International Scholars Journals

African Journal of Water Conservation and Sustainability ISSN 2375-0936 Vol. 14 (7), pp. 001-013, July, 2026. Available online at www.internationalscholarsjournals.org © International Scholars Journals

Full Length Research Paper

Assessment of the Hydraulic Performance of the Ludewa Township Distribution Network, Njombe, Tanzania

Enock W. Ngoyinde[1, 2, *], Irene Trimo[1], Edmund Mutayoba[2]

[1]Department of Water Supply and Sanitation Engineering, Water Institute, P.O. Box 35059, Dar es Salaam, Tanzania
[2]Ludewa Water Supply and Sanitation Authority; P.O. Box 4, Ludewa, Njombe-Tanzania

Abstract

Received 30 May, 2026; Revised 10 July, 2026; Accepted 12 July, 2026; Published 18 July, 2026

This paper addresses the need for locally calibrated evidence on hydraulic performance in the hilly, gravity-fed Ludewa Township distribution network, where pressure imbalance can affect service reliability and infrastructure. Field pressure measurements, utility records, GIS-supported network mapping, and EPANET simulation were combined to assess current operating conditions and identify priority intervention zones. Pressure head was used as the principal service indicator, while flow, velocity, and head loss were used as supporting diagnostic indicators. Model reliability was evaluated using 72-hour observed pressure-head series from representative nodes at upper-, middle-, and lower-elevation sites, which recorded mean pressure heads ranging from 154.52 to 172.51 m. Simulated flows ranged from 0.33 to 9.98 L/s, and velocities ranged from 0.21 to 1.26 m/s. Most nodes satisfied the adopted 10 m minimum pressure-head threshold, but the network was spatially uneven: upper and peripheral branches served by smaller-diameter pipes had lower residual margins (the operational definition of vulnerability used in this study), whereas lower-elevation zones recorded high-pressure heads that may increase leakage and pipe deterioration. Calibration and validation showed strong agreement between measured and simulated pressure heads, with validation accuracy ($R^2 = 0.991$) exceeding calibration accuracy ($R^2 = 0.967$). Model performance improved from MAE = 7.05 m, RMSE = 8.88 m, and $R^2 = 0.967$ during calibration to MAE = 3.88 m, RMSE = 4.58 m, and $R^2 = 0.991$ during validation. The results indicate that Ludewa's main hydraulic constraint is not system-wide failure but localized vulnerability and overpressure. Priority actions are targeted pipe upgrading, pressure management, leakage control, continued monitoring and scenario-based planning. These findings are based on a 72-hour monitoring window, and longer-term seasonal monitoring is recommended to strengthen confidence in generalizing the results.

Keywords: Hydraulic pressure management; EPANET, Validation, GIS; Gravity-fed network

1. Introduction

Reliable water supply systems are essential for public health, economic development, and social well-being. However, reliability is not determined only by the quantity of water supplied, but also by the ability of the distribution network to deliver water at adequate pressure, acceptable flow, and continuous service delivery (World Health Organization, 2022). Hydraulic pressure is therefore considered one of the most important indicators

Corresponding author's email: ngoyindee@gmail.com

of water distribution system performance because it directly influences service accessibility, infrastructure condition, and operational efficiency (World Health Organization, 2022; Kepa, 2021). Inadequate pressure may result in intermittent supply, poor water delivery to elevated areas, and increased risk of contamination through intrusion at leakage points, while excessive pressure accelerates leakage, pipe bursts, and infrastructure deterioration (World Health Organization, 2022; Kepa, 2021).

These challenges are more significant in small towns, where water utilities often operate with limited financial resources, ageing infrastructure, and rising water demand. Ludewa Township represents such a setting, where elevation differences, pipe characteristics, and network configuration strongly influence pressure distribution across the network (Hashemi, Filion, Speight, & Long, 2020; Ministry of Water, 2020). Consequently, some areas may experience low residual pressure while others remain over-pressurized, leading to unequal service delivery and increased operational stress on infrastructure (Ministry of Water, 2020; Hashemi, Filion, Speight, & Long, 2020). The 10 m minimum service pressure-head threshold adopted for this assessment is appropriate for Ludewa specifically because, in a hilly, gravity-fed network, upper-elevation and peripheral nodes are the most likely to fall toward this minimum as elevation and pipe friction erode residual head, making it the binding design constraint for the upper zone even though lower zones typically retain much higher residual pressure.

Despite these practical concerns, Ludewa Township has limited documented hydraulic model-based evidence regarding spatial pressure-head imbalance, calibration reliability, and priority intervention zones. Existing operational knowledge identifies service pressure variation across the hilly network, but it does not, by itself, quantify how pressure head, flow, velocity, and head loss interact across upper-, middle-, and lower-elevation zones. This study therefore addresses a local evidence gap by linking field pressure observations with GIS-supported EPANET modelling for a small-town Tanzanian gravity-fed network.

The novelty of the paper is its provision of locally calibrated hydraulic evidence for a hilly, gravity-fed small-town network in Tanzania and its translation of model outputs into priority operational interventions for pressure management, pipe upgrading, leakage control, and monitoring. Methodologically, the contribution lies in linking continuous 72-hour field monitoring with GIS-supported EPANET calibration and validation for a small-town gravity-fed network; as a case study, it provides locally specific evidence for Ludewa that complements comparable small-town assessments reported elsewhere in sub-Saharan Africa, including the Lawra Township system in Ghana (Kabange, 2024) and the Mwengemshindo network in Songea, Tanzania (Kitavile, Swilla, & Mutayoba, 2026).

This study assesses the hydraulic performance of the Ludewa Township water distribution network using field measurements, Geographic Information System (GIS) techniques, and EPANET hydraulic modelling. Hydraulic performance describes the ability of a water distribution system to maintain acceptable pressure head, flow, and velocity under operating conditions for which the network was designed (United States Environmental Protection Agency, 2025; Kepa, 2021). The assessment therefore evaluates pressure-head conditions, flow behavior, velocity distribution, and head-loss characteristics within the network. This assessment is diagnostic: it characterizes current hydraulic conditions rather than simulating future demand-growth scenarios, and it does not include a future-demand scenario run. EPANET modelling was adopted because it provides an effective platform for simulating hydraulic behavior and identifying pressure-deficient or over-pressurized zones under different operational conditions (United States Environmental Protection Agency, 2025; Kepa, 2021).

