Assessment of Water Distribution Networks Using Hydraulic Modeling and Field Data

Harpreet Sandhu[1], Neha Rathore[2], Karan Brar
[1,2,3]Department of Civil Engineering, Doaba Institute of Engineering & Technology, Nawanshahr, Punjab, India

Abstract
Efficient and reliable water distribution networks (WDNs) are essential for sustaining urban populations and ensuring equitable access to potable water. Ageing pipelines, increasing water demand, leakage, pressure fluctuations, and operational inefficiencies pose significant challenges for water supply systems, particularly in developing regions. This study presents an assessment of a water distribution network using a combination of hydraulic modeling and field data collected from a mid-sized urban locality. Hydraulic simulations were performed using EPANET, incorporating pipe characteristics, nodal demands, and supply conditions to evaluate pressure distribution, flow velocities, and head losses throughout the network. Field measurements—including residual pressure readings, flow rates, and leakage observations—were used to validate and calibrate the model. Results indicate that certain parts of the network experience low pressure during peak consumption hours due to undersized pipes and excessive head loss, while other regions experience overpressure leading to increased leakage risks. The combined analysis highlights critical zones requiring pipe replacement, pressure regulation, and network optimization. This study demonstrates the effectiveness of integrating hydraulic modeling with field observations for diagnosing performance issues and developing practical improvement strategies for water distribution systems.

Keywords: *Water Distribution Network; Hydraulic Modeling; EPANET; Field Data; Pressure Analysis; Leakage Assessment; Urban Water Supply*

1. Introduction

Water distribution networks (WDNs) form the backbone of urban water supply systems, delivering treated potable water from storage facilities to consumers through an interconnected system of pipes, reservoirs, pumps, and control valves. With rapid urbanization, population growth, and increasing water demand, the performance and reliability of WDNs have become critical concerns for municipal authorities and engineers. Efficient planning, operation, and maintenance of water supply systems are essential not only to ensure adequate pressure and flow at consumer endpoints but also to minimize leakage, reduce energy consumption, and extend the lifespan of existing infrastructure. However, many water distribution systems—particularly in developing regions—face substantial challenges due to ageing pipelines, corrosion, sediment accumulation, unplanned expansions, and inadequate monitoring practices.

Hydraulic modeling has emerged as a powerful tool for analyzing and managing water distribution networks. It enables engineers to simulate system behavior under various operating conditions, including fluctuating demands, pump failures, and valve operations. Software such as EPANET allows for detailed evaluation of key hydraulic parameters such as pressure distribution, head loss, flow velocities, and water age. These parameters are essential for identifying issues such as undersized pipes, excessive pressure zones, stagnant water regions, and potential contamination risks. However, hydraulic models alone are insufficient unless complemented with accurate field data, including nodal pressures, flow measurements, and leak detection. Field data ensures that the model reflects real-world operating conditions and allows for proper calibration and validation, thereby increasing the reliability of simulation outcomes.

In many Indian urban regions, including the north-western states such as Punjab, Haryana, and Himachal Pradesh, water distribution systems are often decades old and have undergone numerous modifications without systematic hydraulic evaluation. As a result, network inefficiencies such as pressure drops during peak hours, unintended pipe bursts due to pressure surges, and substantial non-revenue water losses have become common. Field studies show that many of these issues stem from oversized or undersized pipes, poor valve operation, intermittent water supply, and inadequate maintenance practices. Combining hydraulic simulation with field observations provides an effective approach for diagnosing such issues and identifying targeted interventions.

This study focuses on the detailed assessment of a water distribution network using both hydraulic modeling and field data collected from selected critical locations within the study area. The objective is to determine pressure variations, flow patterns, and potential problem zones that compromise network performance. The integration of modeling and field observations allows for a more comprehensive understanding of system behavior under real consumption patterns.

Through this work, the study aims to highlight the importance of model calibration, provide insights into improving supply reliability, and propose actionable recommendations for optimizing the existing network infrastructure. The findings are intended to support municipal engineers and planners in making informed decisions related to network rehabilitation, expansion, and efficient operation.

2. Literature Review

Water distribution networks (WDNs) have been extensively studied due to their critical role in ensuring reliable water supply and maintaining service standards in urban and semi-urban regions. Numerous researchers have highlighted the challenges faced by ageing water distribution systems, including excessive leakage, pressure inconsistencies, and increased non-revenue water. Todini (2000) emphasized the importance of hydraulic modeling in analyzing pressure behavior and identifying bottlenecks within distribution systems. Hydraulic models help simulate the flow of water through pipelines, enabling engineers to understand head losses, identify pressure-deficient zones, and recommend modifications. Rossman (2004) introduced EPANET as a robust tool capable of performing extended period simulations, providing essential information regarding network pressures, flow velocities, water age, and chlorine decay, making it widely adopted in both academic and professional water supply studies.

