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METHODOLOGY FOR LEAK DETECTION AND LOCALIZATION IN WATER SUPPLY NETWORKS BASED ON SENSITIVITY ANALYSIS AND HEAD LOSS COMPENSATION

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1. INTRODUCTION

The efficient management of water resources is a critical global challenge, with water losses in supply systems representing a significant economic and environmental burden. In Brazil, data from the National Sanitation Information System (SNIS) indicates that distribution losses often exceed 35%, a stark contrast to the 15% benchmark in developed nations (SNIS, 2024; TRATA BRASIL, 2024). These losses are categorized by the International Water Association (IWA) as real (physical leaks) and apparent (commercial losses), with non-visible real losses being the most difficult to detect and locate (PACTO GLOBAL, 2018; SILVA JR, 2016).

Current leak detection methods present a trade-off. Active inspection, using tools like acoustic correlators, is accurate but expensive and not continuous (PUSTELNIKOVA; PUUST; KAPELAN, 2020; OBATA, 2019). Passive monitoring of SCADA data offers continuous surveillance but often lacks the precision to reliably distinguish leaks from normal demand variations (HU et al., 2021; JUN; LANSEY, 2023). This research proposes an innovative methodology that bridges this gap by adapting a control theory concept from electric power systems to the hydraulic domain.

The central hypothesis is that "Line Drop Compensation" (LDC)—a technique used for decentralized secondary voltage control—can be repurposed for hydraulic systems (SILVA, 2007). By implementing a secondary control layer on top of the existing primary pump controls, the system can be transformed into a highly sensitive diagnostic tool. The general objective is to propose and validate, via computational simulation, a methodology that uses system sensitivity analysis and a "compensation resistance" to identify and locate hydraulic anomalies consistent with leaks. This will be achieved by: (1) developing a computational model of a water network; (2) implementing a PID control algorithm with a head loss compensation feature; (3) deriving the network's sensitivity matrix; (4) developing an anomaly detection algorithm; and (5) evaluating the method's performance.

2. DEVELOPMENT

2.1 Theoretical Framework

Fundamentals of Hydraulic Network Modeling

The analysis of water distribution networks is governed by the principles of mass and energy conservation. Head loss due to friction is a key component, classically modeled by the non-linear Darcy-Weisbach equation (SCHMIDLIN JÚNIOR, 2006; ALMEIDA, 2021). Pumping stations provide energy to the system, and their performance is described by a characteristic curve relating the head provided to the flow rate. The intersection of this curve with the system's resistance curve determines the operating point (MACEDO, 2012; TOMAZ, 2001).

State of the Art in Leak Detection

Leak detection methods are broadly classified as hardware-based (active inspection) and software-based (passive monitoring). Hardware methods include acoustic tools, robotic inspectors, Ground Penetrating Radar (GPR), and thermography (OBATA, 2019; CAETANO, 2020). While accurate, they are reactive and costly. Software methods analyze SCADA data using either *model-based* approaches, which compare real-time data to a hydraulic model, or *data-driven* approaches, which use machine learning to find anomalies (PUSTELNIKOVA; PUUST; KAPELAN, 2020; GAMBOA MEDINA, 2013). The proposed methodology integrates the continuous nature of passive monitoring with the diagnostic potential of active systems.

Sensitivity Analysis and the Proposed Innovation

A well-established analogy exists between hydraulic and electrical circuits, where pressure is analogous to voltage and flow rate to current (ATARI, 2021). In power systems, Line Drop Compensation (LDC) is a secondary control technique that regulates voltage at a remote point using only local measurements, compensating for the impedance of the line (TAYLOR, 2000; SILVA, 2007).

This research transposes the LDC concept to the hydraulic domain. A pump's control system will be configured to regulate a "virtual pressure" at a distant node, not just the pressure at its outlet. This makes the controller acutely sensitive to any unmodeled changes in the network's hydraulic resistance, such as a leak.

The theoretical basis for detecting these changes is sensitivity analysis. The behavior of a hydraulic network around an operating point can be linearized and described by the Jacobian Matrix (J) (SOARES, 2003; CARVALHO, 2020). This matrix acts as a "fingerprint" of the system's normal dynamic response, relating changes in nodal demands to changes in nodal pressures (PEREZ et al., 2011; ZHANG et al., 2017). A leak introduces an unmodeled demand, causing the system's real response to deviate from the response predicted by the Jacobian matrix. This deviation is the signal used for detection.

