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Smart Sensor Deployment: An Innovative Strategy for Proactive Monitoring Implementation

(Developed under WRF Project 5239)

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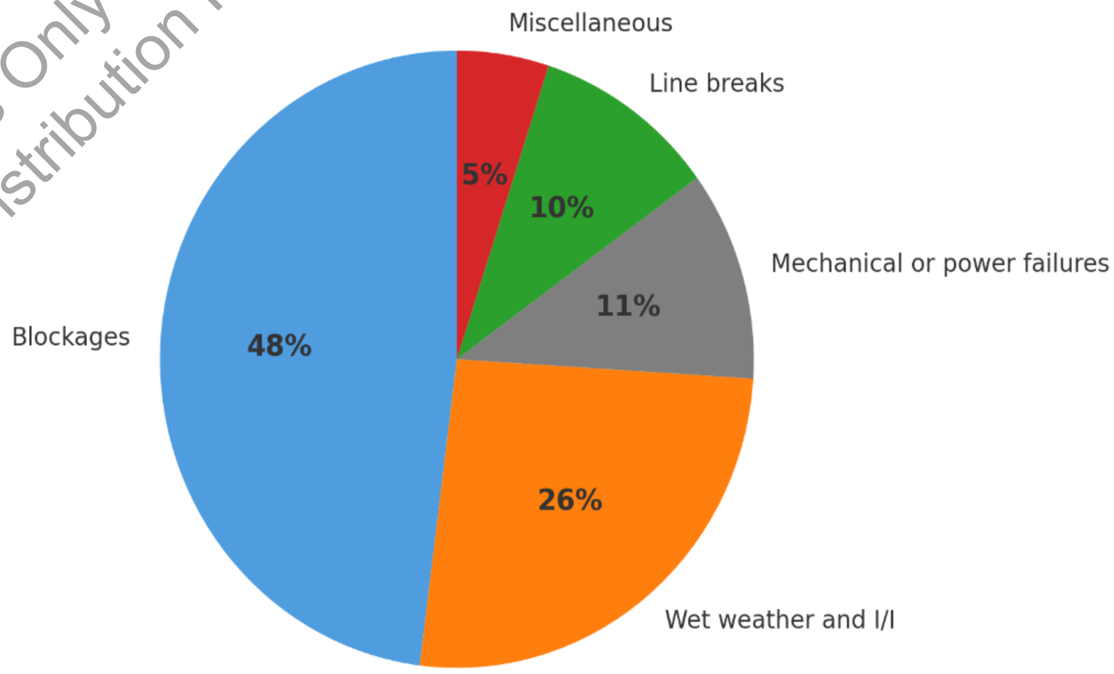
Introduction

Condition Assessment Challenges

- U.S. wastewater systems are aging and deteriorating
- One-third of waterways fail Clean Water Act standards
- Blockages cause ~50% of SSOs; I/I causes ~25%
- Many blockages are low-cost, quick fixes
- Limited improvement observed since 2021



Causes of SSO Events (U.S. EPA, 2021)

Research Needs

- **Liggett et al. (2018):** Industry reluctance, high costs, and uncertain sensor performance limit adoption
- **Kimbrough (2019):** Reactive maintenance and limited inspections hinder proactive risk management
- **Salveson (2023):** Actionable intelligence requires real-time analytics and AI integration
- **Banik et al. (2017):** Effective monitoring depends on optimal sensor location and density
- **Salem & Abokifa (2022):** Sensor placement models remain largely theoretical, with limited real-world validation