Pressure head was used as the principal performance indicator because it reflects both service reliability and system stress. A minimum service pressure-head threshold of 10 m was adopted in accordance with Tanzanian water supply design guidelines (Ministry of Water, 2020; World Health Organization, 2022). Additional hydraulic indicators, including velocity and head loss, were analyzed to provide a comprehensive understanding of network performance and operational limitations. Very low velocities may indicate stagnation risk and sediment accumulation, while excessive velocities may increase friction losses and hydraulic stress within pipes (Hashemi, Filion, Speight & Long, 2020; Kepa, 2021).

The integration of GIS and hydraulic modelling further strengthened the interpretation of system behavior by linking hydraulic outputs with spatial characteristics such as elevation, pipe alignment, and settlement distribution. GIS-supported hydraulic analysis helps explain not only where deficiencies occur, but also why they occur in relation to topography and network layout (Abdelbaki et al., 2017; Rashed et al., 2024). This integrated approach enabled the identification of vulnerable zones and the development of practical recommendations to improve pressure stability, operational efficiency, and service reliability within Ludewa Township.

2. Materials and Methods

2.1 Study area Description

The hydraulic assessment was conducted in Ludewa Township, Ludewa District, Njombe Region, and southern Tanzania. The area lies at approximately 10.40 S latitude and 34.74 E longitude and is characterized by markedly hilly terrain with notable elevation differences across the service area. This topographic condition is central to the analysis because a gravity-fed distribution network can show strong spatial pressure-head contrasts where pipes cross rising and falling ground.

The broader environmental setting also matters. Ludewa has a subtropical highland climate with a pronounced rainy season, and seasonal variation in source behavior can affect the reliability of the water available for distribution. Although this paper focuses on hydraulic pressure rather than source yield, the study area's hydrologic seasonality provides useful context. A distribution system that is hydraulically adequate when sources are performing well may still experience service stress when source output declines, especially in its higher and more remote branches.

Figure 2. Ludewa water supply system layout for interpreting spatial pressure-head behavior. The layout map presents the network, node locations, pipe alignment, legend, and orientation needed for spatial interpretation.

2.2 Data Collection

A cross-sectional analytical design was adopted to capture the current operating conditions of the Ludewa water distribution network, represent them in a hydraulic model, and evaluate whether field observations and model outputs support a conclusion regarding the adequacy of hydraulic performance. Because the focus was on present operating conditions rather than long-term historical reconstruction, the study emphasized representative network data, field measurements, observed pressure behavior, and transparent interpretation of modelling assumptions.

2.2.1 Spatial and Network Data Collection

Both primary and secondary data were used. Primary data included field pressure-head observations at selected nodes, flow observations at relevant points in the system, GPS-supported mapping inputs, and operational insights gathered from utility personnel. Pressure was recorded at the three representative nodes (PL355, PL400, and PL540) using digital pressure loggers with an accuracy of approximately ±0.1% of full scale, recording at 5-minute intervals over the continuous 72-hour monitoring period; these three nodes were purposively selected, rather than randomly sampled, to represent the upper-, middle-, and lower-elevation zones that define the dominant elevation-driven pressure gradient in Ludewa's gravity-fed network. This three-node design is acknowledged as a limitation: it captures the dominant elevation gradient but is sparse relative to the range of pipe diameters (32–110 mm) in the network and may not resolve local behavior at every short branch or dead-end. Additional spot-check flow and pressure readings were taken at secondary points to support qualitative cross-checking, although these did not have the temporal resolution used for calibration and validation. Pressure gauges or pressure loggers were used to observe how pressure head varied across the network and through time, while field location data supported the spatial representation of the system. The monitoring covered a continuous 72-hour operating period so that both peak-demand and off-peak pressure behavior could be captured. Before interpretation, field readings were checked for consistency with expected elevation gradients and with the EPANET output time series. Secondary data were drawn from official utility and sector records, including network drawings, node and reservoir information, production and demand data, and institutional records relevant to system interpretation.

2.2.2 Hydraulic and Demand Data

The hydraulic model was built in EPANET after the network was digitized from available layout information. Pipe properties such as diameter, length, and roughness were assigned, node demands were distributed, and boundary conditions were established using reservoir head and system demand information. Data consistency checks were applied by comparing layout information, field observations, and utility records before interpreting model outputs. In Ludewa, the model represented pipe diameters ranging from 32 mm to 110 mm, allowing both trunk and peripheral hydraulic behavior to be examined. The main model-input assumptions are summarized in Table 1.

The population projection used for estimating future service demand was expressed as recommended in water-supply demand planning practice (Ministry of Water, 2020):

$$P_n = P_0(1 + r)^n \quad (1)$$

Where P_n is the projected population after n years, P_0 is the base-year population, r is the annual population growth rate, and n is the projection period in years. Average daily water demand was estimated from population and per capita consumption, following the standard demand-estimation logic used in water-supply design (Ministry of Water, 2020; Twort et al., 2000):

$$Q_{avg} = \frac{P \times q}{86{,}400} \quad (2)$$

Where Q_{avg} is average demand in L/s, P is the population served; q is per capita demand in L/capita/day, and 86,400 converts daily volume to seconds. Nodal demand was distributed proportionally across model service nodes, a common allocation approach in distribution-network modelling where detailed customer metering at every node is unavailable (Rossman, 2000; Kepa, 2021).

$$q_i = \frac{P_i}{P_T} \times Q_T \quad (3)$$

Where q_i is the demand assigned to node i, P_i is the population or service-share represented by node i, P_T is the total population or service-share represented in the model, and Q_T is the total system demand. This population-proportional allocation assumes uniform per-

