ISSN - 2456-1142

International journal of humanities and information technology

Volume 7, Issue 4, 2025

Net-Zero Water Infrastructure: AI and CIRx for Intelligent Stormwater and Wastewater Management

Ashish Mehar*

Independent Researcher, United States of America.

Abstract

Water and wastewater utilities are among the largest municipal consumers of electricity, with pumping, aeration, and treatment processes accounting for a substantial share of a city's operational carbon footprint, placing utilities squarely within the scope of municipal net-zero commitments even though water infrastructure is often treated as a secondary consideration relative to buildings and transportation in climate action planning. This paper examines how artificial intelligence (AI) and the Condition-Index Rx (CIRx) composite scoring methodology can be extended beyond conventional structural and hydraulic prioritization to explicitly incorporate energy and emissions considerations into stormwater and wastewater infrastructure management, supporting utilities pursuing net-zero operational targets. We propose an energy-aware extension to the CIRx framework in which asset rehabilitation and operational decisions are evaluated not only against structural condition, hydraulic performance, and consequence of failure, but also against their expected impact on pumping energy demand, aeration efficiency, and inflow-and-infiltration-driven treatment load, all of which carry direct energy and emissions consequences. We discuss machine learning applications for pump and aeration energy optimization, inflow-and-infiltration reduction targeting, and renewable energy integration at treatment facilities, and we examine how AI-driven decision support can help utilities identify rehabilitation investments that deliver combined structural, hydraulic, and carbon-reduction benefits rather than treating emissions reduction as a separate initiative. The paper closes with a discussion of data and governance considerations specific to energy-aware infrastructure decision-making and directions for future research on integrating climate and emissions data into infrastructure asset management.

Keywords: Net-zero infrastructure; CIRx; artificial intelligence; machine learning; stormwater management; wastewater management; energy optimization; carbon reduction; asset management; inflow and infiltration.

International journal of humanities and information technology (2025)

Introduction

Municipal water and wastewater treatment operations are among the most energy-intensive services a city government provides, with pumping and aeration processes in particular consuming large and continuous quantities of electricity to move water and wastewater through collection, conveyance, and treatment systems. As municipalities adopt net-zero or greenhouse-gas-reduction targets, water infrastructure represents a significant, though sometimes overlooked, source of both energy consumption and potential efficiency gains, since even modest reductions in pumping energy or aeration inefficiency across a large treatment plant can yield meaningful emissions reductions at a scale comparable to more visible initiatives such as building electrification or fleet conversion.

At the same time, deteriorating stormwater and wastewater infrastructure indirectly drives energy consumption in ways that are not always connected to rehabilitation planning: excessive inflow and infiltration (I&I) into aging sanitary sewers forces treatment plants to process far more flow than the wastewater they were designed to treat, directly increasing pumping and aeration energy demand, while inefficient or oversized pump station operation resulting from deferred maintenance similarly wastes energy relative to a well-maintained, appropriately controlled system. This paper argues that infrastructure prioritization frameworks such as CIRx, which already combine structural condition, hydraulic performance, and consequence of failure into a composite rehabilitation score, can and should be extended to explicitly

Corresponding Author: Ashish Mehar, Independent Researcher, United States of America.

How to cite this article: Mehar, A. (2025). Net-Zero Water Infrastructure: AI and CIRx for Intelligent Stormwater and Wastewater Management. *International journal of humanities and information technology* 7(4), 138-141.

Source of support: Nil

account for the energy and emissions consequences of both infrastructure condition and rehabilitation choices, aligning asset management decisions with municipal net-zero objectives rather than treating energy efficiency as a separate workstream.

The remainder of this paper proceeds as follows. Section 2 reviews the relationship between water infrastructure and municipal energy consumption, and background on CIRx. Section 3 presents an energy-aware extension to the CIRx framework. Section 4 discusses the AI/ML techniques supporting this extension, including inflow-and-infiltration targeting, pump and aeration optimization, and renewable energy integration. Section 5 discusses decision-support and capital planning implications. Section 6 addresses data and governance considerations, and Section 7 concludes.