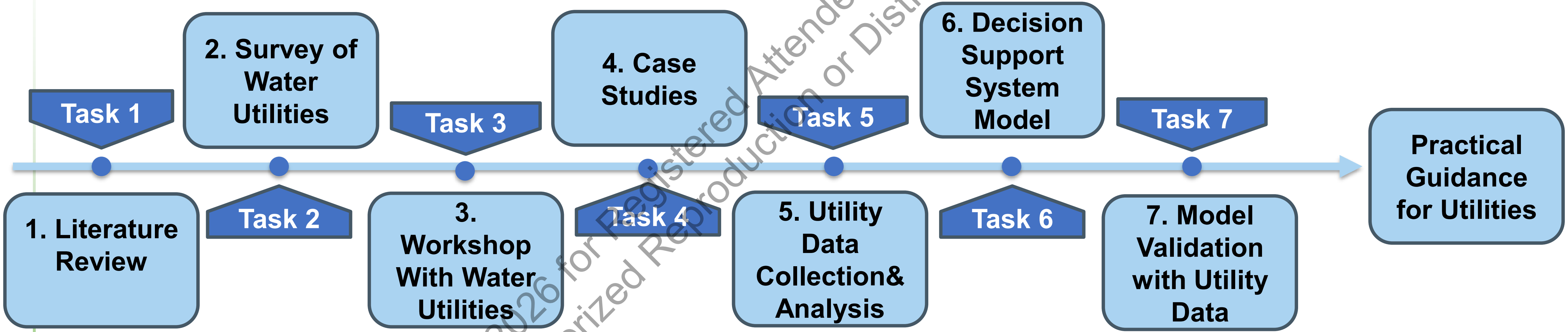
Objectives

- ✓ **To support proactive, risk-informed decision-making** that enhances system reliability, operational resilience, and long-term infrastructure sustainability for wastewater and stormwater utilities.
- ✓ **To develop a data-driven framework for optimizing sensor placement in wastewater collection systems** through the integration of multi-source utility data and advanced analytical modeling.
- ✓ **To maximize the total covered system risk using a limited number of monitoring sensors** by formulating and solving a multi-objective optimization problem under operational and budgetary constraints.

Scope of Work

Included	Excluded
Comprehensive literature review on **sensor network design, optimization strategies, and advanced sensing techniques** for collection systems.	Literature review and data analysis related to **aboveground water infrastructure**.
Data collection from **municipal utilities and analysis of wastewater collection system assets including gravity mains, force mains, manholes, and pump stations.**	**Laboratory testing** of sensor equipment, hardware, or emerging technologies.
Development of a **decision-support framework** for optimizing **sensor placement, data analytics, forecasting tools, and ML-driven decision-making** for collection system management.	Independent validation of the **accuracy and reliability of municipal datasets**.
Development of a machine learning–based model to estimate sewer asset failure probability using real utility data.	Physical installation or real-time deployment of sensors in the field.
Review of most used sensors based on established technologies, case studies, and a research survey, water depth/flow/pressure sensors, and rain gauges.	Hardware development or lab testing of new sensors; focus is on application and optimization of existing tools.

Overall Approach



Task 1

1. Literature Review

Task 2

2. Survey of Water Utilities

Task 3

3. Workshop With Water Utilities

Task 4

4. Case Studies

Task 5

5. Utility Data Collection& Analysis

Task 6

6. Decision Support System Model

Task 7

7. Model Validation with Utility Data

Practical Guidance for Utilities

Overall Project Approach and Task Sequence Leading to Practical Guidance for Utilities

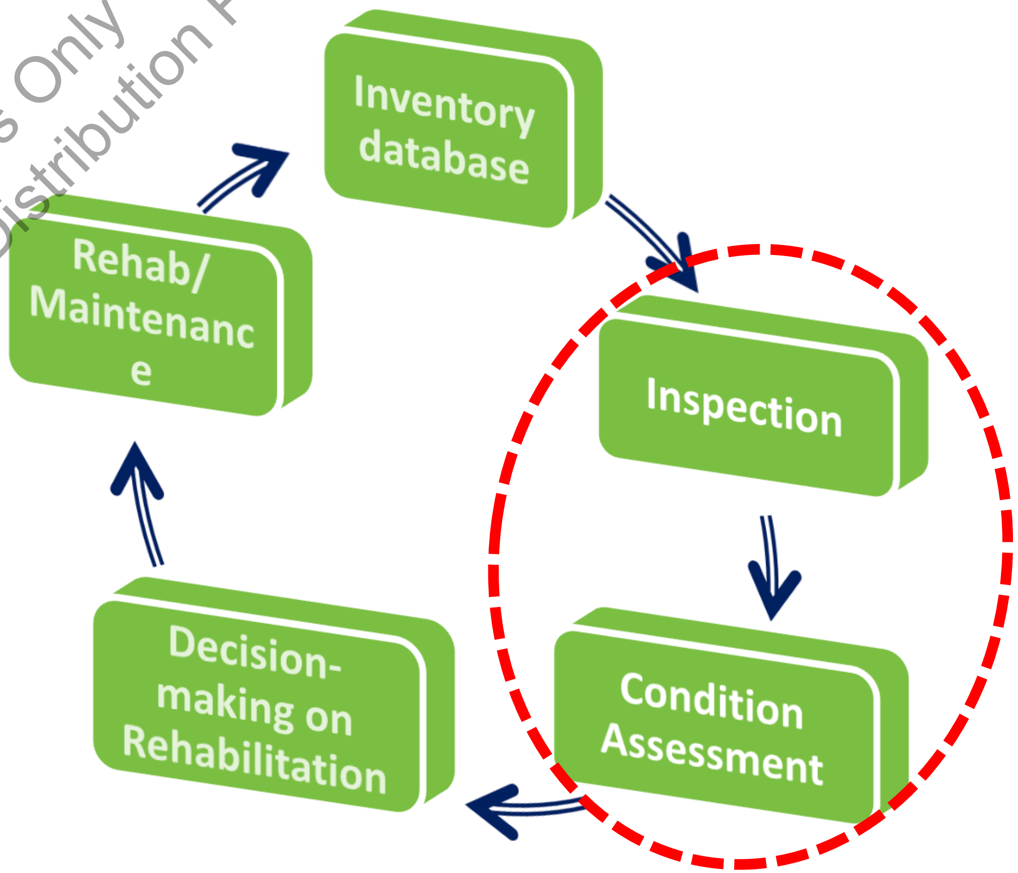
Infrastructure Asset Management

Asset Management in Water Systems

- Adopted widely since the early 2000s
- Continuous process to optimize service and control costs