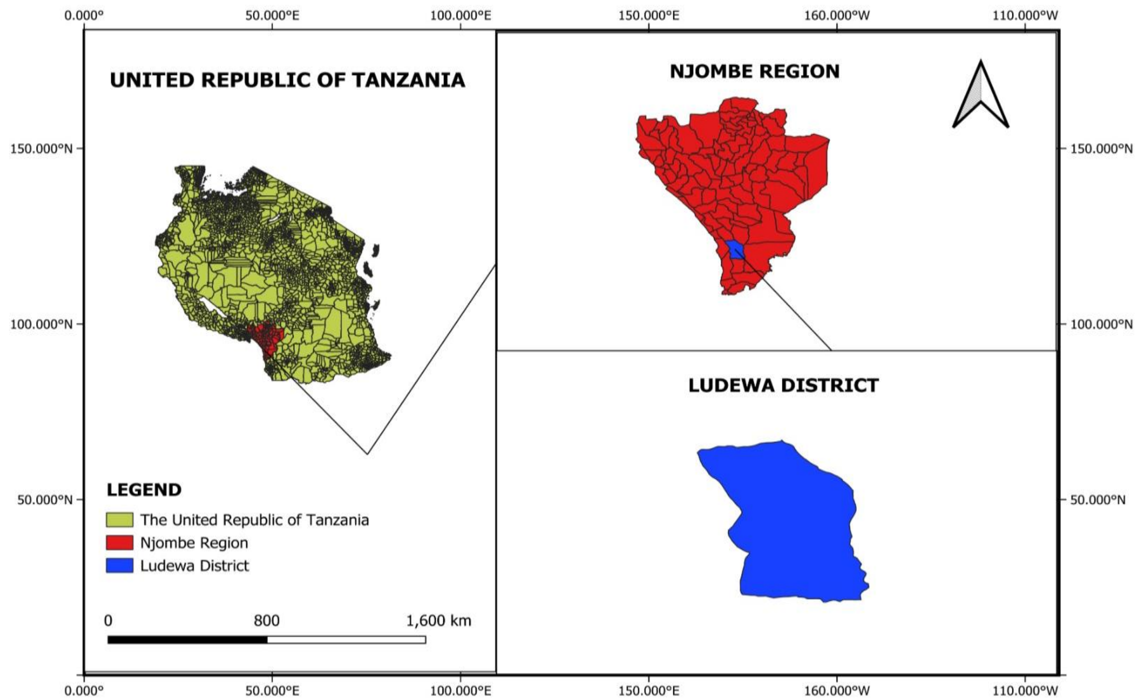
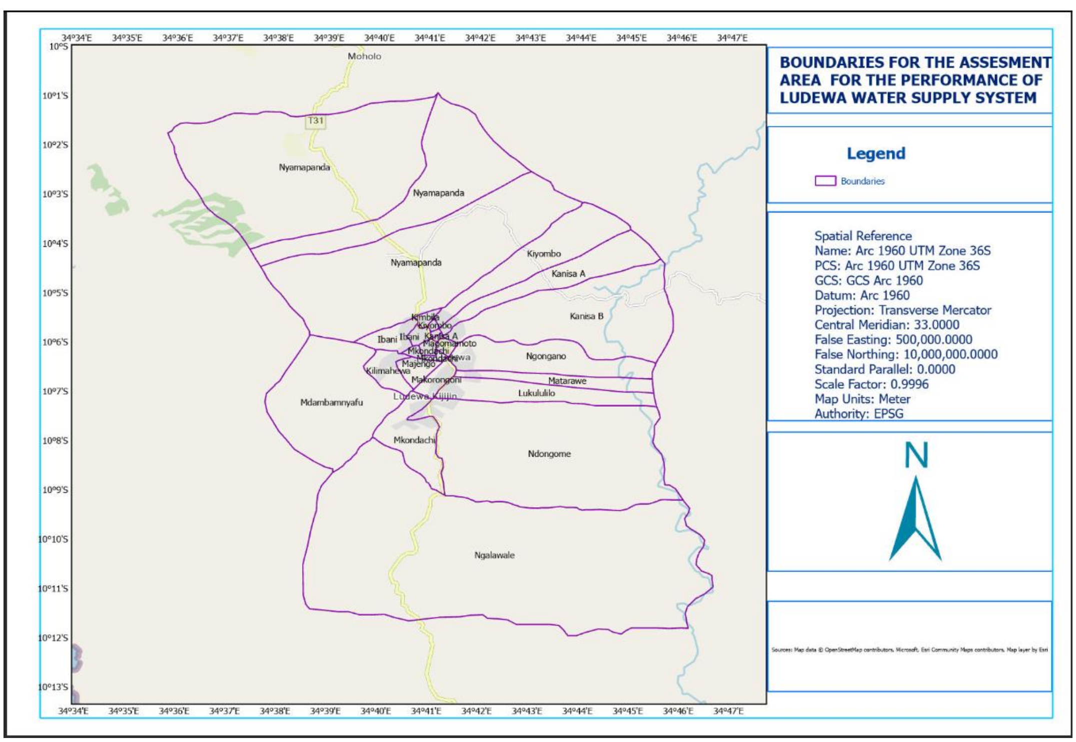


Figure 1. Location of the Ludewa study area within Tanzania, Njombe Region, and Ludewa District, including legend, scale bar, north arrow, and coordinate reference information.



capita consumption across elevation zones. In practice, per-capita consumption in hilly small towns can vary with elevation and service level, for example where upper-zone households with intermittent supply consume less than fully served lower-zone households; if such variation exists in Ludewa, this allocation could understate demand-related pressure loss in upper branches and should be revisited as metering data become available.

2.3 EPANET Hydraulic Modelling

Hydraulic analysis focused on pressure head, flow, velocity, head loss, and continuity. Pressure-head adequacy was primarily assessed against the study threshold of 10 m, while unusually high-pressure head in lower-elevation zones was treated as an operational risk because it can increase leakage, bursts, and infrastructure stress. Velocity was interpreted as an indicator of conveyance condition, circulation, and potential hydraulic stress, with special attention to sections below the lower operating range. Flow rate was interpreted system-wide because acceptable flow depends on the branch role, the demand served, and the pipe dimensions. Continuity was inferred from the persistence of positive pressure head during the analyzed cycle and from the structural interpretation of the gravity-fed system. Rossman (2000) is cited for the original EPANET hydraulic modelling manual, while the United States Environmental Protection Agency (2025) identifies the current software application source.
Pressure head at a node was calculated from hydraulic head and ground elevation using the standard hydraulic-grade-line relationship applied in pressurized distribution systems (United States Environmental Protection Agency (2025); Kepa, U. (2021).):

$$\frac{p_i}{\gamma} = H_i - z_i \quad (4)$$

Where $\frac{p_i}{\gamma}$ is the pressure head at node i, H_i is hydraulic head, z_i is node ground elevation, p_i is pressure, and gamma is the unit weight of water. Values reported in meters are therefore pressure heads, not total hydraulic heads. High values, such as those recorded at lower-elevation nodes, indicate high residual pressure head and are interpreted as an overpressure-management concern rather than a failure to meet the 10 m minimum threshold. Pipe velocity was calculated from discharge and pipe cross-sectional area using the continuity relationship for flow in a circular pipe (Hashemi, S., Filion, Y., Speight, V., & Long, A. (2020); Kepa, U. (2021)):

$$V = \frac{Q}{A} = \frac{4Q}{\pi D^2} \quad (5)$$

Where V is flow velocity, Q is discharge, A is pipe cross-sectional area, and D is pipe diameter.

