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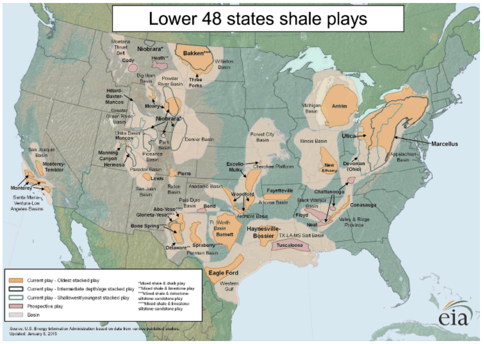

Water Security Software Tools

Methane Emissions Collaboration Meeting

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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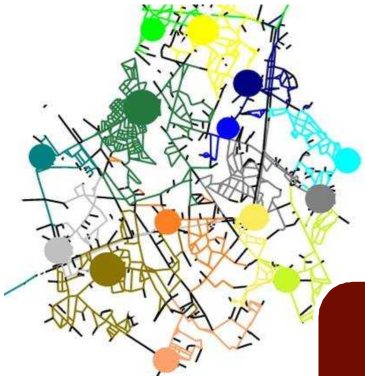
12/7/2015

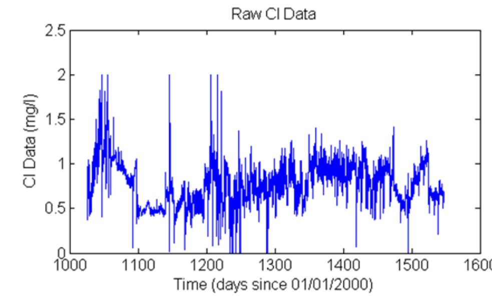
Outline

- Water Security Software Tools
  - Network Models
  - Vulnerability Assessment
  - Sensor Placement Optimization
  - Event Detection
  - Source Inversion
  - Manual Sampling
  - Resilience
- Application to Methane Emissions
  - Monitoring Domains
  - Sensor Technology
  - Available Models

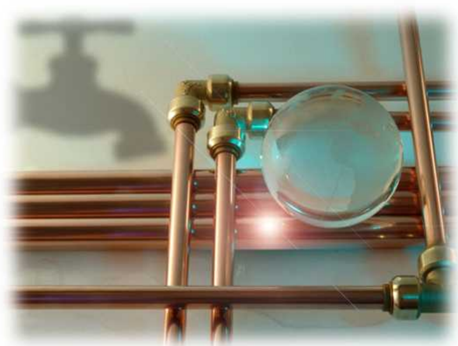
Water Security Tools



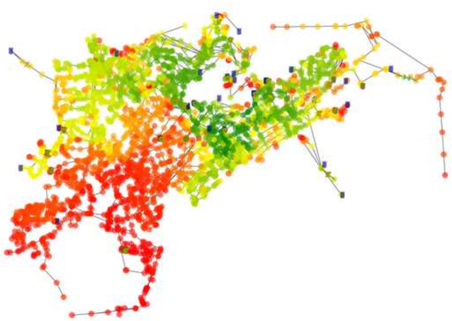
CANARY
Real-time event detection



SPOT
Sensor placement optimization

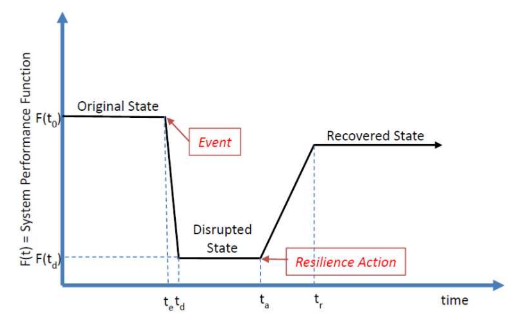


WST
Response action plans



TEVA
Hydraulic/water quality simulation and vulnerability assessment

WNTR
Recovery and adaption plans



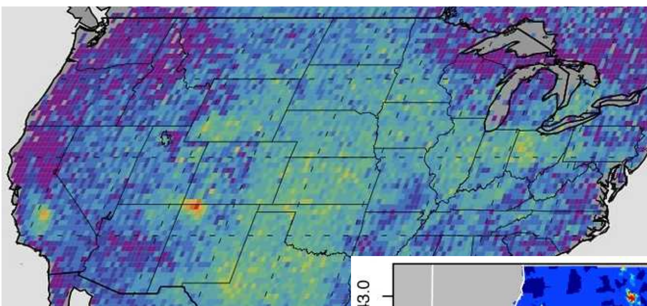
Application to Methane Emissions

Common Goals:

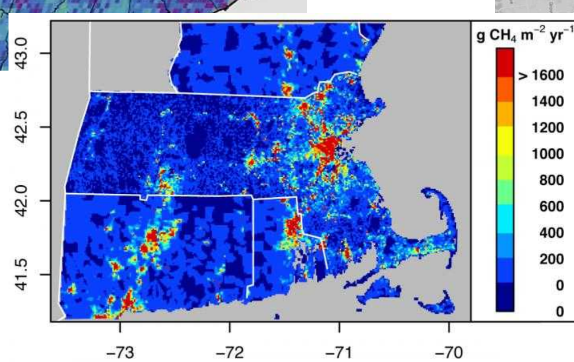
1. Understand current sensor technology (accuracy, cost, spatial resolution, temporal resolution) and available models
2. Quantify impact and identify sensors locations that maximize information
3. Track sensor readings and alert an operator if readings are abnormal
4. Use sensor readings to identify a possible source
5. Identify sampling locations for confirmation (gather more information on a leak or confirm that the leak has been fixed)
6. Develop repair strategies and minimize the magnitude and duration of future events

Monitoring Domains

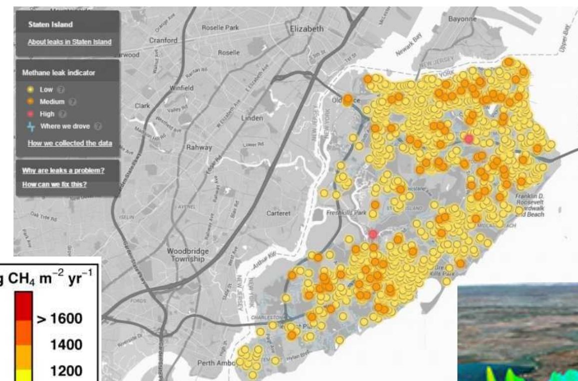
	Regional	City-level	Pipeline
Sensor locations	Satellite Aircraft Radio towers Cars	Radio towers Buildings Cars	Inside or near the pipeline



