Adaptive Pipe Replacement Planning Using Graph Neural Networks: A Multi-Factor Predictive Model for Infrastructure Renewal

CIE 500 Research Project

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Background

Water distribution systems are critical infrastructures that require continuous maintenance to ensure reliable service. A**ging pipes, increasing roughness, and frequent pipe breaks** lead to reduced efficiency, higher maintenance costs, and potential health risks. Traditional pipe replacement strategies rely on heuristic methods or rule-based approaches, which may not be optimal in terms of cost-effectiveness and long-term system performance.

Motivation

Aging Water Infrastructure: Many water distribution systems worldwide are over **50–100 years old**, experiencing increasing failures.

High Cost & Limited Budgets: Pipe replacement is **expensive**, and utilities must optimize **where and when** to replace pipes for maximum impact.

Reactive vs. Predictive Strategies: Traditional maintenance focuses on **fixing failures after they occur**, rather than **preventing** them with data-driven insights.

Advances in Graph Neural Networks: GNN provide a **network-aware** learning framework, capturing **topological dependencies** and predicting failures **before they occur**.

Reference 1 – Convolutional Graph Neural Networks for Leak Detection

- Uses **Convolutional GNN** to detect leaks in water distribution networks.
- Combines **node and pipe-segment features** for improved leak detection accuracy.
- Achieves **high precision even in sparse sensor networks**.
- Synthetic and real-world leak data validate the model's robustness.

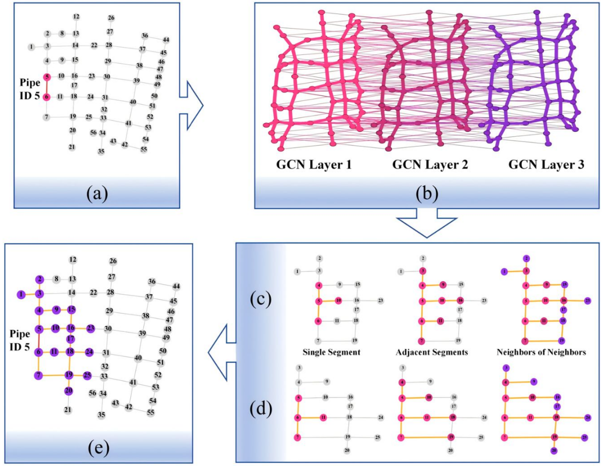

Figure 3. The process of fusing node features into segment features through convolutional layers. (**a**) Pipe segment 5 in the water supply network. (**b**) Convolutional layer connectivity. (**c**) Receptive field expansion of node 5. (**d**) Receptive field expansion of node 6. (**e**) Final receptive field of pipe segment 5.

Li, X., & Wu, Y. (2024). A Convolutional Graph Neural Network Model for Water Distribution Network Leakage Detection Based on Segment Feature Fusion Strategy. *Water*, *16*(24), 3555. https://doi.org/10.3390/w16243555

Reference 2 – Decision Strategies for Pipe Maintenance

- Highlights the **importance of values and trade-offs** in pipe maintenance decisions.
- Uses **Monte Carlo simulations** to assess long-term pipe replacement strategies.
- Studies the impact of **different operator priorities** (e.g., cost, service reliability, sustainability).
- Finds that **proactive pipe replacement** reduces failures and improves service quality.

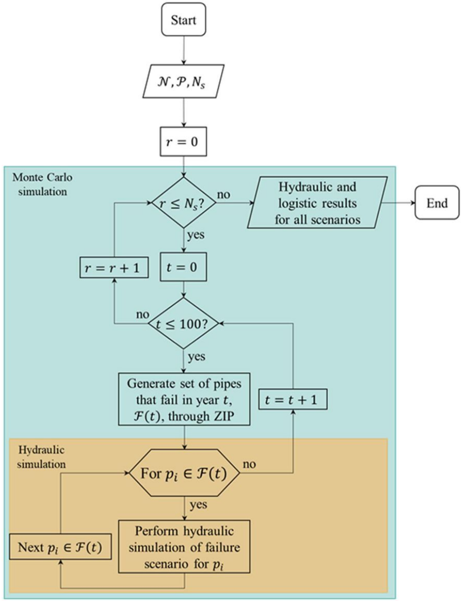

Fig. 1. Global flow diagram for the Monte Carlo pipe failure model.

Zuluaga, Santiago & Karney, Bryan. (2024). Roles of Value in the Evaluation and Modeling of Decision Strategies for Pipe Maintenance in Water Distribution Networks. Journal of Water Resources Planning and Management. 150. 10.1061/JWRMD5.WRENG-6171.

Reference 3 – Leakage Detection and Water Loss Management Using NN

- Proposes a **DBSCAN-MFCN model** for leakage detection in water supply networks.
- Uses **Density-Based Spatial Clustering (DBSCAN)** to segment the water network into zones.
- Applies a **Multiscale Fully Convolutional Network (MFCN)** for detecting leaks within those zones.
- Demonstrates **78% improvement over SVM, 72% over Naïve Bayes, and 28% over k-Nearest Neighbors (KNN)**.
- Uses **hydraulic simulations from EPANET** to train the detection model.

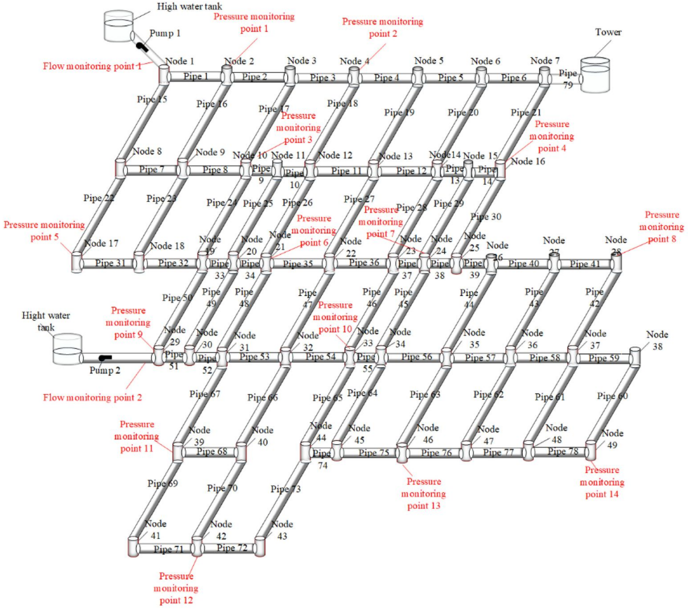

Fig. 2. Hydraulic model.

Hu, Xuan & Han, Yinlan & Yu, Bin & Geng, Zhiqiang & Fan, Jinzhen. (2020). Novel Leakage detection and Water Loss Management of Urban Water Supply Network using Multiscale Neural Networks. Journal of Cleaner Production. 278. 123611. 10.1016/j.jclepro.2020.123611.

How The Project Advances the Field

- This model shifts from leak detection to **predictive pipe replacement**, incorporating **wear, roughness, and breaks**.
- **Optimized pipe replacement schedules** using multi-objective learning.
- **Cost-effective planning strategies** considering utility budgets and service reliability.
- Integrate **real-time sensor data** for improved forecasting.