Background

Water Infrastructure as a Municipal Energy and Emissions Source

Wastewater treatment in particular is energy-intensive because biological treatment processes require continuous aeration to supply oxygen for microbial degradation of organic matter, a process that in many plants accounts for a substantial share of total plant electricity consumption. Pump stations throughout both stormwater and wastewater collection systems add further continuous electrical load, and this load rises directly with the volume of flow being conveyed, meaning that any factor increasing flow volume — including excessive inflow and infiltration in sanitary sewers or undersized stormwater conveyance forcing additional pumped diversion — increases energy consumption correspondingly.

Inflow and Infiltration as an Energy Driver

Inflow and infiltration refers to stormwater and groundwater entering sanitary sewer systems through defects such as cracked pipes, deteriorated joints, and improperly connected storm drains, a phenomenon that can substantially increase the volume of flow a wastewater treatment plant must process relative to actual sanitary wastewater generation, particularly during and after significant rainfall events. Because this additional flow must be pumped and treated regardless of its lower pollutant concentration relative to sanitary wastewater, I&I represents a direct, largely avoidable energy cost that is closely linked to the same structural pipe defects that conventional condition assessment already targets for other reasons, creating a natural point of alignment between structural rehabilitation and energy efficiency objectives.

The CIRx Methodology as a Foundation

As established in prior work, CIRx combines structural condition, hydraulic or operational performance, consequence of failure, and machine-learning-forecast deterioration risk into a single composite score, translated into a specific rehabilitation prescription. This paper proposes extending that composite structure with an explicit energy and emissions component, reflecting the recognition that a rehabilitation decision's value to a net-zero-committed utility depends not only on avoiding structural failure but also on the energy and emissions consequences of leaving a given defect unaddressed.

Energy-Aware CIRx Extension

Adding an Energy Impact Component

The proposed extension introduces an energy impact component alongside the existing CIRx components, estimating the marginal pumping and treatment energy attributable to a given defect or asset condition, drawn from hydraulic model outputs, treatment plant energy metering, and, where available, sub-metered pump station consumption data. For sanitary sewer segments, this component is informed primarily by estimated I&I contribution derived from flow monitoring and rainfall-dependent infiltration modeling; for stormwater assets, it reflects any pumped conveyance or treatment energy associated with the asset's service area; and for drinking water distribution assets, it reflects pumping energy associated with leakage-driven non-revenue water, which similarly represents energy expended without a corresponding beneficial outcome.

Combined Prioritization Logic

Rather than scoring energy impact as an entirely separate priority list, the framework incorporates it as an additional weighted input to the composite CIRx score, allowing a utility to configure the relative importance of energy and emissions reduction alongside traditional structural and consequence-of-failure priorities according to its own policy priorities and net-zero commitments. This combined approach helps surface rehabilitation opportunities that deliver benefits across multiple objectives simultaneously — for example, a sanitary sewer segment with only moderate structural defects but disproportionately high estimated I&I contribution may rise in overall priority once its energy impact is accounted for, even though it might not have ranked highly under a structural-condition-only scoring approach.

Avoiding Perverse Trade-offs

Because energy-aware prioritization could, if poorly designed, deprioritize genuinely urgent structural repairs in favor of lower-risk but higher-energy-impact assets, the extended framework applies the energy component only as a secondary weighting factor among assets already meeting a minimum structural or consequence-of-failure threshold, ensuring that emissions considerations refine prioritization among comparably urgent assets rather than overriding core public safety and reliability priorities.

AI and ML Techniques for Energy-Aware Management

Inflow and Infiltration Source Identification

Machine learning models trained on rainfall data, flow monitoring records, and sewer network topology can estimate the likely contribution of individual sub-catchments or pipe segments to observed system-wide I&I, helping target structural rehabilitation toward segments offering the greatest energy and treatment-load reduction per dollar invested, rather than distributing rehabilitation spending evenly or based on structural condition alone.