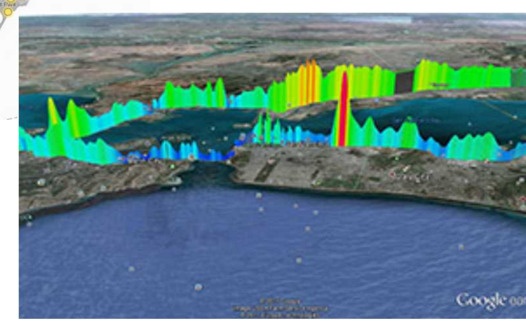
Satellite data from NASA/JPL-Caltech/University of Michigan showing methane anomalies



Inversion results using air quality data and an atmospheric model from Harvard SEAS



Air quality data from The Environmental Defense Fund



Los Gatos Research Natural Gas Leak Detection

Sensor Technology

From NETL report:

Technology Status Report on Natural Gas Leak Detection in Pipelines

Appendix-A: Comparison of Different Natural Gas Leak Detection Techniques

Method group	Technique	Feature	Advantages	Disadvantages
Non-optical methods	Acoustic sensors	Detects leaks based on acoustic emission	Portable Location identified Continuous monitor	High cost Prone to false alarms Not suitable for small leaks
	Gas sampling	Flame Ionization detector used to detect natural gas	No false alarms Very sensitive Portable	Time consuming Expensive Labor intensive
	Soil monitoring	Detects tracer chemicals added to gas pipe line	Very sensitive No false alarms Portable	Need chemicals and therefore expensive Time consuming
	Flow monitoring	Monitor either pressure change or mass flow	Low cost Continuous monitor Well developed	Prone to false alarms Unable to pinpoint leaks
	Dynamic modeling	Monitored flow parameters modeled	Portable Continuous monitor	Prone to false alarms Expensive
Active Optical methods	Lidar absorption	Absorption of a pulsed laser monitored in the infrared	Remote monitoring Sensitive Portable	Expensive sources Alignment difficult Short system life time
	Diode laser absorption	Absorption of diode lasers monitored	Remote monitoring Portable Long range	Prone to false alarms Expensive sources Short system life time
	Broad band absorption	Absorption of broad band lamps monitored	Portable Remote monitoring Long range	Prone to false alarms Short system life time
	Evanescent sensing	Monitors changes in buried optical fiber	Long lengths can be monitored easily	Prone to false alarms Expensive system
	Millimeter wave radar systems	Radar signature obtained above pipe lines	Remote monitoring Portable	Expensive
	Backscatter imaging	Natural gas illuminated with CO2 laser	Remote monitoring Portable	Expensive
Passive Optical methods	Thermal imaging	Passive monitoring of thermal gradients	No sources needed Portable Remote monitoring	Expensive detector Requires temperature difference
	Multi-spectral imaging	Passive monitoring using multi-wavelength infrared imaging	No sources need Portable Remote monitoring Multiple platform choices	Expensive detectors Difficult data interpretation

Pipeline ↓

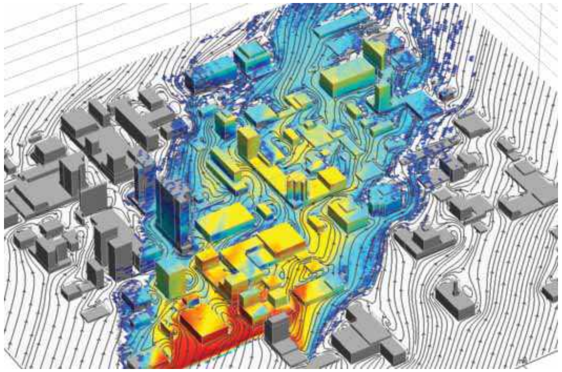
Regional/City-level ↓

Available Models

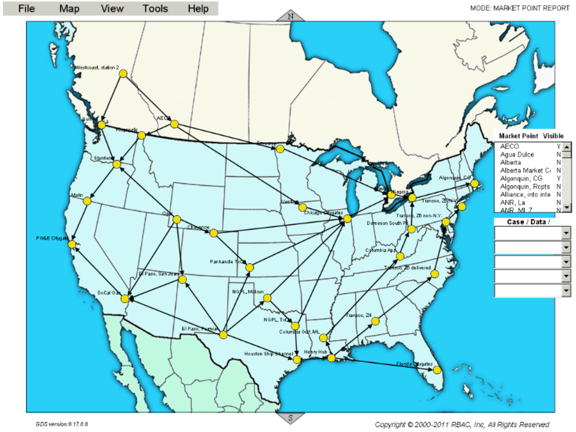
Sandia National Laboratories

- Regional atmospheric transport models
  - Velocity field predicted by a weather model
- Urban “building aware” transport and dispersion models
  - City architecture alters flow fields, creating flow channels, abrupt changes in the flow field, updraft/downdraft
- Pipeline transport models
  - Regional models
  - Street level models