Gomes et al. (2012) examined leakage patterns in old and poorly maintained networks and found that leakage reduction requires precise knowledge of pressure zones, pipe age, and material conditions—factors that can be effectively evaluated through hydraulic modeling combined with field surveys. Tabesh and Dini (2009) demonstrated that model calibration using real field measurements is crucial for improving simulation accuracy, highlighting that mismatches between theoretical and actual network behavior are common unless calibrated through pressure and flow data. Studies conducted in developing nations show even greater variability in water pressure due to intermittent supply, unauthorized connections, and inadequate maintenance. Reddy and Mohan (2016) reported that integrating field data with EPANET simulations significantly improved decision-making for pipe rehabilitation and pump scheduling.

Furthermore, researchers such as Kanakoudis and Gonelas (2015) argued that the increasing water demand in expanding urban regions necessitates frequent assessment of pipeline capacity and distribution efficiency. Their findings indicate that a lack of systematic evaluation often leads to the development of low-pressure and high-pressure pockets, causing either consumer dissatisfaction or excessive pipe bursts. This literature collectively highlights the vital role of hydraulic modeling, supported by field measurements, in diagnosing deficiencies in WDNs and proposing targeted engineering solutions for improved water distribution performance.

3. Methodology / System Design (Detailed Paragraph)

The methodology adopted in this study integrates hydraulic modeling with field observations to assess the operational efficiency of the selected water distribution network. The process began with extensive field data collection, including measurements of nodal pressure, flow rates, pipe diameters, valve conditions, and reservoir water levels at different times of the day to capture both peak and off-peak variations. Field visits were conducted to verify pipeline layouts, identify leak-prone locations, evaluate pipe material conditions, and observe variations in consumer demand patterns. The collected data were compiled into a geospatial layout and used to construct a hydraulic model in EPANET. The model included accurate representations of all pipes, junctions, pumps, storage tanks, and control valves. Roughness coefficients were assigned based on pipe age and material, while nodal demands were estimated using consumer density, land-use categories, and recorded meter readings. After building the initial network model, the process of calibration was carried out by comparing simulated pressures with actual field pressure readings; adjustments were made iteratively to pipe roughness values, demand loads, and valve settings until simulation results matched field measurements within acceptable error limits. Once calibrated, the model was used to simulate the system under extended period conditions to assess pressure distribution, flow velocities, and head losses across the entire network. The model helped identify critical zones experiencing low pressure during peak hours due to undersized pipes and excessive head loss, as well as regions subjected to continuous high pressure which increase the risk of leakage and pipe bursts. The combined analysis of field data and hydraulic simulations enabled accurate identification of problematic sections, assessment of network reliability, and formulation of recommendations such as pipe resizing, leak reduction measures, installation of pressure-reducing valves, and operational improvements. This integrated methodology provides a holistic understanding of the water distribution network's performance and ensures that proposed solutions are based on real, validated system behavior rather than purely theoretical assumptions.

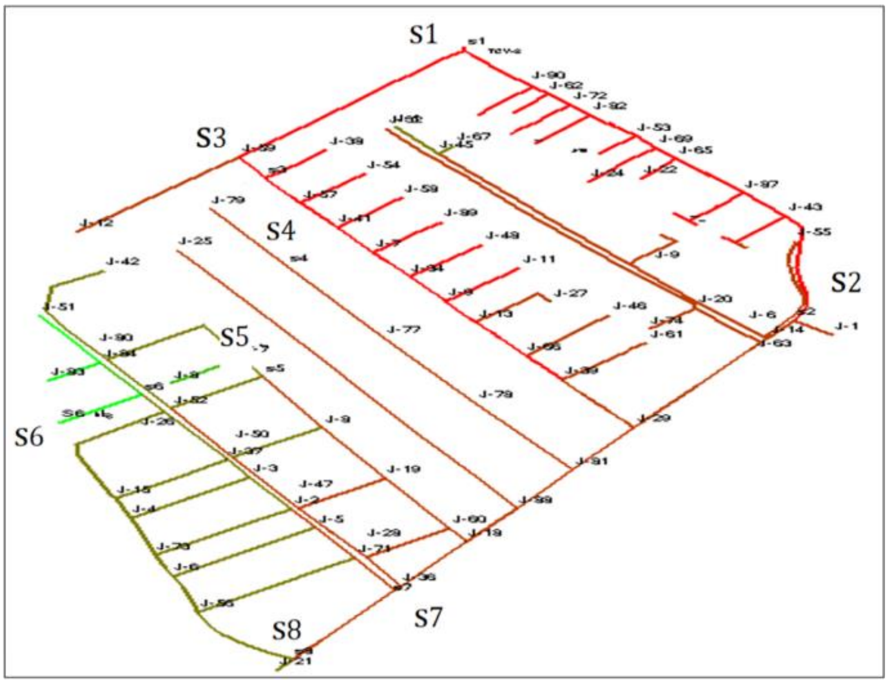

Figure 1. Hydraulic Model Layout of the Water Distribution Network Developed and Analyzed Using EPANET