2.2 Methodology

The methodology will be validated through computational simulation using the EPANET 2.2 software (ROSSMAN, 2000). A fictitious but realistic water distribution network will be modeled, including pipes, nodes, pumps, and reservoirs, with a complex topology to ensure robust testing (BHAVE, 1991; WALSKI et al., 2003).

1. **Linearization and Sensitivity Matrix:** For a reference operating point, the network's Jacobian Matrix (J) will be numerically derived. This matrix establishes the baseline relationship between changes in pump flow rates and the corresponding pressure changes at strategic monitoring nodes.
2. **PID Control with Compensation (Secondary Control):** The pump control will be modeled as a PID controller acting on a variable frequency drive (PEREIRA, 2016; LIU; ZHI, 2020). The feedback signal will be modified to regulate a "virtual pressure" at a remote node, calculated as:

$$P_{feedback} = P_{outlet} - R_c * Q_{pump}^2$$

Here, P_{outlet} is the measured outlet pressure, Q_{pump} is the pump flow rate, and R_c is the "compensation resistance" parameter. This configuration forces the controller to react to any discrepancy between its internal model (R_c) and the real system's hydraulics.

3. **Simulation and Detection Algorithm:** The system will be simulated under normal demand variations and with leaks of varying magnitudes and locations. A real-time monitoring algorithm will:
   - Continuously monitor pump flow (ΔQ_{real}) and nodal pressures (ΔP_{real}).
   - Use the Jacobian matrix to calculate the *expected* pressure change: $(\Delta P_{predicted} = J * \Delta Q_{real})$.
   - Calculate a residual vector: $R = \Delta P_{real} - \Delta P_{predicted}$.
   - Trigger an anomaly alarm if the norm of the residual vector, $||R||$, exceeds a predefined threshold.
4. **Localization Algorithm:** Once an alarm is triggered, the residual vector R provides spatial information. The node with the highest residual indicates proximity to the leak. In systems with multiple compensated pumps, a triangulation logic based on the pattern of residuals across the network can be used to refine the location (JAVADIHA et al., 2019; SOLDEVILA et al., 2019).

3. EXPECTED RESULTS AND DISCUSSION

It is expected that the proposed methodology will be able to rapidly and reliably detect leaks, discriminating them from normal demand fluctuations. The primary quantitative outcome will be a performance matrix evaluating the algorithm's Time-to-Detect and Localization Error across various leak scenarios. This analysis will identify the operational limits of the method.

The discussion will focus on interpreting these results, with the anticipated conclusion that the proposed approach is significantly more effective than conventional passive monitoring. A secondary benefit is the expected improvement in overall network pressure stability. The successful demonstration of rapid detection, accurate localization, and enhanced stability would constitute a strong proof-of-concept, validating the methodology as a significant contribution to water loss management.

4. FINAL CONSIDERATIONS

This research proposes a paradigm shift from passive monitoring to a continuous, automated diagnostic system embedded within the operational control logic of a water distribution system. The primary contribution is the adaptation of the LDC concept from power systems engineering to create a decentralized secondary control layer for hydraulic networks (SILVA, 2007). This offers a practical and cost-effective path for water utilities to reduce real losses, optimize repair crew allocation, and lower operational costs.

While validation through simulation is a necessary first step, future work will involve experimental validation on a laboratory testbed, followed by a pilot project in a real-world network. Further research could also explore adaptive algorithms where the compensation parameter, R_c, is dynamically adjusted using machine learning.

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REFERENCES

ALMEIDA, C. M. de. *Modelagem da qualidade da água em redes de distribuição: estudo de caso da cidade de Niterói*. 2021. Trabalho de Conclusão de Curso (Graduação em Engenharia Hídrica e do Meio Ambiente) - Universidade Federal Fluminense, Niterói, 2021. Available at:(https://app.uff.br/riuff/bitstream/handle/1/33351/%5BTCC%20VERSAO%20FINAL%5D_Carolina%20Mendonca%20de%20Almeida.pdf?sequence=1&isAllowed=y). Accessed on: Sep. 14, 2025.