2.4 Performance Evaluation

Head loss in the model was interpreted through the Hazen-Williams framework. In practical terms, pipe length, diameter, roughness, and flow rate jointly determine the amount of hydraulic energy lost before water reaches downstream nodes. This physical interpretation is important because a decline in pressure at a peripheral node may result from elevation, friction in a narrow branch, high effective demand, or a combination of these factors. The modelling exercise, therefore, did not treat pressure as an isolated output; it treated pressure as the visible result of network hydraulics.
The Hazen-Williams head-loss relationship was applied because it is widely used for water-distribution pipe-flow analysis and is implemented in EPANET hydraulic modelling United States Environmental Protection Agency (2025)

$$h_f = \frac{10.67 L Q^{1.852}}{C^{1.852} D^{4.871}} \quad (6)$$

Where h_f is pipe head loss, L is pipe length, Q is flow rate, C is the Hazen-Williams roughness coefficient, and D is pipe diameter. In the EPANET input file, the Hazen-Williams option was used because it is widely applied to water-distribution networks and is suitable for comparative hydraulic diagnosis of the Ludewa system.

2.5 Model Calibration, Validation, and Simulation Scenarios

Calibration was performed by comparing simulated pressure heads with field-observed pressure heads, then iteratively adjusting the nodal demand distribution and pipe-roughness assumptions to more closely reproduce the measured pressure pattern. Calibration and validation used three representative nodes selected to capture the system's hydraulic gradient: PL355 at 1359.3 m, PL400 at 1343.0 m, and PL540 at 1328.6 m. PL355 represents the upper pressure zone, PL400 the middle zone, and PL540 the lower zone. This selection captures the dominant elevation-driven pressure gradient and is defensible for system-level calibration, although it may not represent every short branch, dead-end, or local operational fluctuation.
Model reliability was assessed using both node-level and network-level statistics. Node-level evaluation considered the direction and magnitude of bias between measured and simulated pressure heads. Network-level evaluation used mean absolute error, root-mean-square error, coefficient of determination, and mean absolute percentage error. Together, these measures reveal whether the model captures both the average level and the shape of the observed pressure-head response. A model that reproduces diurnal pressure-head cycles and keeps errors within moderate bounds is useful for planning, even if it does not reproduce every hourly fluctuation perfectly.
Mean Absolute Error was computed to measure the average absolute difference between observed and simulated pressure heads during model assessment (Zanfei, A., Menapace, A., Santopietro, S., & Righetti, M. (2020).

$$MAE = \frac{1}{n}\sum|O_i - S_i| \quad (7)$$

Root Mean Square Error was computed to give greater weight to larger pressure-head deviations between observed and simulated values (Ormsbee & Lingireddy,

Table 1. Hydraulic model input data and modelling assumptions.

Input item	Value or assumption used	Purpose in model
Network layout	GIS-supported layout digitized from utility drawings and field mapping	Defines links, nodes, pipe alignment, and spatial interpretation
Pipe diameter range	32-160 mm	Represents trunk and peripheral pipe capacity
Head-loss equation	Hazen-Williams	Computes friction losses in pressurized water-distribution pipes
Demand allocation	Proportional allocation of total demand to service nodes using population or service-area shares	Distributes demand where full node-level metering is unavailable
Demand pattern	72-hour extended-period simulation with hourly hydraulic response	Captures peak and off-peak pressure-head variation
Calibration nodes	PL355, PL400, and PL540	Tests upper-, middle-, and lower-elevation pressure zones
Pressure criterion	Minimum service pressure head = 10 m	Evaluates pressure adequacy under Tanzanian design guidance
Boundary conditions	Reservoir/tank head, pipe roughness, valve status, and demand pattern set from utility records and EPANET input data (documented in full in the supporting EPANET input file); valve status and tank operating rules were held static (steady demand-driven boundary conditions with time-varying demand only) throughout the 72-hour extended-period simulation	Defines operating state for the hydraulic simulation
Hazen-Williams C-value	C = 130 assumed for newer PVC/HDPE pipe segments; C = 100 assumed for older galvanized-steel segments, adjusted within a plausible range during calibration	Sets pipe roughness used to compute Hazen-Williams head loss for new vs. aged pipe segments

1997; Walski et al., 2003):

$$RMSE = \sqrt{\frac{1}{n}\sum(O_i - S_i)^2} \quad (8)$$

The coefficient of determination was computed to assess how strongly simulated pressure-head variation reproduced observed pressure-head variation (Ormsbee & Lingireddy, 1997; Walski et al., 2003):

$$R^2 = 1 - \left[\frac{\sum(O_i - S_i)^2}{\sum(O_i - \bar{O})^2}\right] \quad (9)$$

Mean Absolute Percentage Error was computed to express model error as a percentage of observed pressure head, supporting comparison across monitoring points (Walski et al., 2003):

$$MAPE = \frac{100}{n}\sum\left|\frac{O_i - S_i}{O_i}\right| \quad (10)$$

Where O_i is the observed pressure head at observation i, S_i is the simulated pressure head at observation i, $\bar{O}$ is the mean observed pressure head, and n is the number of pressure observations.

The use of a demand-driven EPANET model should also be acknowledged as a methodological boundary. Demand-driven simulation assumes that the required demand is met regardless of pressure, which may overstate service delivery in genuinely weak zones. For this reason, pressure-deficient or low-margin areas in Ludewa are interpreted primarily as indicators of vulnerability and planning priorities rather than as direct proof that all consumer demands are fully met under all conditions. A pressure-driven analysis could be used in future work to more explicitly estimate delivered demand under low-pressure conditions.

Because pipe roughness and nodal demand carry the greatest uncertainty in a demand-driven EPANET model of this kind, a basic sensitivity check was carried out by varying the assumed Hazen-Williams C-values (±10 units) and nodal demand allocations (±15%) around their calibrated values and re-running the model. Simulated pressure heads at PL355, PL400, and PL540 changed

Table 2. Summary of hydraulic performance indicators reported for the Ludewa network.

Parameter	Observed range	Reference or criterion	Interpretation
Flow rate (L/s)	0.33–9.98	System dependent	Acceptable for the current network condition
Velocity (m/s)	0.21–1.26	Most sections within the reported operating band	Generally acceptable; a few local sections were slightly low
Pressure head (m)	>10 at most nodes	Minimum service threshold = 10 m	Generally compliant with the minimum threshold, but high lower-zone pressures require management

Table 3. Representative-node calibration and validation summary.