QUIC Fast building-Aware Atmospheric Dispersion Model developed at LANL

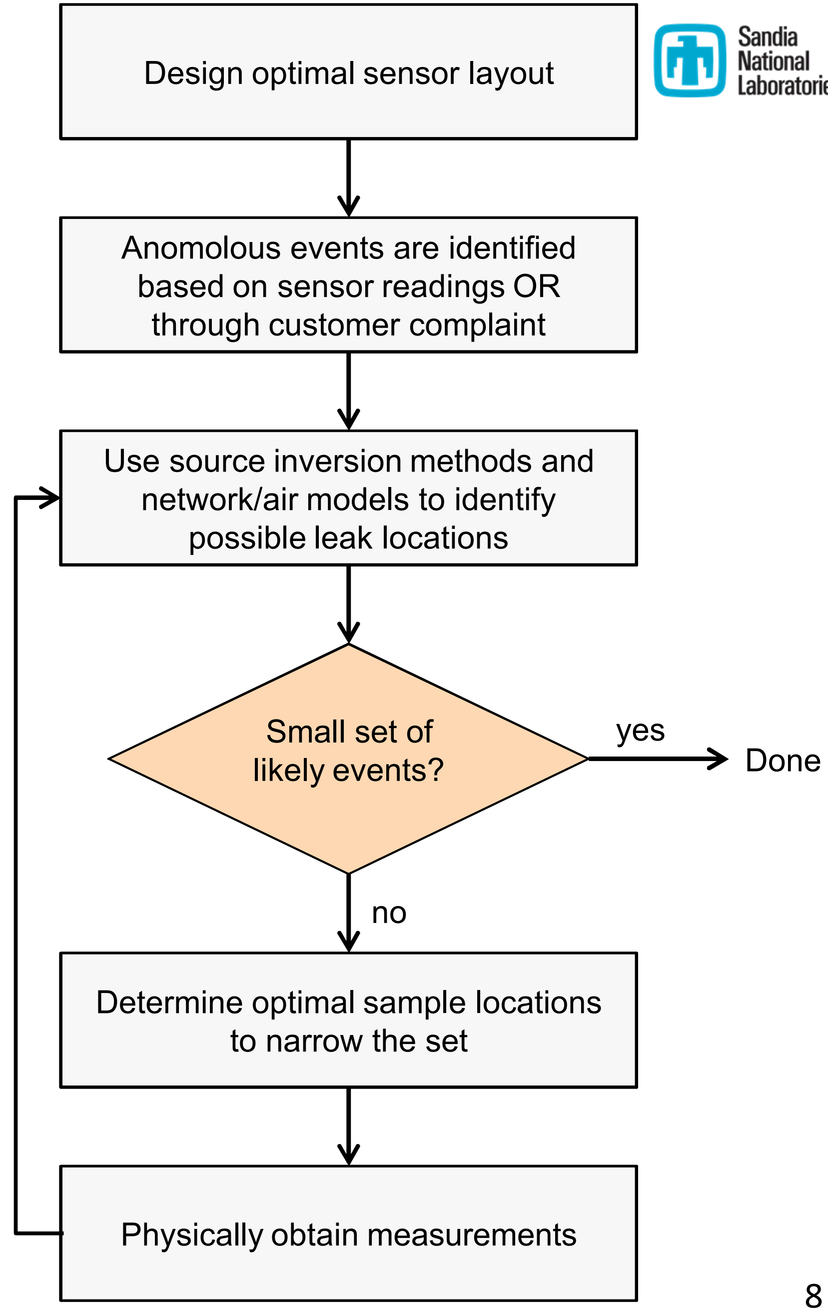


GPCM Natural Gas Market Forecasting System developed by RBAC Inc.



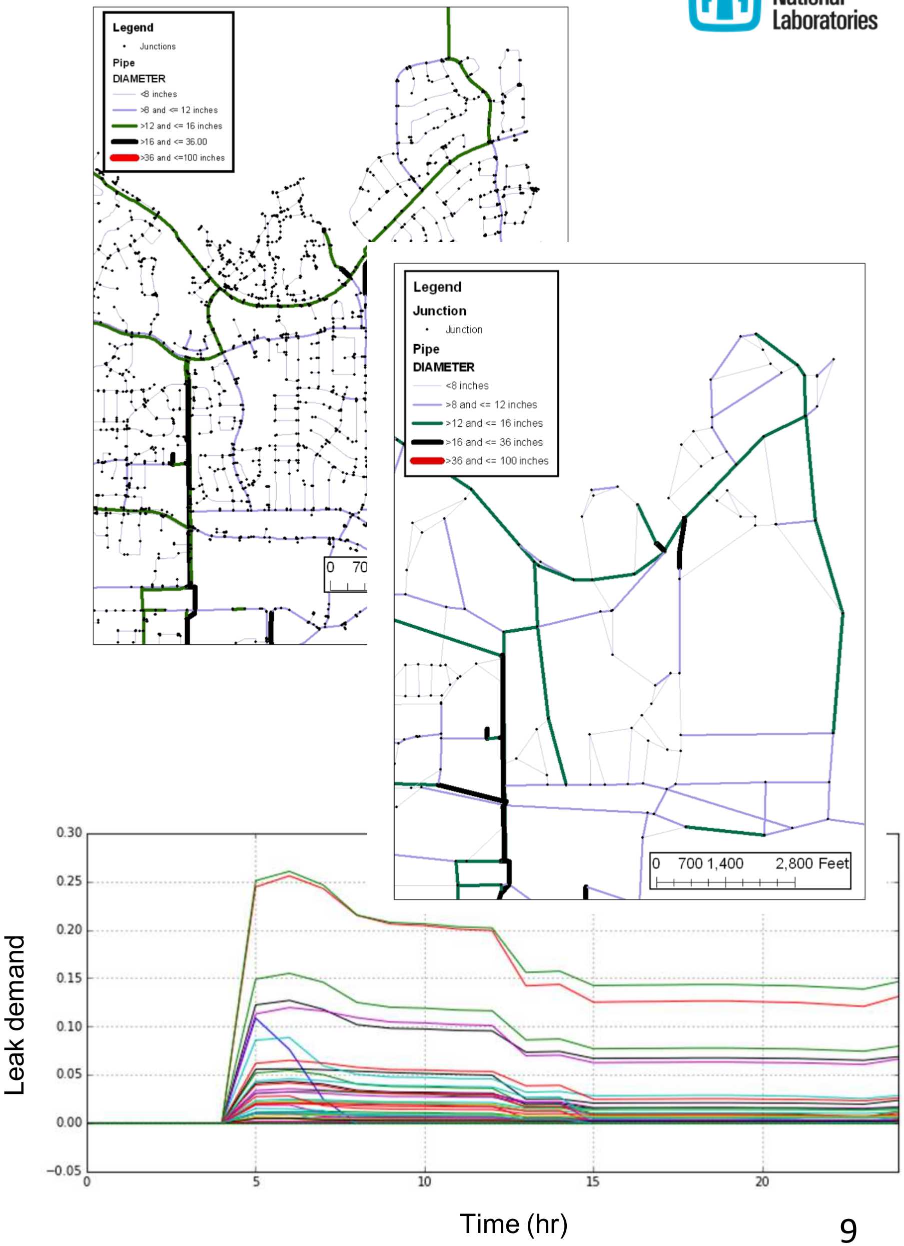
Water Security Tools

- Network model
- Vulnerability Assessment
- Sensor Placement Optimization
- Event Detection
- Source Inversion
- Manual Sampling