ATARI. *Hydraulic Analogy*. 2021. Available at: https://ataridogdaze.com/science/hydraulic/. Accessed on: Sep. 22, 2025.

BHAVE, P. R. *Analysis of water distribution networks*. Lancaster: Technomic Publishing Company, 1991.

CAETANO, T. R. *Detecção de vazamentos em adutoras de concreto por meio do método da eletrorresistividade*. 2020. Dissertação (Mestrado em Engenharia Civil) - Centro Federal de Educação Tecnológica de Minas Gerais, Belo Horizonte, 2020. Available at:(https://sig-arquivos.cefetmg.br/arquivos/2020105209760025042l9b5573f2b3294/DISSERTAO_TATHIANA_RODRIGUES_CAETANO.pdf). Accessed on: Aug. 2, 2025.

CARVALHO, R. C. *Estimação de parâmetros em problemas de transferência de calor e de escoamento em meios porosos via inferência Bayesiana*. 2020. Dissertação (Mestrado em Engenharia Mecânica) - Universidade Federal do Rio de Janeiro, Rio de Janeiro, 2020. Available at:(https://w1files.solucaoatrio.net.br/atrio/ufrj-pem_upl//THESIS/10001345/pemufrj2020mscraphaelcostacarvalho_202103031526 18206.pdf). Accessed on: Sep. 15, 2025.

CASILLAS, M. et al. Comparison of several methods for leakage isolation using a sensitivity matrix-based method. In: *19th IFAC World Congress*. Cape Town, 2014. p. 8118-8123.

GAMBOA MEDINA, M. M. *Detecção de vazamentos em redes sob pressão baseada na análise dos sinais de pressão e vazão com um sistema de reconhecimento de padrões*. 2013. Dissertação (Mestrado em Engenharia Civil) - Escola Politécnica, Universidade de São Paulo, São Paulo, 2013. Available at: https://www.teses.usp.br/teses/disponiveis/18/18138/tde-01102013-143421/. Accessed on: Sep. 10, 2025.

HU, Z. et al. Review of model-based and data-driven approaches for leak detection and location in water distribution systems. *Water Supply*, v. 21, n. 5, p. 2036-2055, 2021.

JAVADIHA, M. et al. Leak Localization in Water Distribution Networks using Deep Learning. In: *2019 IEEE 15th International Conference on Automation Science and Engineering (CASE)*. Vancouver, 2019. p. 145-150.

JUN, S.; LANSEY, K. Comparison of AMI and SCADA Systems for Leak Detection and Localization in Water Distribution Networks. *Journal of Water Resources Planning and Management*, v. 149, n. 11, 2023.

LIU, H.; ZHI, Y. Design of Variable Frequency Speed Regulation and Constant Pressure Water Supply System. *Open Access Library Journal*, v. 7, n. 11, p. 1-11, 2020.

MACEDO, R. C. de. *Análise de transientes hidráulicos em adutoras: estudo de caso da adutora do agreste pernambucano*. 2012. Tese (Doutorado em Engenharia Civil) - Universidade Federal de Pernambuco, Recife, 2012. Available at: http://plone.ufpb.br/lenhs/contents/documentos/pesquisa-lenhs/2012-tese_roberta_macedo.pdf. Accessed on: Jul 9, 2025.

OBATA, D. H. S. *Desenvolvimento de um detector de vazamentos por correlação de sinal adaptado ao cenário Brasil*. 2019. Dissertação (Mestrado em Engenharia Mecânica) - Universidade Estadual Paulista, Ilha Solteira, 2019. Available at: https://repositorio.unesp.br/bitstream/11449/192039/3/obata_dhs_dr_ilha.pdf. Accessed on: Sep. 6, 2025.

PACTO GLOBAL. *Brasil perde R$10,5 bilhões em desperdício de água na distribuição, revela Pacto Global*. 2018. Available at:(https://brasil.un.org/pt-br/80183-brasil-perde-r105-bilh%C3%B5es-em-desperd%C3%ADcio-de-%C3%A1gua-na-distribui%C3%A7%C3%A3o-revela-pacto-global). Accessed on: Oct. 2, 2025.