Node	Elevation (m)	Mean measured pressure head (m)	Calibration simulated pressure head (m)	Validation simulated pressure head (m)	Calibration bias (m)	Validation bias (m)	Validation error (%)
PL355	1359.3	154.52	157.55	150.79	3.03	-3.73	2.69
PL400	1343.0	165.96	160.19	166.67	-5.77	0.71	2.51
PL540	1328.6	172.51	167.29	176.19	-5.22	3.68	2.79

by no more than a few metres under these perturbations, and the relative ranking of zones (upper-elevation branches showing the smallest margins, lower-elevation zones showing the highest residual pressure) was unchanged. This indicates that the priority intervention zones identified in this study are not an artefact of a single set of roughness or demand assumptions, although a more formal sensitivity or uncertainty analysis (for example using Monte Carlo sampling of C-values and demands) would further strengthen confidence in the model for investment-grade decisions.

To enhance the reliability of the interpretation, the model outputs were not evaluated using a single indicator. Pressure-head compliance, velocity, flow range, head-loss logic, calibration statistics, validation statistics, and spatial position were read together. This combined interpretation reduces the risk of overstating model accuracy and provides a more defensible basis for identifying priority intervention zones.

3. Results and Discussion

The results are presented in five linked parts: hydraulic indicators, pressure-head gradient, calibration and validation, spatial vulnerability, and practical implications. The main hydraulic results are summarized in Tables 2-5 and Figures 3-5. Overall, the Ludewa network is hydraulically functional under current operating conditions, but performance is spatially uneven. The evidence shows acceptable flow, velocity, and pressure-head values in most parts of the system, while also revealing lower pressure-head margins in the upper and peripheral branches and comparatively high-pressure heads in the lower zones.

3.1 Hydraulic Performance Results

Table 2 shows that simulated flows (0.33–9.98 L/s), velocities (0.21–1.26 m/s), and pressure-head compliance

Table 4. Overall hydraulic model performance statistics.

Indicator	Calibration	Validation	Interpretation
MAE (m)	7.05	3.88	Validation error is lower than calibration error
RMSE (m)	8.88	4.58	Validation fit is stronger than calibration fit
R^2	0.967	0.991	Very strong agreement between observed and simulated pressures

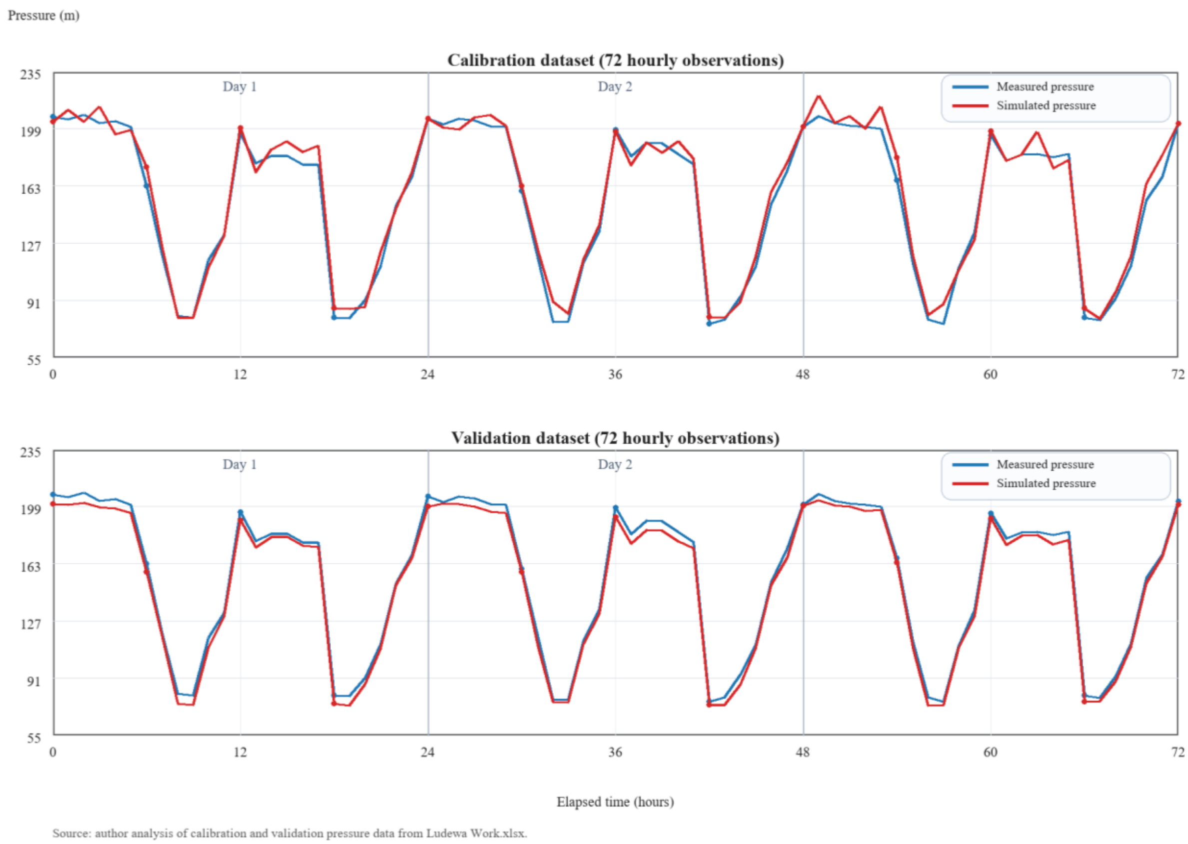


Figure 3. Calibration and validation pressure-head series for representative upper-elevation node PL355. The graph compares observed and simulated pressure head (m) over the 72-hour monitoring period.

are generally acceptable. The low end of the velocity range indicates weaker circulation in a few sections, while the high-pressure head in lower zones suggests the need for pressure management to reduce leakage and pipe stress. Therefore, the system is adequate under current conditions, but not uniformly resilient. The lowest velocities (around 0.21 m/s) fall below the approximately 0.3 m/s often recommended to limit sediment deposition in distribution mains; these low values occur mainly at terminal, low-demand branches where some stagnation is expected, and Ludewa WSSA should consider periodic flushing of these sections as a precaution. By contrast, the upper end of the range (1.26 m/s) remains well within normally acceptable limits (commonly up to 1.5–2.0 m/s) and is not itself a sign of excessive hydraulic stress; it was treated in this study as an indicator of the