Critical components

- Inventory
- Condition Assessment
- Decision-Making on Rahab Technique(s)
- Repair and Maintenance Activities



Infrastructure Management System Framework (WRF 4797A, 2025)

Intelligent Collection System Foundation

Source: https://www.gartner.com/en/research/methodologies/garner-hype-cycle.

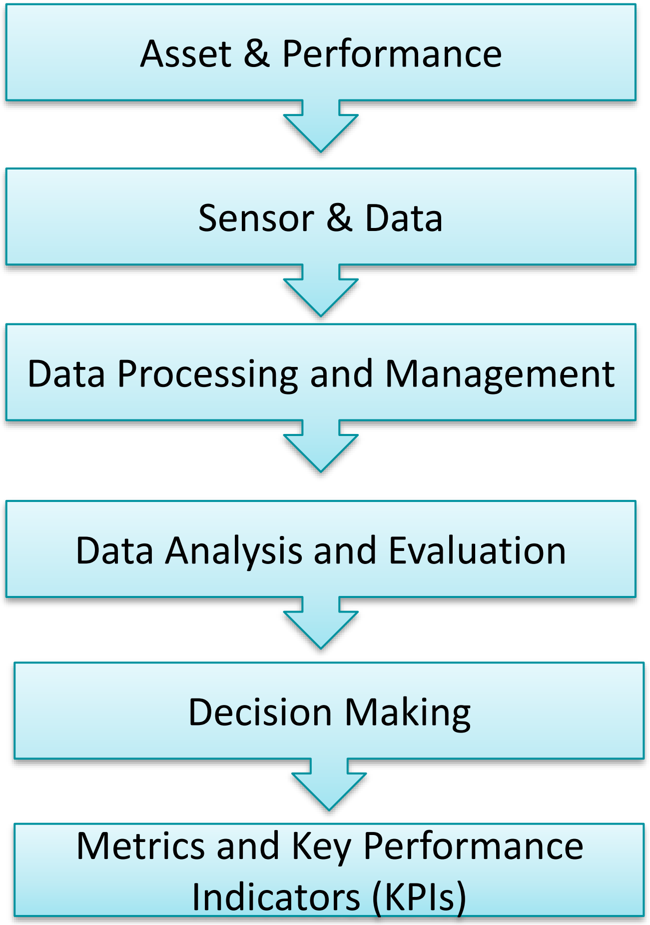
Collection System Monitoring Cycle (Salveson, 2023)

* Utilities need protection of source water for potable reuse.
1 Real-time monitoring probes become cost-effective.
2 WRF 4835 survey says that utilities desire online probes.
3 WRF 4908 begins at three partner utilities.
4 Installation challenges experienced in WRF 4908.
5 Maintenance challenges during WRF 4908 identify need for improved probe system accuracy, precision, and reliability.
6 CWS innovates sensor holders for sewershed environment.
7 Key findings from previous studies integrated in WRF 5048.

From Sensors to Decisions

- Multiple sensor types are used across collection systems
- Sensors support monitoring, control, and alarm functions
- Value depends on placement, integration, and maintenance

Monitoring class (Wang 2017)	Monitoring class (Diego Calderón 2024)	Frequency	Comments
Very Low	Low Frequency / As-Needed	Every year to every few years	Used for invasive or expensive non-permanent sensors
Low	Periodic	Every week to every few months	Logged or manually read data
Moderate	Periodic	Every hour to every week	Logged or manually read data
High	Periodic	Every 15 minutes to every hour	Logged and wirelessly delivered data
Near continuous	Near-Real-Time	Every sub-second to every few minutes	Monitoring of data delivered wired or wirelessly in real-time



Data-Driven Framework

Common Sensors in Collection Systems

- A limited set of sensors supports most collection system monitoring needs
- Sensor performance depends heavily on placement, hydraulics, and maintenance
- Data are available, but integration for system-wide decision support is limited