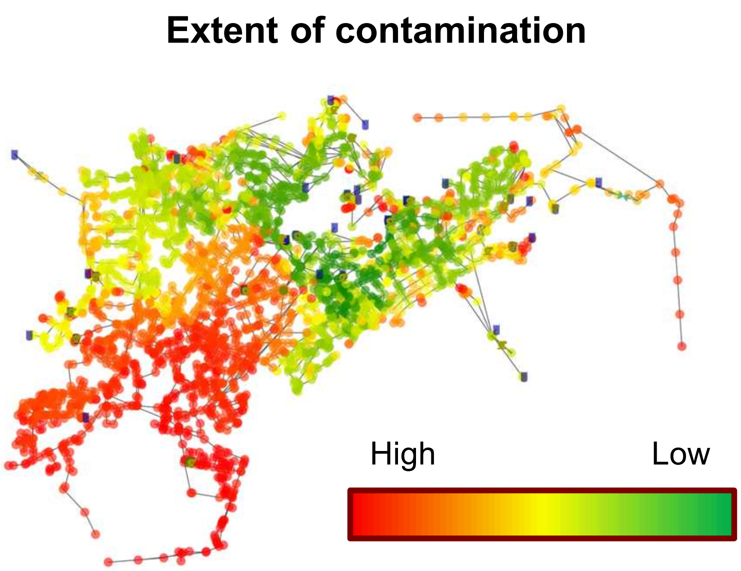
Network Models

- Graph structure
  - Nodes = junctions, tanks, reservoirs
  - Links = pipes, valves, and pumps
  - Coordinates (x, y, elevation)
- Additional input includes
  - Demand patterns, pump curves, surface roughness, tank shape, operational controls, …
- Hydraulic and water quality simulation
- Skeletonization methods



Vulnerability Assessment

- Quantify impact given a set of possible scenarios
- Scenarios include:
  - Contamination
  - Pipe break
  - Power outage
- Impact metrics include:
  - Mass consumed
  - Volume leaked
  - Fraction of demand met
  - Extent of contamination
  - Population exposed
- Metrics are used in optimization techniques



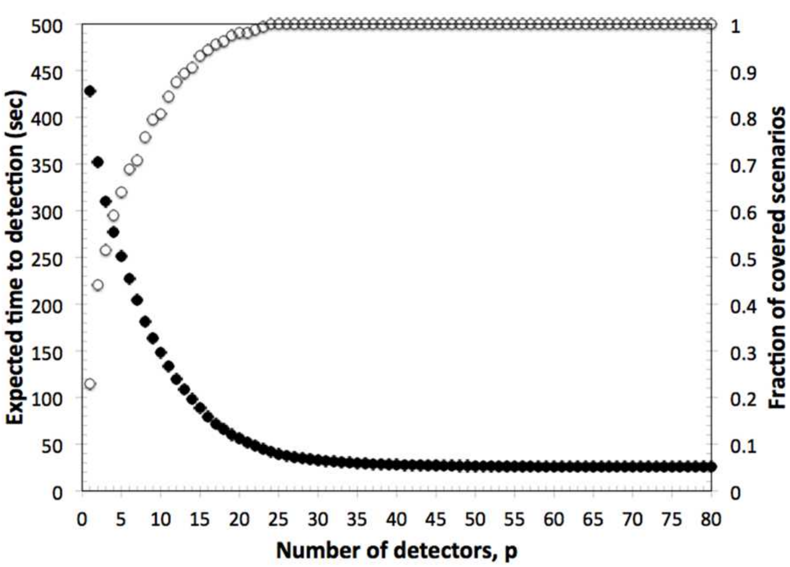
Sensor Placement Optimization

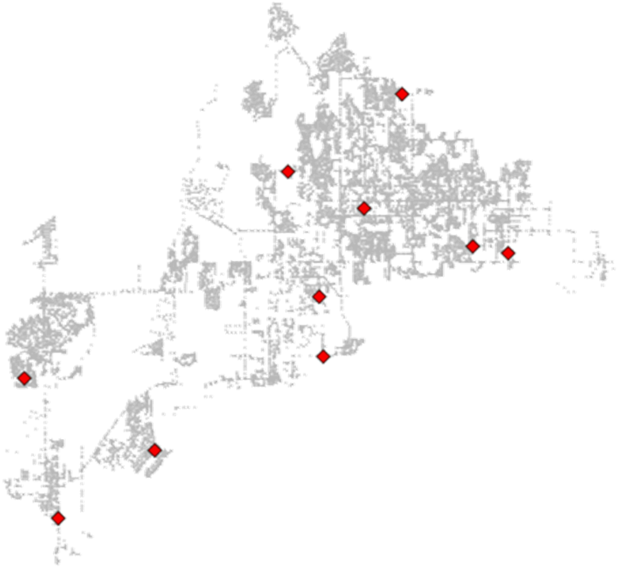
- Optimize the location of sensors to minimize some measure of impact
- MIP formulation, P-median facilities locate problem
  - Facilities = sensors
  - Customers = contamination scenarios
  - Distance = impact of contamination
- Solvers
  - MIP and heuristic solvers
- Additional formulations include
  - Sensor cost
  - Imperfect sensors
  - Worst case
  - Voting

minimize	$\sum_{a \in A} \alpha_a \sum_{i \in \mathcal{L}_a} d_{ai} x_{ai}$	
subject to	$\sum_{i \in \mathcal{L}_a} x_{ai} = 1$	$\forall a \in A$
	$x_{ai} \leq s_i$	$\forall a \in A, i \in \mathcal{L}_a$
	$\sum_{i \in L} c_i s_i \leq p$	
	$s_i \in \{0, 1\}$	$\forall i \in L$
	$0 \leq x_{ai} \leq 1$	$\forall a \in A, i \in \mathcal{L}_a$