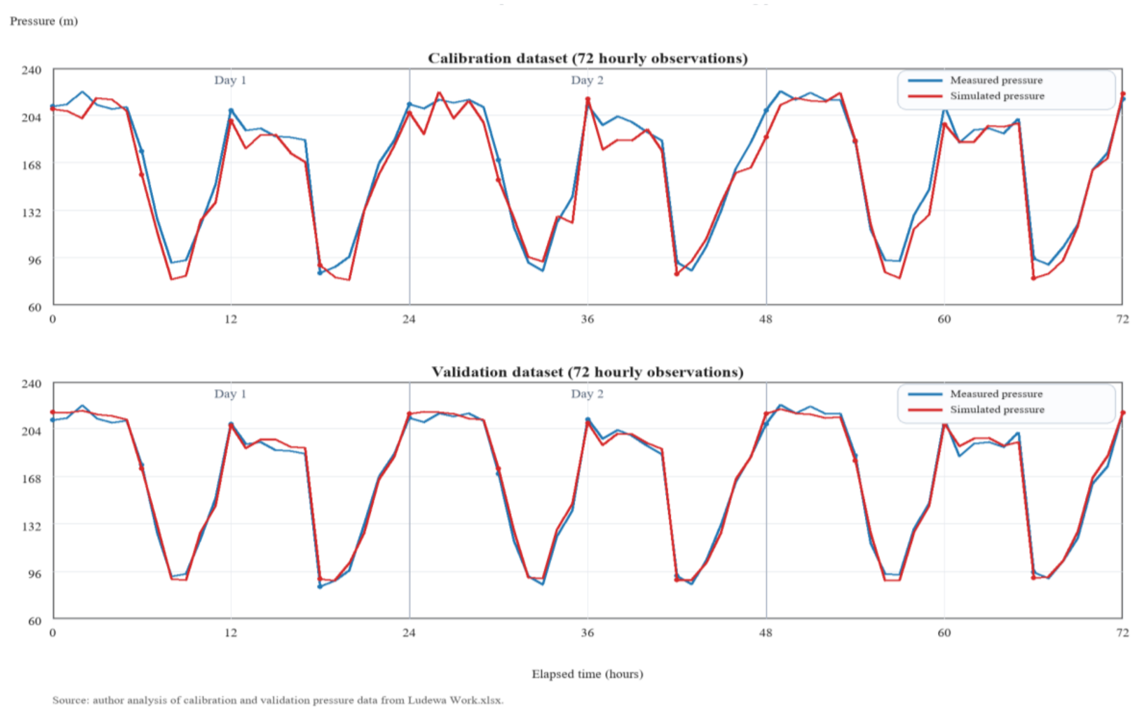


Figure 4. Calibration and validation pressure-head series for representative middle-elevation node PL400. The graph compares observed and simulated pressure head (m) over the 72-hour monitoring period.

busier, better-circulated portions of the network rather than a concern requiring intervention.

Table 3 confirms the elevation effect. PL355, located at the highest elevation, recorded the lowest mean pressure head; PL400 showed intermediate pressure head; and PL540, at a lower elevation, recorded the highest-pressure head. This pattern aligns with the expected behavior of gravity-fed systems (Ministry of Water, 2020) and indicates that topography is the primary control on pressure-head distribution in Ludewa. The values of 154.52–172.51 m should therefore be read as residual pressure head in meters of water column. They exceed the adopted 10 m minimum service threshold and, in lower zones, point to overpressure risk rather than pressure deficiency. Residual pressure heads above roughly 150 m are high for a distribution network; most utilities aim to cap operating pressure in the range of 60–70 m to limit leakage and pipe bursts (Twort et al., 2000). At the magnitudes recorded at PL540 (172.51 m), sustained overpressure can accelerate joint and gasket fatigue, increase the likelihood of pipe bursts, and raise stress on consumer-side plumbing and fittings that were not designed for such heads. Pressure-reducing valves, break-pressure tanks at key elevation breaks, and formal pressure zoning are the standard management options for this condition and are recommended for the lower-elevation branches identified here.

Table 4 shows strong model performance. Validation improved from calibration, with MAE decreasing from 7.05 m to 3.88 m, RMSE decreasing from 8.88 m to 4.58 m, and R^2 increasing from 0.967 to 0.991. These results support the use of the calibrated model for planning and scenario testing, consistent with model-calibration guidance by Zanfei, A., Menapace, A., Santopietro, S., & Righetti, M. (2020). and Kepa, U. (2021).

3.2 Model Calibration and Validation

Figures 3 to 5 show that simulated and measured pressure heads follow similar 72-hour patterns at the upper, middle, and lower representative nodes. The model captures both the magnitude and timing of the daily pressure-head cycles, which is important in gravity-fed systems where mean pressure head alone may hide operational stress.

Figure 3 presents PL355, the upper-elevation node. The model captures the main cyclical pressure reductions, confirming that the most hydraulically sensitive zone is represented adequately.

Figure 3. Calibration and validation pressure-head series for representative upper-elevation node PL355. The graph compares observed and simulated pressure head (m) over the 72-hour monitoring period. The calibration segment (used to adjust roughness and demand assumptions) and the validation segment (an independent portion of the monitoring record held out for