Sensor / Device	Measures	Typical placement	Typical uses	Notes
Level sensors (ultrasonic, radar, pressure transducer)	Liquid level	Manholes, interceptors, wet wells	Surcharge/overflow alarms, wet-well control	Common and low maintenance; watch for fouling/splashing
Area–velocity flow meters	Velocity, flow rate	In-pipe or open-channel sites	Capacity tracking, I/I studies, model calibration	Needs stable hydraulics and good velocity profile
Pressure transducers (incl. high-rate for transients)	Static pressure, surges	Force mains, pump discharge headers	Surge/burst detection, pump diagnostics, air-valve issues	Calibration and air management are important
Rain gauges (tipping-bucket)	Rainfall intensity/total	Across basins/catchments	Correlate rainfall with I/I and overflow events	Siting and upkeep affect accuracy
Float switches / wet-well level controls	High/low level states	Wet wells	Basic pump start/stop, alarms	Very common, low cost

Common Sensors in Collection Systems (Cont.)

- Collection systems rely on a small number of widely used sensor types
- Sensors support core functions such as monitoring, alarms, and system control
- Effectiveness depends on placement strategy, data quality, and maintenance

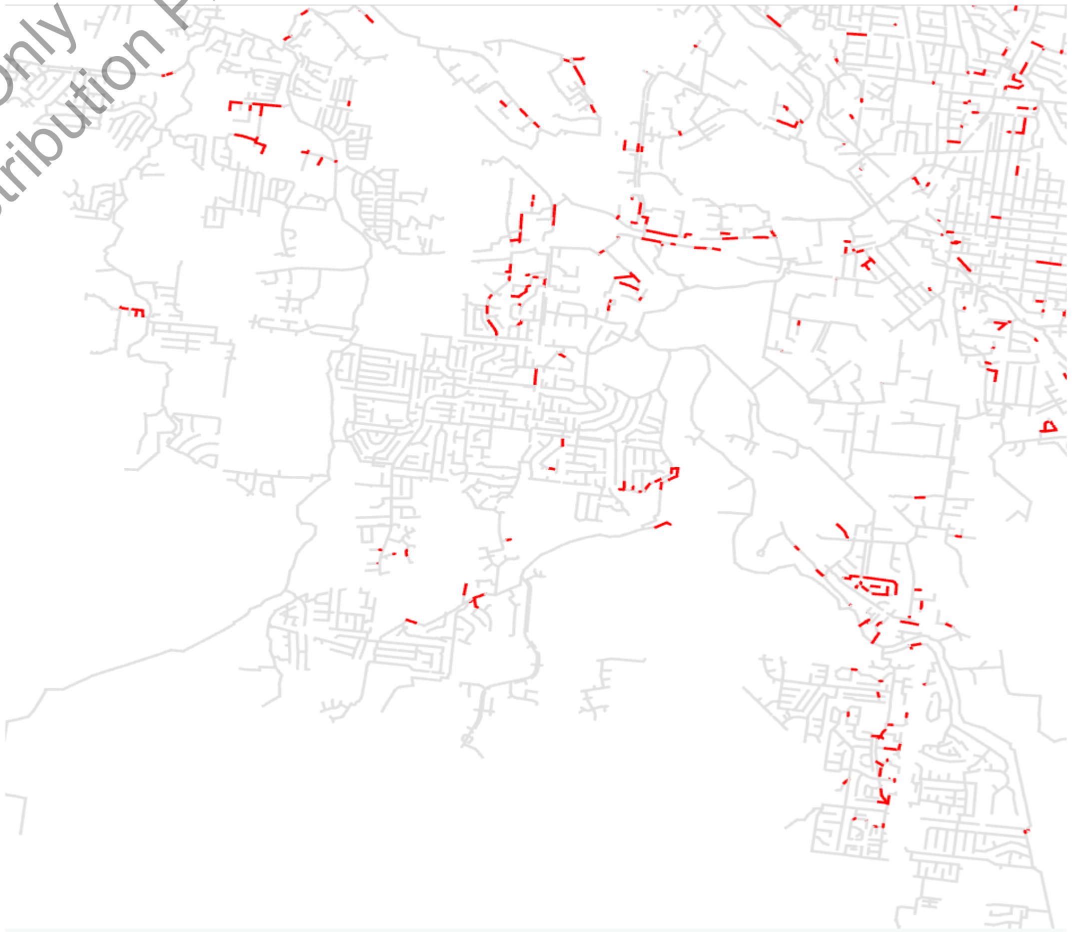
Sensor / Device	Measures	Typical placement	Typical uses	Notes
Pump run-time / power monitors (SCADA tags)	Status, run-time, amperage/power	Pump stations/MCCs	Performance and energy diagnostics, failure detection	Requires SCADA/telemetry integration
Water-quality probes (pH, conductivity, temperature, turbidity, ammonia)	Chemical/physical parameters	Wet wells, interceptors, headworks	Illicit discharge flags, corrosion/odor risk, wet-weather characterization	Prone to fouling; needs cleaning/calibration
Fixed gas monitors (H_2S, CH_4, O_2)	Toxic/flammable gases, oxygen	Wet wells, headworks, confined spaces	Safety compliance; corrosion/odor management	Sensor life limits; bump-tests/calibration needed
CCTV / zoom cameras (crawler, push-rod, pole-cam)	Visual defects/grades	Inside pipes during planned surveys	Condition assessment, rehab planning, verification	Episodic (not continuous); access/flow control required