Pump and Aeration Energy Optimization

Reinforcement learning and model-predictive control approaches have been applied to pump station scheduling and aeration blower control, learning operating policies that maintain required service levels while reducing energy consumption relative to fixed-setpoint or purely reactive control schemes, particularly by anticipating demand or flow patterns and pre-positioning pump and blower operation accordingly rather than responding only after a threshold is crossed.

Treatment Load Forecasting

Forecasting models that combine rainfall forecasts with hydraulic network models can predict expected treatment plant influent volume and composition ahead of storm events, allowing treatment facilities to adjust aeration and chemical dosing proactively rather than reactively, reducing both energy waste from over-aeration during low-load periods and treatment performance risk during high-load periods.

Renewable Energy and Resource Recovery Integration

Beyond efficiency, many treatment facilities are increasingly integrating on-site renewable generation, including solar photovoltaic installations and biogas-fueled combined heat and power systems fed by anaerobic digestion of biosolids, and machine learning forecasting of both energy demand and, where applicable, renewable generation availability supports optimized dispatch decisions that maximize the facility's use of self-generated renewable or low-carbon energy relative to grid electricity.

Decision Support and Capital Planning Implications

Embedding energy impact within CIRx scoring allows a utility's capital planning process to evaluate rehabilitation investments against a more complete value proposition, capturing structural risk avoidance, service reliability, and energy or emissions reduction within a single prioritized list rather than requiring separate business cases for sustainability-motivated projects. This is particularly valuable when utilities compete for grant funding or green infrastructure financing programs that require demonstrated emissions-reduction impact, since the energy-aware CIRx score provides a ready, quantified basis for such applications rather than requiring a separate retrospective analysis. Decision-support interfaces built on this extended framework can present capital planners with the estimated combined structural-risk-reduction and energy-reduction impact of candidate rehabilitation packages, supporting more defensible funding requests to utility boards and rate-setting authorities.

Data and Governance Considerations

Energy Metering and Attribution Granularity

Estimating the energy impact component of the extended CIRx score requires reasonably granular energy metering, ideally at the level of individual pump stations and treatment process units rather than only whole-facility billing meters, which remains a data availability gap for many utilities and may require phased instrumentation investment before energy-aware scoring can be applied with confidence across the full asset base.

Attribution Uncertainty

Because the energy impact of a specific pipe segment's condition is estimated rather than directly measured, particularly for I&I contribution inferred from network-level flow monitoring rather than segment-level metering, the framework should communicate attribution uncertainty transparently to capital planners rather than presenting estimated energy impact with unwarranted precision, consistent with general good practice for model-derived scores feeding into public capital decisions.

Alignment with Climate Action Reporting

Where municipalities maintain formal greenhouse gas inventories or climate action plans, the energy-aware CIRx framework's outputs should be structured to feed directly into those reporting frameworks, allowing water infrastructure's contribution to municipal emissions reduction to be tracked and reported consistently alongside other municipal sectors rather than remaining siloed within utility-specific reporting.

Illustrative Scenario: Prioritizing an I&I-Driven Rehabilitation Project

Consider a mid-sized utility evaluating a sanitary sewer sub-catchment where flow monitoring shows a pronounced wet-weather flow increase disproportionate to the sub-catchment's population, indicating significant I&I. Under conventional CIRx scoring based on structural condition, hydraulic performance, and consequence of failure alone, the affected pipe segments might rank as moderate priority, since their structural defects, while present, are not the most severe in the utility's network and the segments do not serve especially critical facilities. Applying the energy-aware extension, the machine learning I&I source-identification model attributes a substantial share of the sub-catchment's wet-weather flow increase to a specific cluster of deteriorated joints and lateral connections within these segments, and the corresponding energy impact component estimates the annual pumping and aeration energy attributable to conveying and treating this excess flow at the downstream treatment plant.