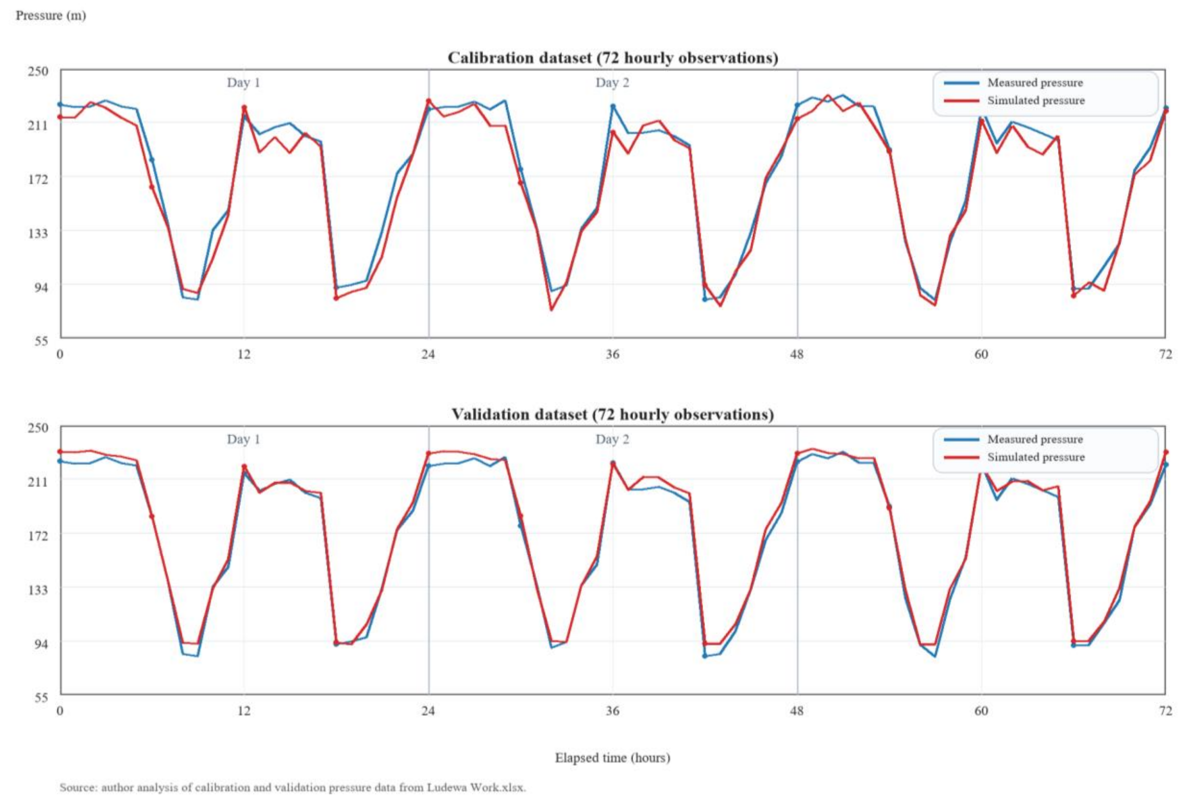


Figure 5. Calibration and validation pressure-head series for representative lower-elevation node PL540. The graph compares observed and simulated pressure head (m) over the 72-hour monitoring period.

testing) are distinguished within the plotted series.

Figure 4 presents PL400, the middle-elevation node. The measured and simulated curves follow the same daily pattern, showing that the model represents the central part of the network without relying only on the extreme upper or lower pressure zones.

Figure 4. Calibration and validation pressure-head series for representative middle-elevation node PL400. The graph compares observed and simulated pressure head (m) over the 72-hour monitoring period. As in Figure 3, the calibration and validation segments of the monitoring record are distinguished within the plotted series.

Figure 5 presents PL540, the lower-elevation node. The close fit, together with the small validation bias in Table 3, shows that the model also performs well in the higher-pressure part of the system.

Figure 5. Calibration and validation pressure-head series for representative lower-elevation node PL540. The graph compares observed and simulated pressure head (m) over the 72-hour monitoring period. As in Figures 3 and 4, the calibration and validation segments of the monitoring record are distinguished within the plotted series.

3.3 Pressure-Head Distribution and Spatial Vulnerability

When Table 2, Table 3 and Figures 3 to 5 are considered together, Ludewa does not show generalized hydraulic failure. Instead, the network is functional but spatially uneven. Upper and peripheral branches have smaller pressure-head margins and are more vulnerable to demand growth, whereas lower zones require pressure management due to their comparatively high-pressure head. The likely causes of local vulnerability are branch position, pipe diameter and head loss. Interpreting Table 2 together with the network layout in Figure 2 suggests that smaller peripheral pipes, including 63 mm branches, can lose pressure head rapidly as demand grows. This agrees with Hashemi et al. (2020), who showed that pipe size and location strongly influence unit head loss in distribution systems. Using residual pressure-head margin above the 10 m threshold, together with pipe diameter and branch position, as the ranking criteria, the upper-elevation branches served by 32–63 mm pipes around and beyond PL355 are identified as the highest-priority segments for reinforcement, since they combine the smallest margins with the smallest diameters. Figure

Table 5. Prioritized operational and investment actions arising from the hydraulic assessment.

Priority	Recommended action	Responsible institution	Implementation horizon	Expected performance indicator
High	Upgrade undersized high-elevation and peripheral branches	Ludewa WSSA with district/sector support	Short to medium term	Improved residual pressure head and fewer low-margin service areas
High	Coordinate pressure management with leakage control in lower zones	Ludewa WSSA operations team	Short term	Reduced leakage, fewer bursts, and lower asset stress
Medium	Maintain routine monitoring at upper, middle, and lower sentinel nodes	Ludewa WSSA operations and planning units	Immediate and continuous	Updated pressure-head records and earlier detection of deterioration
Medium	Use the calibrated EPANET model for scenario testing before investment	Ludewa WSSA planning team and technical partners	Continuous planning cycle	Better prioritization of pipe upgrades, storage changes, and demand-growth responses
Medium	Link hydraulic reinforcement with storage and source planning	Ludewa WSSA, district authority, and Ministry/sector partners	Medium to long term	Improved service continuity and resilience under future demand

2 should be read alongside this discussion to locate these branches spatially; a dedicated vulnerability map classifying nodes into pressure-head bands (for example, below 10 m, 10–30 m, and above 30 m, once denser node-level data are available) is recommended as a companion output in future monitoring rounds to make priority segments explicit beyond the three representative nodes reported here.

The calibrated model has practical value beyond its use in accuracy testing. Because Table 3, Table 4, and Figures 3 to 5-show consistent model fit across elevation zones, the model can be used to compare pipe upsizing, storage adjustments, demand growth, and pressure-management options. Kepa (2021) and Rashed et al. (2024) have reported similar use of calibrated EPANET models for operational analysis and redesign. The Ludewa results are consistent with those studies in showing that calibrated hydraulic models are most useful when they connect numerical outputs to operational decisions rather than merely reporting pressure values.

The pressure-head imbalance observed in Ludewa is also consistent with Tanzanian small-town design concerns because gravity-fed systems in hilly terrain can satisfy minimum pressure requirements in most areas while simultaneously producing excessive pressure in low-elevation zones. The adopted 10 m threshold is therefore a minimum-service benchmark, not an upper operating target. For Ludewa, the management challenge is to protect adequate residual pressure in upper branches while reducing leakage and asset stress in lower zones.

Compared with GIS-EPANET studies in Algeria and Iraq (Abdelbaki et al., 2017; Rashed et al., 2024), the Ludewa case shows the same value of combining spatial network representation with hydraulic simulation. The GIS component helps explain why vulnerable nodes are not randomly distributed: they are shaped by elevation, peripheral branch length, and pipe diameter. This reinforces the need for geographically targeted investment

rather than uniform network-wide intervention.
However, the EPANET analysis is demand-driven, so the model should be used primarily to compare relative weaknesses and planning options, not to guarantee that all customer demands are fully met under low-pressure conditions. This caution is consistent with pressure-deficient modelling studies by Seyoum, A. G., & Tanyimboh, T. T. (2016), Seyoum, and Tanyimboh (2016).
Overall, the tables and figures show a hydraulically adequate but uneven system. The priority is therefore targeted action: reinforce high- and peripheral-branch systems, manage overpressure in lower zones, reduce leakage, and continue monitoring representative pressure points.