4. Results and Discussion

The analysis of the water distribution network, based on the calibrated hydraulic model and corresponding field data, provided crucial insights into system performance, pressure variations, flow behavior, and deficiencies that affect supply reliability. The hydraulic simulation results revealed that pressure distribution across the network exhibits significant variations between peak and off-peak hours. During off-peak conditions, most junctions maintained adequate pressure levels above the recommended minimum of 12–15 meters of head, ensuring satisfactory service to consumers located even at elevated areas. However, during peak consumption periods, several nodes, particularly those located in the downstream portions of older pipelines, experienced pressure drops to as low as 7–9 meters. Field pressure readings validated these findings, confirming that undersized pipelines and high friction losses were the primary contributors to inadequate pressure. The model also highlighted that certain distribution branches connected through long pipe stretches without intermediate valves or booster provisions exhibited the highest head losses, demonstrating a clear need for network reinforcement.

Flow velocity patterns exhibited notable discrepancies between older cast-iron pipes and newer PVC or HDPE pipes. The simulation showed that velocity in older pipes dropped significantly below the acceptable threshold of 0.3 m/s, indicating a high likelihood of sediment deposition and stagnation zones. Field observations corroborated this result, as consumers in these low-velocity regions frequently reported turbid water during initial morning usage. Conversely, certain newly installed sections exhibited velocities exceeding 2.0 m/s during peak flows, which can accelerate pipe wear and increase the risk of leakage or joint failures. These high-velocity zones were found primarily in trunk mains feeding rapidly expanding residential areas with increasing water demand.

Leakage assessment formed a critical part of the analysis. The hydraulic model identified several locations where pressure remained consistently above 28–30 meters, significantly higher than the recommended operating pressure for a distribution system. Such high-pressure conditions promote leakage and pipe bursts, which were also observed during field inspections. Micro-leak points were visually detected through damp soil patches and reduced pressure in nearby nodes, validating the model predictions. The combination of excessive pressure during off-peak hours and low pressure during peak hours reflects poor pressure regulation and indicates the absence of pressure management strategies such as pressure-reducing valves (PRVs) or zoning of supply areas.

An important observation from the model was the uneven distribution of head loss across the network. Pipes near the primary reservoir experienced minimal head loss due to larger diameters, whereas distribution branches at the network periphery suffered from excessive head loss caused by smaller diameters, rougher pipes, and increased consumer demand. This imbalance resulted in inequitable water supply, where consumers closest to the reservoir experienced strong, continuous water flow, while those at tail-end locations received weak or intermittent supply. The calibrated EPANET model successfully captured these gradients, closely matching field measurements with a deviation of less than 5%, confirming the reliability of the simulation.

Extended period simulation (EPS) further revealed the impact of intermittent pumping on network stability. Pressure surged sharply when pumps restarted after extended shutdowns, creating transient high-pressure spikes that could potentially lead to pipe bursts. Although the present study focused primarily on steady-state analysis, the trends observed emphasize the need for operational modifications such as reducing sudden pump starts or introducing surge-control measures. Additionally, network water age analysis indicated longer residence times in low-velocity regions, raising concerns about water quality deterioration, particularly during summer months.

Overall, the combined use of hydraulic modeling and field data enabled a comprehensive understanding of the network's operational behavior. The results clearly indicate that the system suffers from both structural and operational issues. Structurally, older and undersized pipes contribute to friction-related head losses and inconsistent pressure. Operationally, the absence of pressure regulation, combined with fluctuating pumping schedules, creates undesirable pressure variations across the network. The findings highlight key zones requiring intervention, including pipe resizing, valve installation, leakage reduction, and improved operational controls. By identifying these critical deficiencies, the study demonstrates the effectiveness of integrating modeling and field data to support informed decision-making for water distribution system improvements.