Sensor Placement Optimization

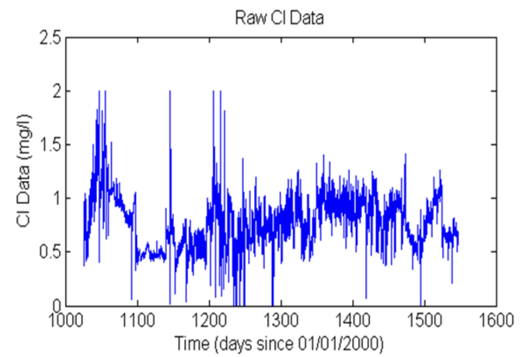
- At a minimum, input includes
  - Feasible sensor locations
  - Vulnerability assessment results from a set of scenarios
- Tradeoff between cost and detection
- The tool has been used to place air quality monitors

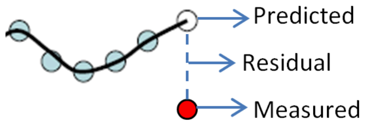


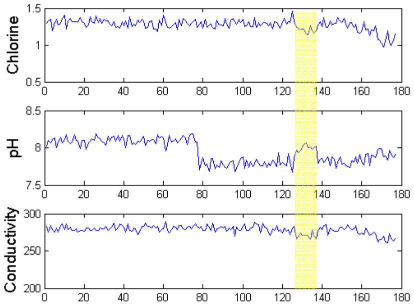


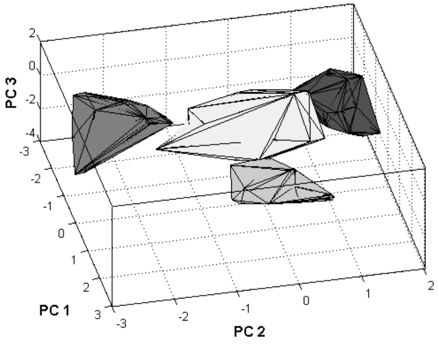
Event Detection

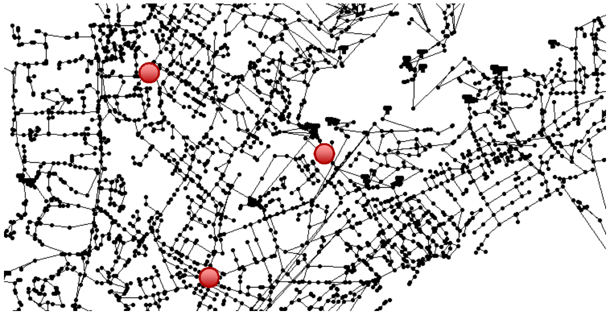
- Data-mining techniques
  - Set-point
  - Rate of change
  - Residual (compared to predicted/modeled value)
  - Cluster analysis
  - Pattern matching
  - Machine learning
- Single or multivariate analysis
- Isolated or networked sensors







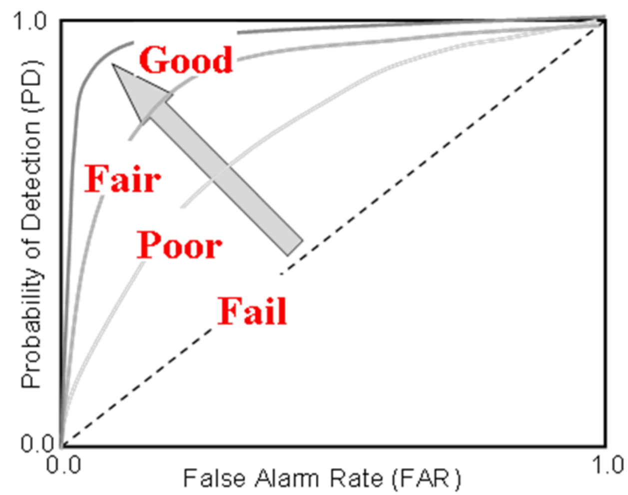




Event Detection

- The tools have been applied to detect anomalies in
  - Water quality monitoring,
  - Weather monitoring
  - Electric properties from PV systems
  - Software testing statistics
- Receiver operating characteristic curves are used for algorithm development/tuning

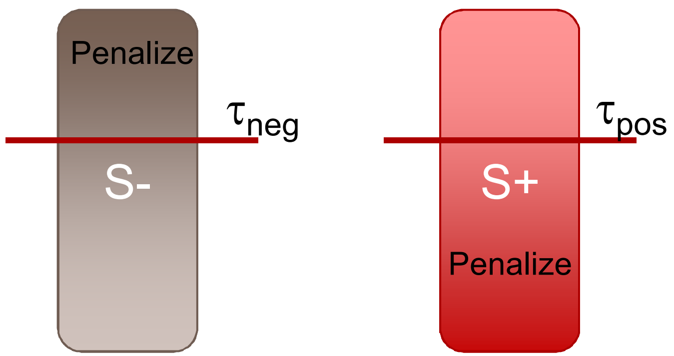
	Actual Background Condition	Actual Anomalous Condition
Predicted Background Condition	True Negative (TN)	False Negative (FN)
Predicted Anomalous Condition	False Positive (FP)	True Positive (TP)
	False Alarm Rate (FAR) = 1+ TN / (TN+FP)	Prob. of Detection (PD) = TP / (TP+FN)