Data Monitoring Problems

- **Optimism vs. Reality:** Field limitations temper early promise of real-time sensing
- **Implementation Challenges:** Maintenance, degradation, power, and connectivity constraints
- **Cybersecurity & Data Transfer:** Secure integration of real-time sensor data remains critical
- **Cost-Effectiveness:** Alternative strategies challenge extensive sensor optimization needs
- **System Complexity:** Aging infrastructure, extreme weather, and regulatory pressures
- **Reactive Monitoring:** Traditional practices lead to inefficiencies and compliance risk

Significance of Sensor Applications

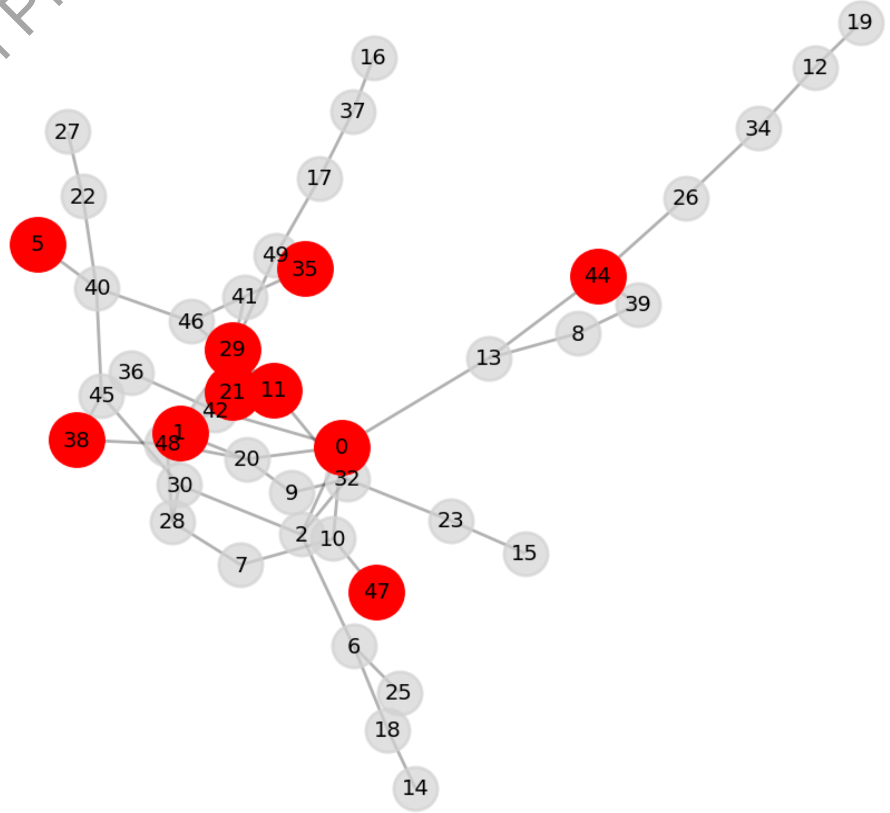
- **Network Scale:**
Thousands of pipes; few drive most risk
- **Risk Focus:**
High-risk segments require active management
- **Objective:**
Identify critical locations for monitoring and maintenance
- **Problem Type:**
Combinatorial optimization (sensor placement–like)
- **Approach Needed:**
Intelligent algorithms to target high-risk areas