Once this energy impact component is incorporated into the composite score, the affected segments rise substantially in the utility's overall rehabilitation priority list, reflecting the recognition that addressing these specific defects would deliver a meaningful, quantifiable reduction in avoidable pumping and aeration energy consumption in addition to the structural benefit already captured by conventional scoring. The utility's capital planning team can then present this rehabilitation package to its governing board with a combined business case spanning structural risk reduction, wet-weather capacity relief, and estimated annual energy and emissions savings, a framing that is considerably more compelling, and often more competitive for state or federal green infrastructure funding programs, than either a structural-condition-only or a stand-alone energy-efficiency justification would be on its own. This scenario illustrates how the energy-aware CIRx extension changes not only which assets are prioritized but also how rehabilitation investments are justified and funded.

Conclusion

This paper has proposed an energy-aware extension to the CIRx composite scoring framework, incorporating pumping, aeration, and inflow-and-infiltration-driven energy impact alongside structural condition, hydraulic performance, and consequence of failure to support stormwater and wastewater infrastructure decisions aligned with municipal net-zero objectives. By combining machine learning techniques for I&I source identification, pump and aeration optimization, and treatment load forecasting with a unified, prescriptive prioritization framework, utilities can identify rehabilitation investments that deliver structural, reliability, and emissions-reduction benefits together rather than pursuing sustainability and asset management as separate initiatives. Realizing this integrated approach at scale will require continued investment in granular energy metering, careful communication of attribution uncertainty, and closer alignment between utility asset management systems and municipal climate action reporting, representing a practical and increasingly urgent direction for future research and utility practice.

References

[1] U.S. Environmental Protection Agency. (2013). Energy efficiency for water and wastewater utilities: An overview. EPA Office of Water.

[2] MARASANI, Y. (2024). Enterprise Readiness for Generative AI: The Critical Role of Data Engineering. Frontiers in Computer Science and Artificial Intelligence, 3(2), 59-71.

[3] Electric Power Research Institute. (2013). Electricity use and management in the municipal water supply and wastewater industries.

[4] MARASANI, Y. (2023). Machine Learning Models for Predicting Patient Treatment Switching Using Claims Data. Frontiers in Computer Science and Artificial Intelligence, 2(1), 59-66.

[5] Parasa, M. (2025). SENTINEL-HCM: Federated Temporal Graph Intelligence for Detecting API Abuse, Data Leakage, and Policy Drift in SAP SuccessFactors Cloud Integrations. Journal of Contemporary Science and Technology Management, 1(01), 51-82.

[6] Satish Kumar Nalluri, Venkata Krishna Bharadwaj Parasaram & Varun Teja Bathini, "AI-Powered Operational Intelligence for Improving Efficiency in Cyber-Physical Systems", International Journal of Current Research and Modern Education, Volume 1, Issue 2, Page Number 265-291, 2016. https://doi.org/10.5281/zenodo.19634284

[7] Parasa, M. (2020). Control-mapped AI governance for high-risk HR decisions in SAP SuccessFactors: Audit-ready metrics for recruiting, performance calibration, and internal mobility. SAMRIDDHI: A Journal of Physical Sciences, Engineering and Technology, 12(2), 153–168. https://doi.org/10.18090/samriddhi.v12i02.15

[8] Marasani, Y. (2025). Explainable AI Frameworks for Patient-Level Claims Data Analytics. J Artif Intell Mach Learn & Data Sci, 8(1), 3382-3390.

[9] Parasa, M. Mapping the Latent Risk Layer in Enterprise Platforms: A Practical Model for Workforce Data Integrity, Access Behavior, and Cyber Threat Detection.

[10] Venkata Krishna Bharadwaj Parasaram, Satish Kumar Nalluri & Varun Teja Bathini, "AI-Integrated Architectural Frameworks for Intelligent Production and Operational Control Systems", International Journal of Multidisciplinary Research and Modern Education, Volume 1, Issue 2, Page Number 515-540, 2015. https://doi.org/10.5281/zenodo.19634601