20,000 samples, and the performance is evaluated using 2,000 test cases.
- For each simulation run, there is at least 1 and at most 5 leak events with arbitrary locations and sizes.

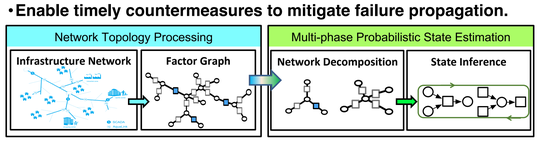


Water Infrastructure Network under Large Disaster

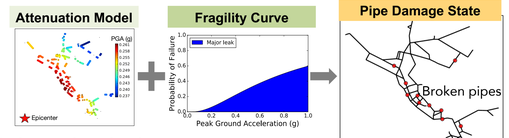
- Water utilities are geographically distributed; sensitive to most man-made or natural disasters.
- Water service disruptions can cause financial, social, environmental and human health consequences.
- Maintaining water supply/delivery is critical during/after events.

The Need for an Efficient Water System State Estimation

- "Fill-in" missing points and "Smooth-out" noisy measurements.
- Produce estimates of the current operating states, and help detect, locate and prevent possible secondary failures.
- Enable timely countermeasures to mitigate failure propagation.



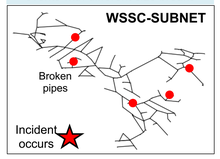
Simulate Earthquake Impacts and Results – Water Network Tool for Resilience (WNTR)



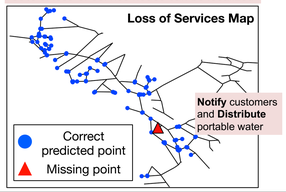
Peak ground acceleration $PGA = 404 \times 10^{0.3M}(R+30)^{-1.2}$ as a function of **PGA**

Probability of failure

Pipe Damage State: 5 pipe break events with different size breaks



99% of loss-of-service nodes can be localized



Human-in-the-loop for Fault Source Identification

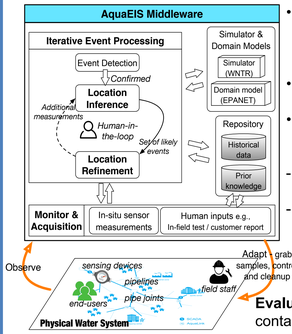
ACM Middleware 2019

- **Exposed over 100,000 residents** to elevated lead levels due to insufficient treatment.
- **Until now, 2,500 lead** service lines still in place

Water security is a worldwide issue
- 2.1 billion people lack access to safe drinking water.
- Cost $500 billion annually.

Water quality facility is limited
- In-situ sensors are spatially sparse, e.g., Novato, CA water service area has 9 stations out of 509 km pipelines.
- Sensing techniques have limitations – yield binary (yes/no) indication of contamination; lab exams are required (6-24 hrs.).

Fast and accurate identification of contaminant source is of utmost importance

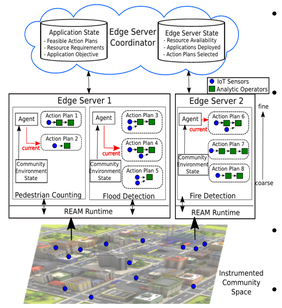


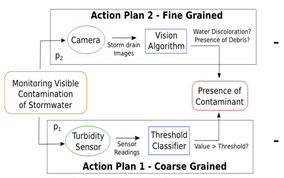
- Integrate multiple sensing modalities (devices, human-as-sensor), computing (ML, simulations) and domain knowledge to enable observation, analysis and adaptation loop.
- **Event driven profile generation**: abstracts physical nature of phenomena spread.
- **Online iterative event processing:** learn from executions and triggers needed actions to reduce human efforts.
  - **Inference**: propose an HMM model to quickly eliminate inconsistent solutions.
  - **Refinement**: implement a RL based approach to determine optimal sampling locations.

Evaluate AquaEIS using a complete ensemble of contamination events on 2 real-world water systems

Significantly reduce the number of sampling cycles, while ensuring localization accuracy (detected 100% of failure events as compared to a baseline that can only identify 38%)

Resource Efficient Adaptive Monitoring at Edge





- **Smart community spaces:** Heterogeneous sensor deployments shared by multiple applications.
- **Smart community applications:** Workflows of operators that derive actionable insights from sensor data. Multiple workflows (action plans) for an application exist with varying resource-cost and result quality (local edge vs. cloud).
- **State of the community**: Events (fire, flood), external information (**e.g. weather, time-of-day).**
- **Determine action plans** to execute the monitoring task to achieve high quality results with low resource consumption.
  - **Use reinforcement learning.** Assign agents to each application that use a Q-learn based method to determine optimal workflow to execute locally at edge.
  - **Adapt action plans at edge** depending on the current state of the community.
- **Evaluate approach over two real-world testbeds:** Stormwater contamination monitoring (Orange County), Pedestrian counting using smart streetlamps (Taiwan)

Reinforcement Learning driven adaptive monitoring framework results in >90% monitoring accuracy while utilizing ~50% less resources compared to existing static approaches.