Critical Failures in Large Networks with Limited Sensor

Why Evaluating All Sensor Placements is Impossible

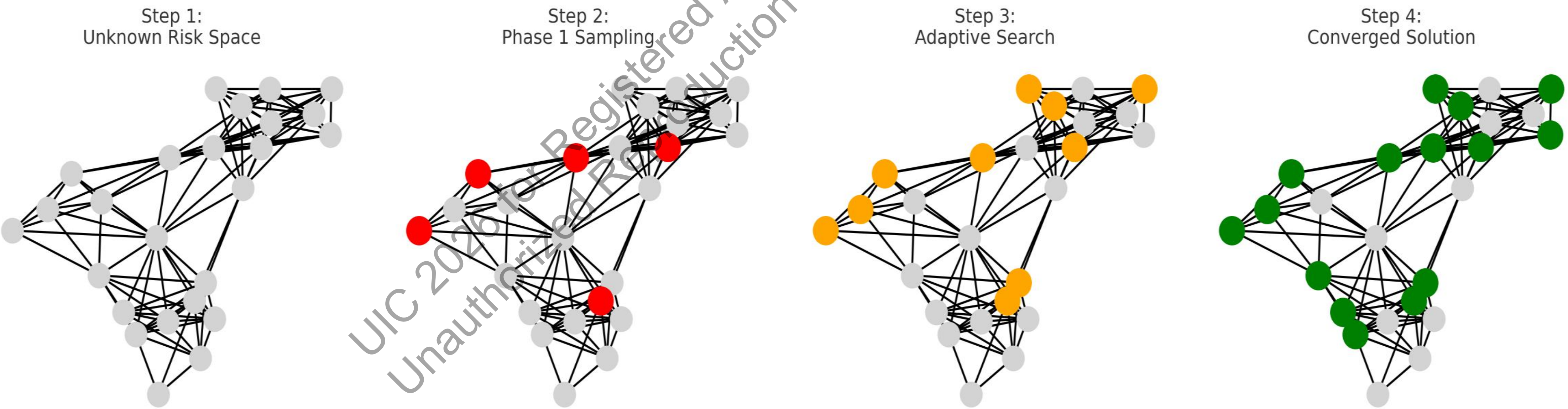
- Thousands of candidate monitoring locations across large networks
- Pipes, manholes, and pump stations as potential sensor sites
- Each placement involves risk, consequence, and coverage trade-offs
- Limited sensor coverage prevents system-wide monitoring
- Optimization and ML needed for efficient sensor placement



Sensor Placement Challenge

Unknown Risk Space – Adaptive Sensor Placement

- Failure risk is **unknown and dynamic**
- Full system monitoring is **infeasible**
- Only **partial risk** revealed by sensors
- **Adaptive monitoring** is required



Adaptive Sensor Placement Strategy for Identifying Critical Areas Within an Unknown Risk Space

Methodology Framework

- **Phase 1 – Data Layer:**

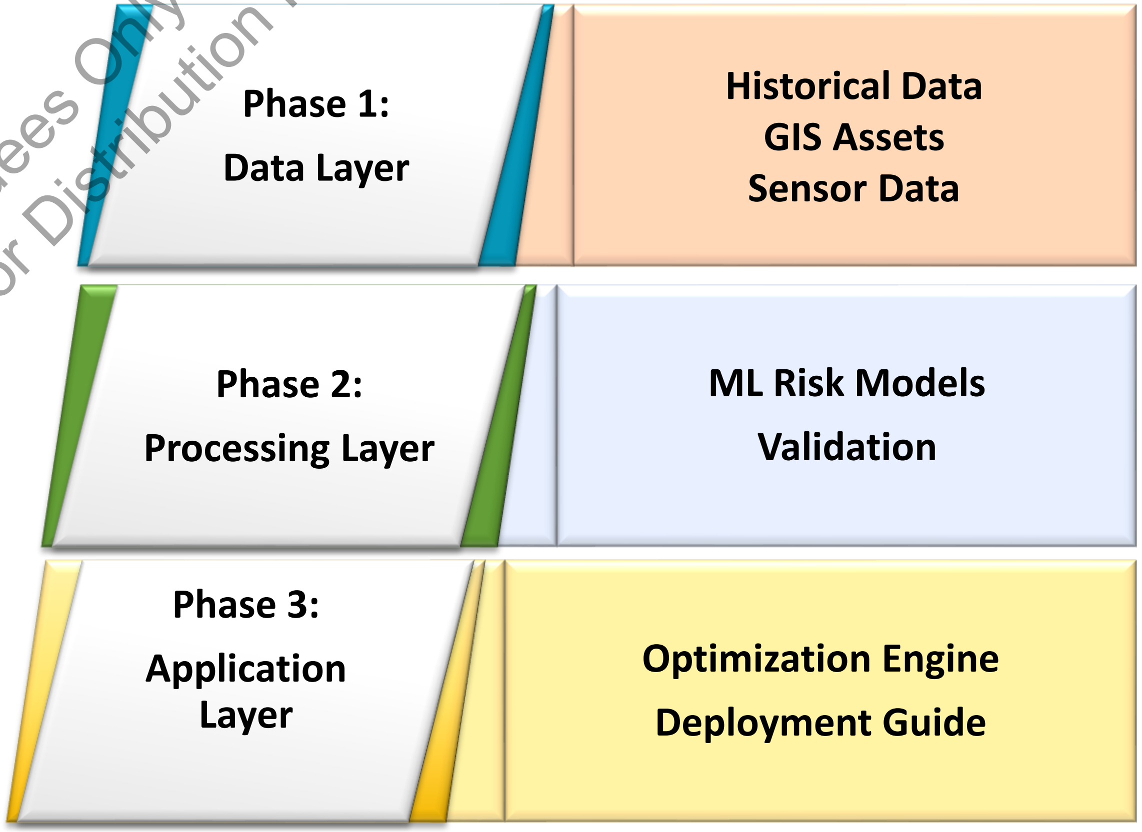
Data integration and preparation

- **Phase 2 – Processing Layer:**

ML-based risk modeling and **validation**

- **Phase 3 – Application Layer**

Optimization and decision support for deployment


Phase 1:

Data Layer

Historical Data
GIS Assets
Sensor Data

Phase 2:

Processing Layer

ML Risk Models

Validation

Phase 3:

Application Layer

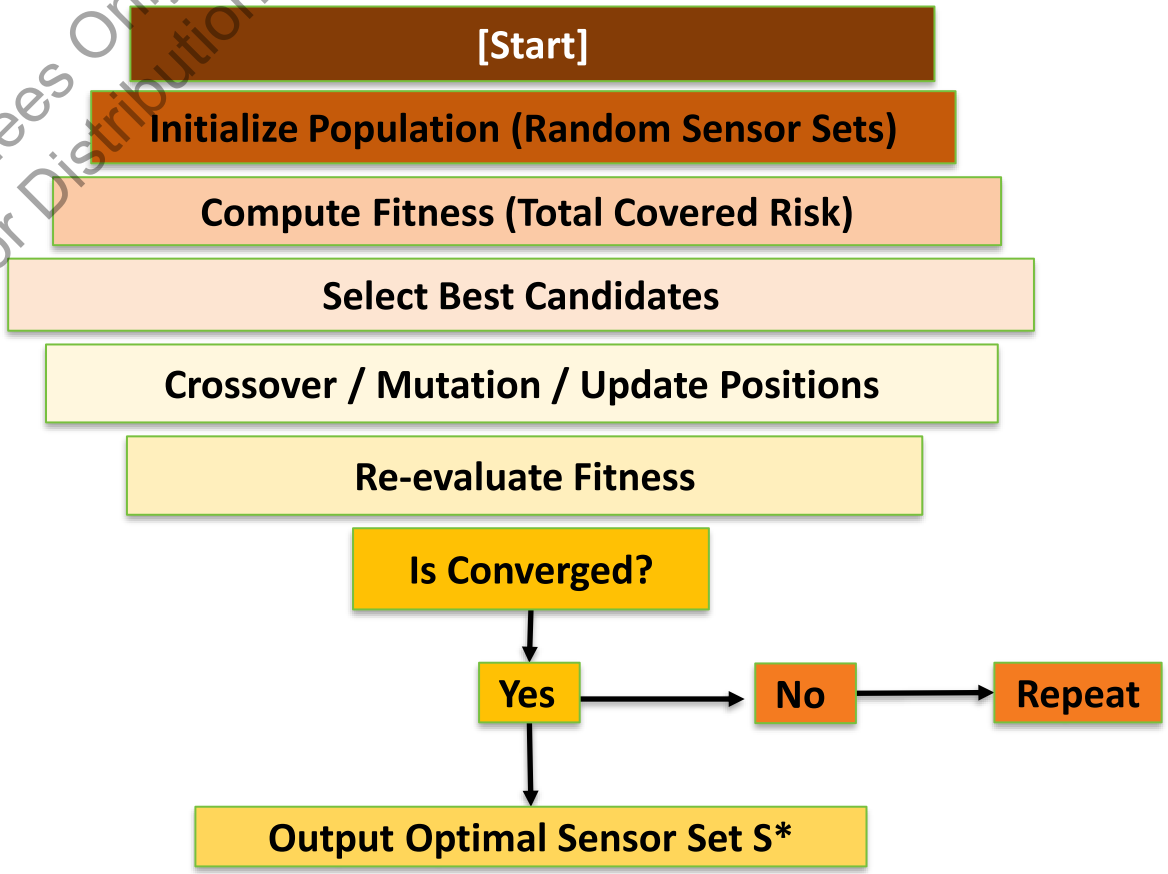
Optimization Engine

Deployment Guide

Three-Phase Methodology Framework

Sensor Placement Framework

- Integrates **risk-based modeling** with **data-driven optimization**
- Simulates failures (blockages, pump issues, wet-weather surcharges) to map risk
- Combines **flow, depth, rainfall, and GIS attributes** into a risk matrix
- Outputs **optimal sensor locations**, risk reduction metrics, and deployment options



[Start]

Initialize Population (Random Sensor Sets)

Compute Fitness (Total Covered Risk)

Select Best Candidates

Crossover / Mutation / Update Positions

Re-evaluate Fitness

Is Converged?