Source Inversion

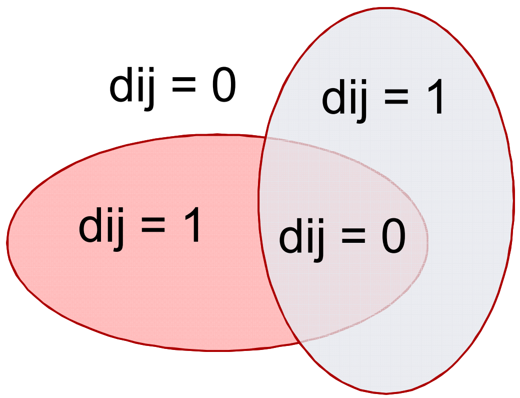
- Determine when/where contaminant entered the system
- MIP formulation with an imbedded linear water quality model
  - concentration at n,t = linear combination of mass injection at n,t
  - Dependent on the velocity flow field through the system
- Using sensor data:
  - Penalize concentrations BELOW a threshold for node-pairs where contaminant WAS detected (S+)
  - Penalize concentrations ABOVE a threshold for node-pairs where contaminant WAS NOT detected (S-)

$$
\begin{array}{lll}
\text{minimize} & \sum_{(n,t)\in\mathbf{S}_-} neg_{n,t} + \sum_{(n,t)\in\mathbf{S}_+} pos_{n,t} & \\
\text{subject to} & Gc_{n,t} = D\mathbf{m}_R & \forall n \in \mathbf{N}, t \in \mathbf{T} \\
& 0 \le m_{n,t} \le By_n & \forall n \in \mathbf{N}, t \in \mathbf{T} \\
& \sum_{n\in\mathbf{N}} y_n \le I_{max} & y_n \in \{0,1\} \\
& neg_{n,t} \ge 0, \quad neg_{n,t} \ge c_{n,t} - \tau_{neg} & \forall\,(n,t) \in \mathbf{S}_- \\
& pos_{n,t} \ge 0, \quad pos_{n,t} \ge \tau_{pos} - c_{n,t} & \forall\,(n,t) \in \mathbf{S}_+ .
\end{array}
$$



Manual Sampling

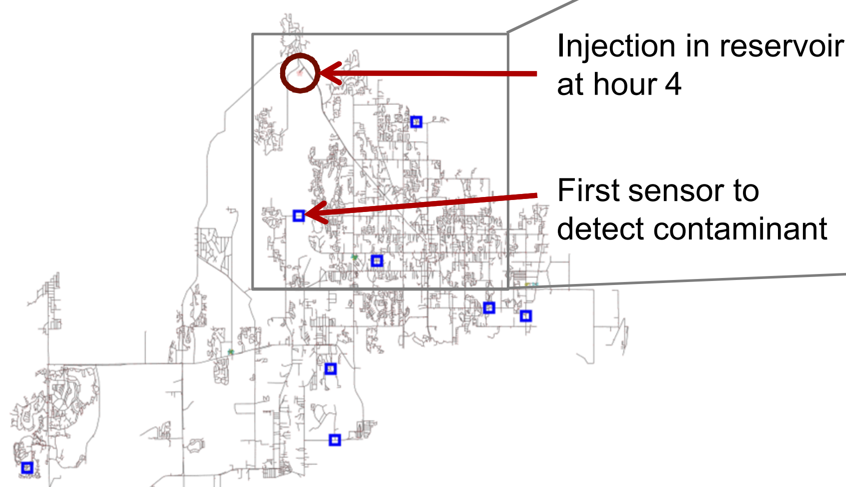
- Determine sampling locations that distinguish between feasible incidents
- Iterative process with source inversion
- Formulations take delay times into account
- MIP formulation uses the pairwise set of possible contaminant incidents (from source inversion)

