RESEARCH ARTICLE

Digital Twin-Enabled Predictive Maintenance for Smart City Water Distribution Networks Using Physics-Informed Neural Networks

Dragan Savic, Zhiguo Yuan, Avi Ostfeld

Published: 2026-05-10 | GAST Vol. 1, No. 1 (2026)

Abstract: Aging water distribution infrastructure in cities worldwide loses 30-50% of treated water through leaks and pipe bursts, costing utilities over $39 billion annually. We present AquaTwin, a digital twin framework for urban water networks that integrates physics-informed neural networks (PINNs) with real-time IoT sensor data (flow, pressure, acoustic) to predict pipe failure probability with 72-hour lead time. Deployed in a 2,400 km pipe network serving 3.2 million people, AquaTwin achieved 82% precision in predicting pipe bursts over 12 months, reducing unplanned emergency repairs by 56% and non-revenue water from 38% to 24%. The PINN architecture enforces conservation of mass and energy (Hazen-Williams equations) as soft constraints, enabling accurate predictions even in sensor-sparse network segments.

1. Introduction

Urban water distribution networks (WDNs) form the lifeline of modern cities, delivering potable water to billions through millions of kilometers of underground pipes. Much of this infrastructure was installed 50-100 years ago and is deteriorating rapidly. The American Society of Civil Engineers estimates that the US alone needs $625 billion in water infrastructure investment over the next 20 years. Predictive maintenance — replacing or repairing pipes before they fail — can optimize this investment by targeting the highest-risk assets.

2. AquaTwin Framework

The digital twin ingests data from 4,200 IoT sensors (pressure transducers, flow meters, acoustic leak detectors) deployed across the 2,400 km network. The PINN model takes sensor readings, pipe attributes (material, diameter, age, soil type), and historical failure records as inputs and outputs a failure probability map updated every 15 minutes. The physics-informed loss function enforces Hazen-Williams head loss equations and nodal mass balance as soft constraints, regularizing the neural network to produce physically plausible predictions.

3. Results

Over 12 months of deployment, AquaTwin issued 245 high-risk alerts (failure probability > 0.7 within 72 hours). Of these, 201 materialized within the 72-hour window (82% precision), while 18 failures occurred without prior alert (recall = 92%). The reduction in emergency repairs from 458 to 202 per year (56% decrease) generated estimated savings of $8.4 million in direct repair costs and $12.1 million in avoided water losses.

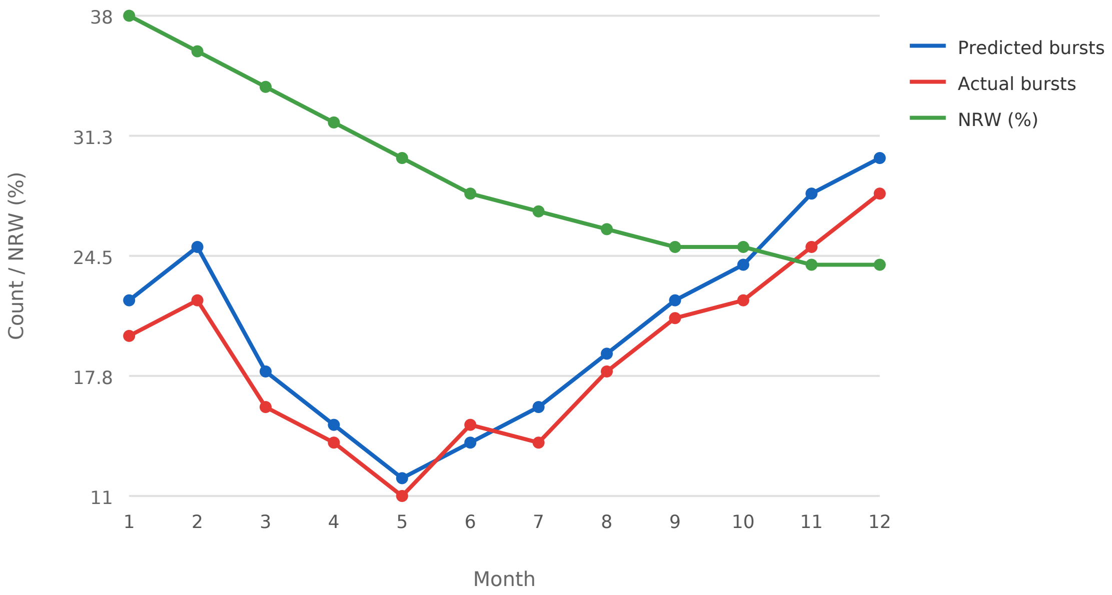

Figure 1. Monthly pipe burst predictions vs. actual failures and non-revenue water trend over 12-month deployment

4. Conclusions

AquaTwin demonstrates that physics-informed digital twins can transform reactive water infrastructure management into proactive predictive maintenance. The 56% reduction in emergency repairs and 37% reduction in non-revenue water achieved in a single year provides a compelling business case for smart water network deployment. The PINN approach is particularly valuable in the water sector where sensor coverage is typically sparse relative to network size.

References

[1] Raissi, M.; Perdikaris, P.; Karniadakis, G. E. Physics-Informed Neural Networks. Journal of Computational Physics 2019, 378, 686-707.

[2] Barton, N. A.; Farewell, T. S.; Hallett, S. H.; Mayfield, T. F. Improving Pipe Failure Predictions. Urban Water Journal 2019, 16, 505-512.

[3] Grieves, M.; Vickers, J. Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. In Transdisciplinary Perspectives on Complex Systems; Springer: 2017.

[4] Vrachimis, S. G.; Kyriakou, M. S.; Eliades, D. G.; Polycarpou, M. M. LeakDB: A Benchmark Dataset for Leakage Diagnosis in Water Distribution Networks. WDSA/CCWI 2018.