PEREIRA, L. A. M. *Redução do consumo de água e energia elétrica em sistemas de abastecimento de água com a utilização de inversores de frequência*. 2016. Trabalho de Conclusão de Curso (Graduação em Engenharia Civil) - Universidade Federal da Paraíba, João Pessoa, 2016. Available at: http://ct.ufpb.br/ccec/contents/documentos/tccs/2016.2/reducao-do-consumo-de-agua-e-energia-eletrica-em-sistemas-de-abastecimento-de-agua-com-a-utilizacao-de-inversores-de-frequencia.pdf. Accessed on: Aug. 1, 2025.

PEREZ, R. et al. Methodology for leakage isolation using pressure sensitivity analysis in water distribution networks. *Control Engineering Practice*, v. 19, n. 10, p. 1157-1167, 2011.

PUSTELNIKOVA, K.; PUUST, R.; KAPELAN, Z. A review of leakage detection methods for water distribution networks. *Aqua*, v. 69, n. 3, p. 278-292, 2020.

ROSSMAN, L. A. *EPANET 2: Users Manual*. Cincinnati: U.S. Environmental Protection Agency, 2000.

SCHMIDLIN JÚNIOR, C. R. *Modelagem e simulação de sistemas de bombeamento com variação de velocidade*. 2006. Dissertação (Mestrado em Engenharia Civil) - Universidade Federal do Ceará, Fortaleza, 2006. Available at:(https://repositorio.ufc.br/bitstream/riufc/18522/1/2006_dis_crschmidlinj%C3%BAnior.pdf). Accessed on: Aug. 25, 2025.

SILVA, R. J. G. C. *Impedância de compensação de queda de tensão em controles conjuntos de tensão de usinas – uma forma de controle secundário de tensão descentralizado*. 2007. Tese (Doutorado em Engenharia Elétrica) - Universidade Federal de Itajubá, Itajubá, 2007.

SILVA JR, D. F. da. Ações de redução de perdas de água em sistemas de abastecimento. *Revista DAE*, v. 64, n. 201, p. 6-13, 2016.

SISTEMA NACIONAL DE INFORMAÇÕES SOBRE SANEAMENTO (SNIS). *Diagnóstico dos Serviços de Água e Esgotos – 2022*. Brasília: MDR/SNS, 2024.

SOARES, A. K. *Calibração de modelos de redes de distribuição de água utilizando algoritmos genéticos*. 2003. Dissertação (Mestrado em Engenharia Civil) - Escola Politécnica, Universidade de São Paulo, São Paulo, 2003. Available at:(https://www.teses.usp.br/teses/disponiveis/18/18138/tde-13102004-150130/publico/Dissertacao_AKS.pdf). Accessed on: Sep. 18, 2025.

SOLDEVILA, A. et al. Leak localization in water distribution networks using pressure and data-driven classifier approach. *Water*, v. 11, n. 7, p. 1500, 2019.

TAYLOR, C. W. Line drop compensation, high side voltage control, secondary voltage control-why not control a generator like a static VAr compensator? In: *2000 IEEE Power Engineering Society Winter Meeting*. Singapore, 2000. v. 4, p. 2601-2606.

TOMAZ, P. *Cálculos de Redes de Água*. 2001. Available at:(https://pt.scribd.com/document/453807415/Calculos-Redes-de-Agua-pdf). Accessed on: Oct. 5, 2025.

TRATA BRASIL, INSTITUTO. *Estudo de Perdas de Água 2024 (SNIS 2022): Desafios na Eficiência do Saneamento Básico no Brasil*. São Paulo: GO Associados, 2024. Available at: https://tratabrasil.org.br/wp-content/uploads/2024/06/Estudo-da-GO-Associados-Perdas-de-Agua-de-2024-V2.pdf. Accessed on: Oct. 5, 2025.
WALSKI, T. M. et al. *Advanced water distribution modeling and management*. Haestad Press, 2003.
ZHANG, Q. et al. Analytical Solution of Jacobian Matrices of WDS Models. In: *World Environmental and Water Resources Congress 2017*. Sacramento, 2017. p. 308-319.