Yes

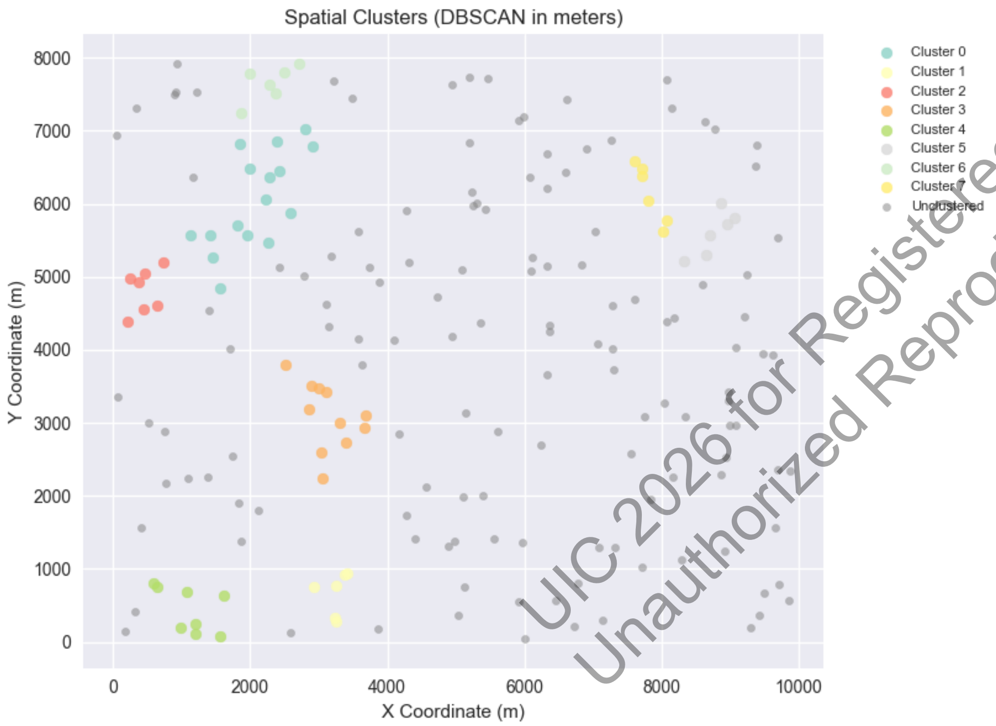
No

Repeat

Output Optimal Sensor Set S*

Sensor Placement Framework

- Sensors target high-risk areas, not uniform spacing
- Clustering avoids over-concentration in one hot spot



Failure Probability Map for Sewer Assets

Spatial Clustering of Sewer Assets Based on Physical Proximity

Expected Outcomes

- Framework to optimize sensor placement using **asset, operational, and historical data**
- **ML-based failure prediction** integrating GIS, monitoring, and maintenance records
- **Metaheuristic optimization** to minimize undetected system risk
- **Decision-support system** combining analytics, spatial modeling, and real-time data
- Advances **intelligent, resilient wastewater management** through data-driven sensing

Conclusions and Future Perspectives

- Provides a **data-driven framework** for optimizing sensor placement and risk management
- Demonstrates **ML + optimization** for failure prediction and proactive maintenance
- Introduces a **Failure Probability Model (FPM)** linking assets, hydraulics, and historical events
- Establishes a **decision-support framework** integrating analytics, GIS, and dashboards
- Contributes a **transferable model** for smart, resilient wastewater monitoring

Project Schedule

As shown in the table below, the project duration is 21 months starting February 1, 2025.

Task Description	2025 F.	2025 M.	2025 A.	2025 M.	2025 J.	2025 J.	2025 A.	2025 S.	2025 O.	2025 N.	2025 D.	2026 J.	2026 F.	2026 M.	2026 A.	2026 M.	2026 J.	2026 J.	2026 A.	2026 S.	2026 O.
Literature Review	■	■	■																		
Survey of Water Utilities			■	■	■	■	■														
Workshop with Water Professionals						■	■														
Conduct Case Studies							■	■	■	■	■										
Decision Tree Logic Optimization											■	■	■	■							
Draft Guidance Document													■	■	■	■	■				
Draft Report															■	■	■	■	■	■	
Draft Report Review by WRF																			■	■	■
Final Report																				■	■
Periodic Meetings		X		X		X		X		X		X		X		X		X		X	

Participate in WRF Project 5239

Hybrid Workshop – Detroit Area
Wednesday, April 22, 2026
Registration takes less than 2 minutes

Please click the link below to complete the workshop registration form:

https://utaedu.questionpro.com/t/AX9XaZ7yMR

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Project Survey (Optional)
Estimated time: 15–25 minutes

Please click the link below to begin the survey:

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Questions and Suggestions

Thank You for Your Attention

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