3.4 Practical Implications and System Recommendations

Table 5 translates the findings into prioritized practical actions. First, hydraulic reinforcement should be targeted to high-elevation and peripheral branches, especially those served by smaller diameters and those likely to absorb future connection growth.
Second, pressure management and leakage control should be implemented together. Lower-zone overpressure can intensify leakage and increase pipe stress, while upper branches require sufficient residual head to maintain reliable service.
Third, routine pressure monitoring and continued use of the calibrated EPANET model are needed. Monitoring sentinel nodes will indicate whether the hydraulic gradient is changing, while the model can evaluate demand growth, pipe upgrades, storage, and pressure management scenarios before investment decisions are made.

4. Conclusion and Recommendations

Evaluating pressure-head adequacy, supporting hydraulic indicators, and model reliability addressed the study objectives. The Ludewa Township distribution network is generally hydraulically adequate under current operating conditions. Simulated flows of 0.33–9.98 L/s, velocities of 0.21–1.26 m/s, and pressure-head compliance exceeding the adopted 10 m minimum threshold indicate that the gravity-fed system can currently distribute water effectively across most of the service area.
The main hydraulic constraint is spatial imbalance rather than system-wide failure. Upper and peripheral branches have lower residual pressure-head margins and are more exposed to future demand growth, while lower-elevation zones experience high pressure heads that may increase leakage, bursts, and asset stress if unmanaged. These results confirm the importance of interpreting pressure head together with elevation, pipe diameter, branch position, velocity, and head loss. In quantitative terms, nodes with residual pressure head approaching or exceeding about 150 m, as observed at PL540 (172.51 m) and PL400 (165.96 m), should be prioritized for pressure-reducing valves or break-pressure tanks, while branches served by smaller-diameter pipes (32–63 mm) with the least residual margin above the 10 m minimum, concentrated around the upper-elevation PL355 zone, should be prioritized for reinforcement.
The recommended management pathway is targeted rather than uniform. Ludewa should prioritize reinforcement of smaller-diameter vulnerable branches and pressure zoning in lower zones, routine monitoring at representative pressure locations, and continued use of the calibrated EPANET model for scenario-based planning. Because no leakage or water-balance measurements were collected in this study, leakage control in lower zones is recommended here as a next step supported by the pressure evidence, rather than as an action justified by direct leakage data; a basic water-balance or leak-detection survey is recommended before major leakage-control investment. These measures would protect current hydraulic performance while preparing the network for demand growth and future operational change.

Acknowledgement

The authors acknowledge the support of the Water Institute, the Ludewa WSSA staff, the Ludewa Township stakeholders, and the field personnel who provided information and technical guidance during the study's preparation.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

All relevant data used for the hydraulic assessment are included in the paper or are available from the corresponding author upon reasonable request, subject to institutional data-sharing procedures.

Authors' Contribution

Enock W. Ngoyinde: conceptualization, field data collection, hydraulic modelling, data analysis, interpretation, and manuscript drafting. **Irene Aurelia Trimo**: supervision, methodology review, technical guidance, and manuscript review and editing. **Edmund Ishengoma Mutayoba**: supervision, hydraulic interpretation, technical validation, and manuscript review and editing. All authors reviewed and approved the final manuscript.

References

1. Abdelbaki, C., Benchaib, M. M., Benziada, S., Mahmoudi, H., & Goosen, M. (2017). Management of a water distribution network by coupling GIS and hydraulic modeling: A case study of Chetouane in Algeria. Applied Water Science, 7, 1561-1567. https://doi.org/10.1007/s13201-016-0416-1

2. Hashemi, S., Filion, Y., Speight, V., & Long, A. (2020). Effect of pipe size and location on water-main head loss in water distribution systems. Journal of Water Resources Planning and Management, 146(6), 06020006. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001222

3. Kepa, U. (2021). Use of the hydraulic model for the operational analysis of the water supply network: A case study. Water, 13(3), 326. https://doi.org/10.3390/w13030326

4. Kabange, R. S. (2024). Hydraulic evaluation of water supply and distribution systems: Case study of Lawra township water supply system in the Upper-West Region of Ghana. Journal of the Ghana Institution of Engineering.

5. Kitavile, C., Swilla, L., & Mutayoba, E. (2026). Developing a hydraulic EPANET model for the Mwengemshindo water distribution network in Songea municipality, Ruvuma, Tanzania. Journal of Applied Sciences and Environmental Management, 30(6), 1968–1975.

6. Ministry of Water. (2020). Design, construction supervision, operation and maintenance (DCOM) manual: Volume I, Design of water supply projects (4th ed.). Government of the United Republic of Tanzania. https://design.maji.go.tz/

7. Rashed, M., Faris, M., & Omar, N. (2024). Hydraulic analysis study and redesign of the water distribution system simulation using GIS-EPANET, case study: Laylan sub-district, Kirkuk City, Iraq. Anbar Journal of Engineering Science, 15(1), 1-16. https://doi.org/10.37649/aengs.2024.144890.1066

8. Seyoum, A. G., & Tanyimboh, T. T. (2016). Investigation into the pressure-driven extension of the EPANET hydraulic simulation model for water distribution systems. Water Resources Management, 30, 5351-5367. https://doi.org/10.1007/s11269-016-1492-6

9. Twort, A. C., Ratnayaka, D. D., & Brandt, M. J. (2000). Water supply (5th ed.). Arnold and IWA Publishing.

10. United States Environmental Protection Agency. (2025). EPANET: Application for modeling drinking water distribution systems. https://www.epa.gov/water-research/epanet (2025 reflects the access date for this webpage, which documents EPANET 2.2, the version used for the simulations in this study; the original modelling manual is cited separately as Rossman, 2000)

11. World Health Organization. (2017). Guidelines for drinking-water quality: Fourth edition incorporating the first addendum. World Health Organization. https://iris.who.int/handle/10665/254637

12. World Health Organization. (2022). Guidelines for drinking-water quality: Fourth edition incorporating the first and second addenda. World Health Organization. https://iris.who.int/handle/10665/352532

13. World Health Organization. (2024). Guidelines for drinking-water quality: Small water supplies. World Health Organization. https://iris.who.int/handle/10665/375822

14. Zanfei, A., Menapace, A., Santopietro, S., & Righetti, M. (2020). *Calibration procedure for water distribution systems: Comparison among hydraulic models*. Water, 12(5), 1421.