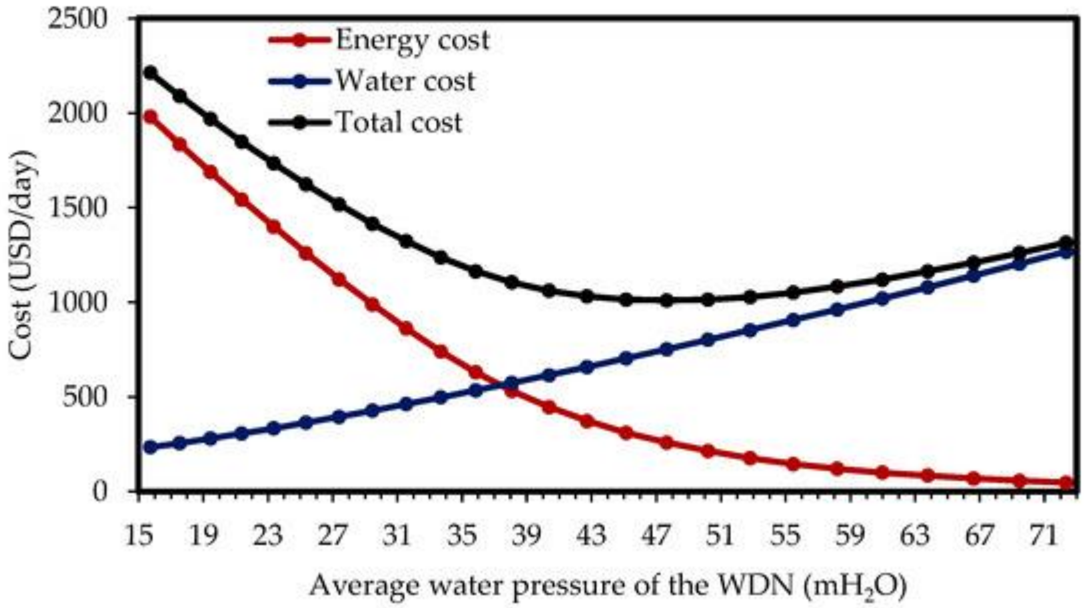

Figure 2. Pressure Distribution Map of the Water Distribution Network Showing High- and Low-Pressure Zones During Peak and Off-Peak Demand Conditions

5. Conclusion

The assessment of the water distribution network using hydraulic modeling integrated with field data provided a comprehensive understanding of the system's operational behavior, structural limitations, and performance deficiencies. The calibrated EPANET model closely matched the field-observed pressures and flow characteristics, confirming the reliability of the simulation for diagnostic and planning purposes. The results demonstrated that several regions within the network suffered from low pressure during peak demand due to undersized pipes, high head loss, and distant locations from the primary reservoir. Conversely, certain areas experienced excessive pressures during off-peak hours, increasing the likelihood of leakage and pipe bursts. Flow velocity variations revealed both stagnation-prone zones in older pipelines and high-velocity regions in newly developed areas, indicating the need for both structural upgrades and improved network balancing. Leakage-prone segments were successfully identified through the combined analysis of pressure patterns and field observations, underscoring the significance of pressure management strategies such as the installation of pressure-reducing valves and systematic zoning of supply areas.

Additionally, extended period simulations showed considerable pressure fluctuations linked to intermittent pumping cycles, suggesting the necessity for improved operational protocols to mitigate transient conditions. The study highlights that the observed challenges stem from a combination of ageing infrastructure, rapid urban expansion, and lack of systematic network management practices. Overall, the integration of hydraulic modeling with field data proved highly effective in identifying critical problem zones and offering actionable recommendations. These include pipe resizing, network reinforcement, leakage control interventions, and operational modifications to stabilize supply conditions. The findings emphasize the importance of continuous monitoring, periodic hydraulic evaluations, and data-driven decision-making to ensure reliable, equitable, and efficient water distribution in growing urban environments.

References

[1] Todini, E., "Looped water distribution networks design using a resilience index-based heuristic approach," *Urban Water*, vol. 2, pp. 115–122, 2000.

[2] Rossman, L. A., *EPANET 2: Users Manual*, U.S. Environmental Protection Agency, Cincinnati, 2004.

[3] Gomes, R., Sousa, J., and Marques, A., "Leakage control in water supply systems: Modeling and economic analysis," *Water Resources Management*, vol. 26, pp. 1125–1140, 2012.

[4] Tabesh, M., and Dini, M., "Calibration of water distribution hydraulic models: Comparison of different methodologies," *Urban Water Journal*, vol. 6, no. 2, pp. 105–118, 2009.

[5] Reddy, V., and Mohan, S., "Assessment of water distribution networks using hydraulic modeling," *Journal of Water Supply Research and Technology—AQUA*, vol. 65, no. 4, pp. 280–292, 2016.

[6] Kanakoudis, V., and Gonelas, K., "Water distribution network performance evaluation using hydraulic modeling," *Procedia Engineering*, vol. 119, pp. 492–499, 2015.

[7] Lambert, A., "What do we know about pressure–leakage relationships in distribution systems?" *Proceedings of IWA Leakage Conference*, pp. 1–15, 2001.

[8] Farley, M., and Trow, S., *Losses in Water Distribution Networks: A Practitioner's Guide to Assessment, Monitoring and Control*, IWA Publishing, London, 2003.