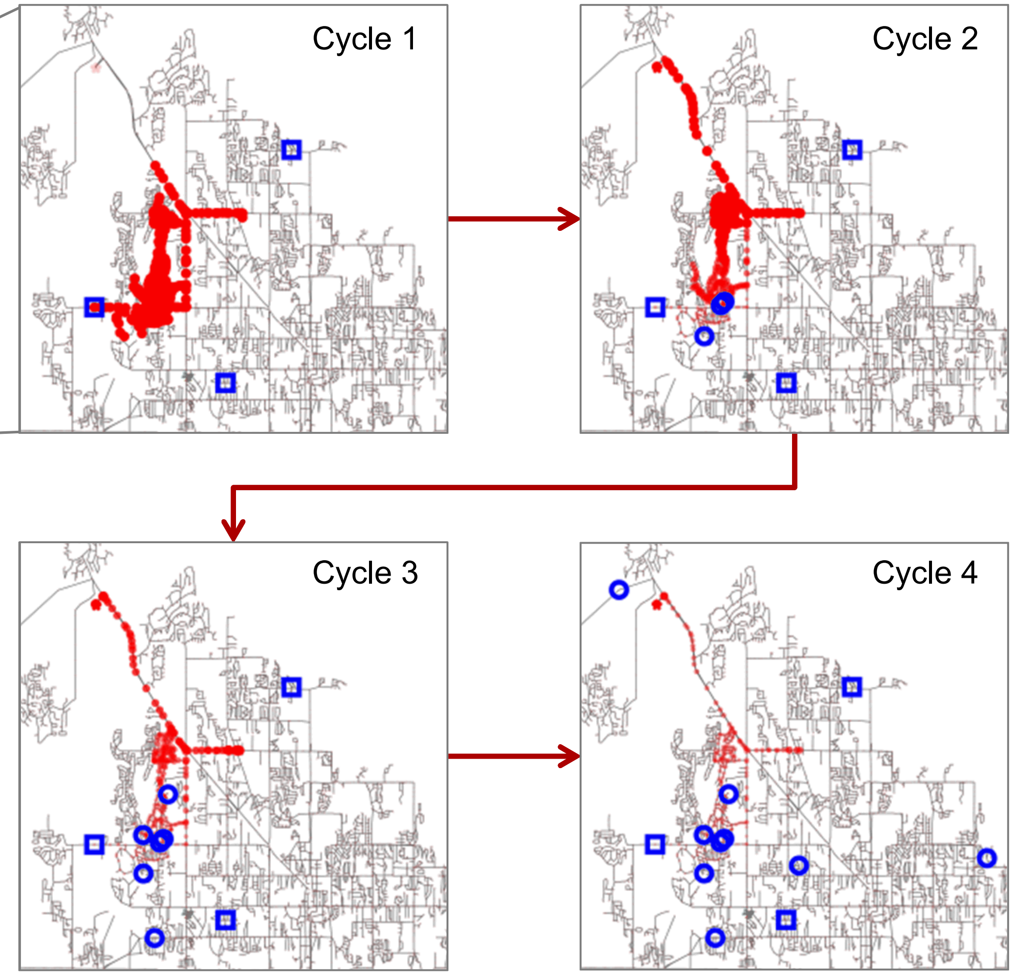


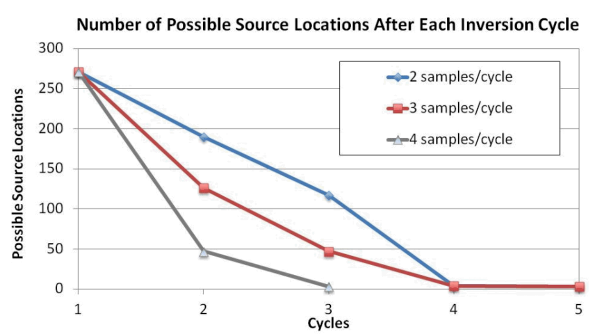
$$
\begin{aligned}
\text{maximize} \quad & \sum_{(i,j)\in PE} d_{ij} & \\
\text{subject to} \quad & \sum_{n\in D_{ij}} s_n \geq d_{ij} & \forall (i,j) \in PE \\
& \sum_{n\in G} s_n \leq S_{max} + |F| & \\
& s_n \in \{0,1\} & \forall n \in G \\
& s_n = 1 & \forall n \in F \\
& 0 \leq d_{ij} \leq 1 & \forall (i,j) \in PE
\end{aligned}
$$

Source Inversion/Manual Sampling

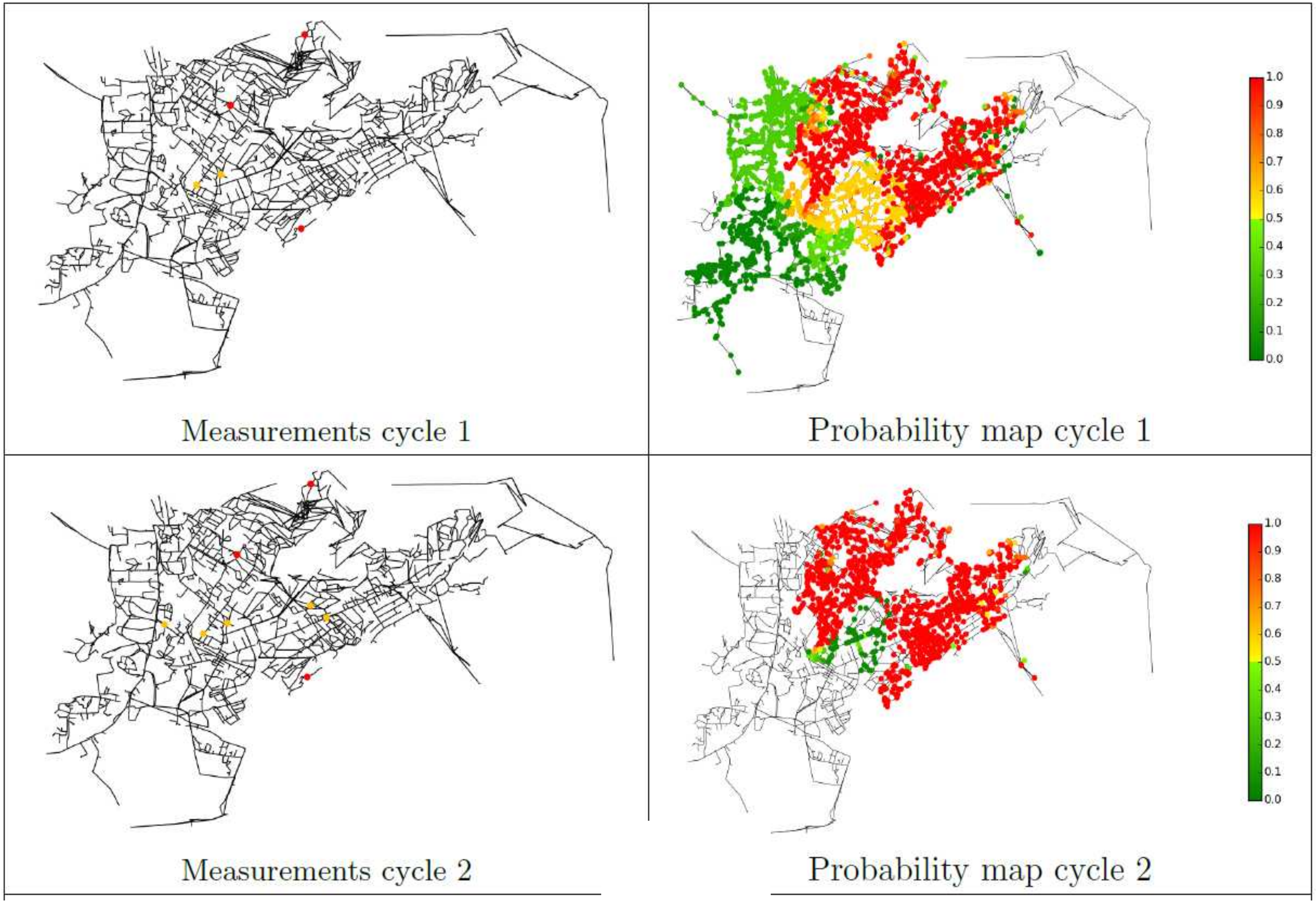
- Sensor locations
- Manual sampling locations
- Possible source (probability indicated by size)







Manual Sampling

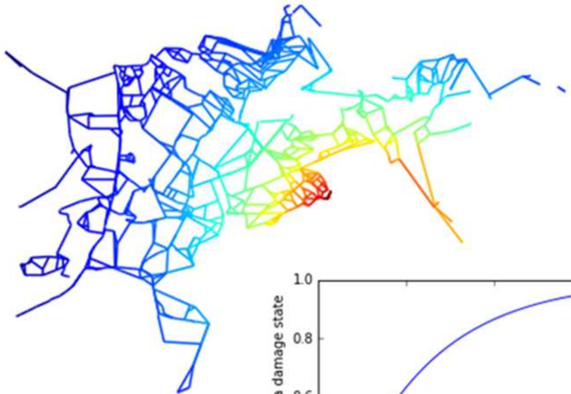


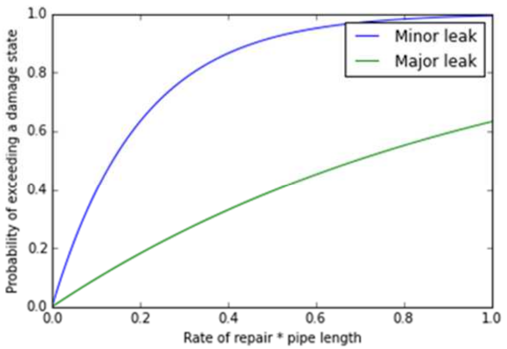
Measurements cycle 1 | Probability map cycle 1

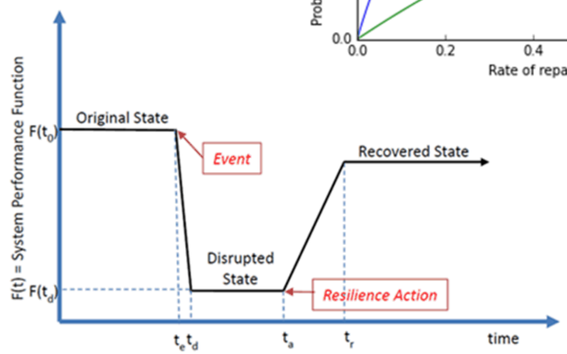
Measurements cycle 2 | Probability map cycle 2

Resilience

- Water distribution systems face multiple challenges:
  - Aging infrastructure, water quality concerns, pipe breaks, uncertainty in supply and demand, natural disasters, environmental emergencies, terrorist attacks.
- Water utilities need to be able to:
  - Predict how their system will perform during disruptive events
  - Understand how to best absorb, recover from, and more successfully adapt.

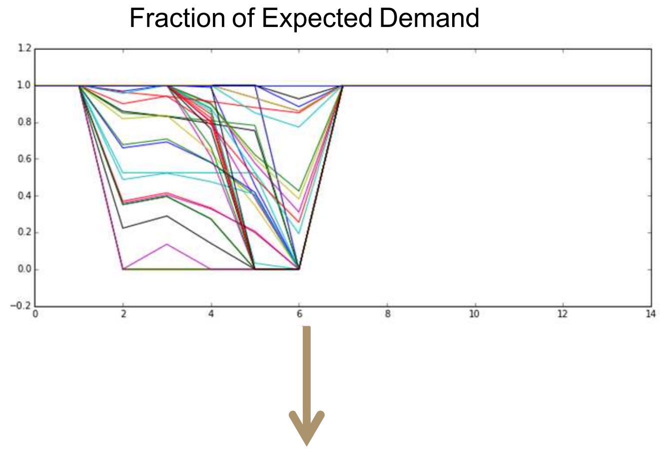


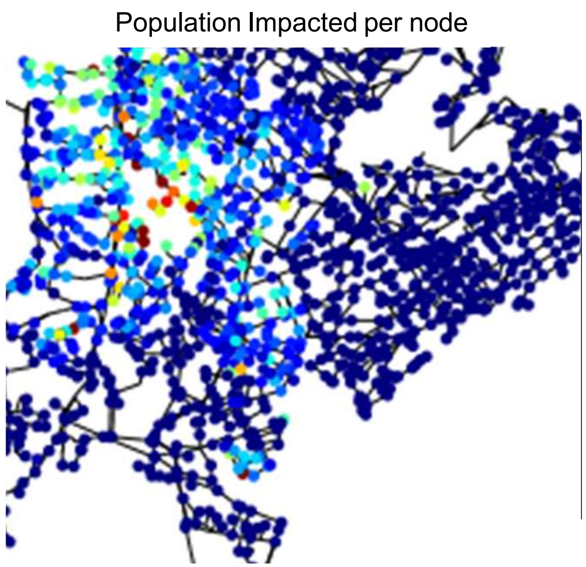


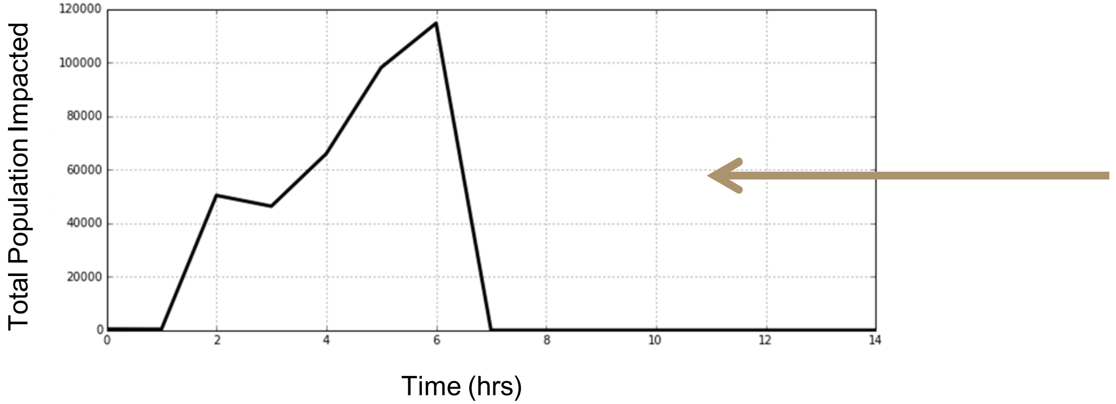


Resilience

- Generate water network models
- Modify network structure/operations
- Add disruptive events
- Evaluate response/repair strategies
- Simulate network hydraulics and water quality
- Compute resilience







Acknowledgements

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  - Cindy Phillips
  - Arpan Seth
  - John Siirola
  - Jean-Paul Watson

- WNTR
  - https://software.sandia.gov/trac/wntr (coming soon)
- CANARY
  - https://software.sandia.gov/trac/canary
- TEVA-SPOT
  - https://software.sandia.gov/trac/spot
- WST
  - https://software.sandia.gov/trac/wst