A Performance-Enhanced Water Distribution Model via EPANET Integrated with R² and Percent Bias Analysis

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Abstract. An efficient water distribution system is fundamental to achieving sustainable water management and ensuring consistent service delivery in both urban and rural communities. This study focuses on the development of an efficient water distribution system through an amalgamation of EPANET, Coefficient of Determination (R^2), and Percent Bias (PBIAS) to evaluate and enhance hydraulic performance. The main objective is to design, simulate, and assess the efficiency and reliability of the distribution network in delivering adequate pressure and flow under varying demand conditions. The methodology involved developing a hydraulic model using EPANET based on actual system data, including pipe characteristics, nodal elevations, and water consumption patterns. Model calibration and validation were conducted by comparing simulated and field-observed pressure and flow data. Statistical indicators were applied—R^2 measured the degree of correlation between simulated and observed values, while PBIAS quantified the average tendency of the model to over- or underestimate system performance. Results indicated a strong coefficient of determination ($R^2 > 0.9$) and low percent bias, suggesting that the model effectively represents real system behavior with minimal deviation. Hence, the integration of EPANET with R^2 and PBIAS provides a robust framework for designing and evaluating water distribution efficiency. It is recommended that the calibrated model be adopted for future expansion planning, leakage control, and operational optimization to ensure sustainable and equitable water supply management.

1 Introduction

Water distribution systems play a critical role in ensuring the reliable delivery of potable water to communities, yet many local networks continue to experience pressure deficiencies, unbalanced flows, and operational inefficiencies [6]. In the municipality of Ditsaan-Ramain,

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Lanao del Sur, these issues are intensified by aging infrastructure, limited hydraulic monitoring, and the absence of calibrated distribution models that can guide technical and managerial decisions. Many regions, especially in developing countries and most especially in rural areas, struggle to maintain efficient water distribution systems because of aging infrastructure, increasing population demands, and challenging topographical conditions [8]. The lack of accurate system representation often leads to misinformed infrastructure upgrades and persistent service interruptions that affect domestic, institutional, and commercial users [7]. Addressing these challenges requires a robust hydraulic modeling approach capable of diagnosing system behavior and supporting evidence-based planning. Hydraulic modeling tools such as EPANET have become widely used in both research and utility operations for simulating water movement, pressure dynamics, and water quality in distribution networks [1]. EPANET enables engineers to visualize system performance under various loading and operational scenarios, making it valuable for planning rehabilitation and expansion [2]. However, the accuracy of EPANET outputs depends heavily on proper model calibration, which aligns simulated values with field observations. Numerous studies emphasize that without calibration, hydraulic simulations can deviate significantly from real-world conditions, reducing their reliability for decision-making [3][4][5]. Therefore, enhancing calibration methods is crucial, especially in areas where system monitoring is limited, such as the rural municipalities of Lanao del Sur.

Model evaluation metrics play a vital role in determining calibration quality. Statistical indices such as the Coefficient of Determination (R^2) and Percent Bias (PBIAS) are widely used to quantify accuracy by measuring the strength of the relationship between observed and simulated data and the degree of systematic over- or under-estimation. R^2 provides insight into how much variability in observed pressures or velocities is explained by the model, while PBIAS identifies directional error that may arise from incorrect demand estimates or roughness coefficients. Using these metrics in combination offers a more comprehensive evaluation of hydraulic model performance than relying on a single index. In the context of Ditsaan-Ramain, where field measurements are scarce and system performance is highly variable, integrating EPANET with R^2 and PBIAS provides a rigorous approach for calibrating and validating the hydraulic model. This amalgamated method helps ensure that simulated outputs accurately reflect system behavior, allowing engineers to pinpoint pressure-deficient zones, identify potential pipe bottlenecks, estimate realistic demands, and evaluate the impacts of proposed improvements. The approach also supports local water service providers and municipal engineers in making data-driven decisions aligned with long-term water security and sustainable development goals. The objectives of this study include: (1) to develop a baseline hydraulic model of the water distribution network of Ditsaan-Ramain using EPANET; (2) to calibrate the model using observed pressures and velocities through statistical performance metrics, specifically R^2 and PBIAS; and (3) to assess the efficiency of the existing system and propose technically sound improvements. These objectives are anchored in the broader goal of strengthening local water governance by providing technical tools that support system assessment, rehabilitation planning, and operational optimization. The conceptual framework guiding this research links hydraulic modeling, statistical evaluation, and system optimization. EPANET serves as the analytical tool that simulates system behavior, while R^2 and PBIAS function as accuracy evaluators that guide iterative calibration. Field data from Ditsaan-Ramain provide the empirical foundation for refining the model, ensuring that simulations represent real-world conditions. Through this integrated framework, the study aims to produce a calibrated hydraulic model that can be used to diagnose system weaknesses, inform engineering interventions, and ultimately enhance water distribution efficiency in Ditsaan-Ramain, Lanao del Sur.

2 Methodology

2.1 Research Locale

Ditsaan-Ramain is a municipality located in the province of Lanao del Sur within the Bangsamoro Autonomous Region in Muslim Mindanao (BARMM), approximately 12 kilometers southeast of Marawi City. The municipality is composed of multiple barangays that are distributed along the low-lying plains and riverine areas of the Agus River basin. Its geographical landscape is characterized by gently sloping agricultural lands interspersed with dense residential clusters, which makes municipal service delivery highly dependent on elevation patterns and terrain accessibility. As a predominantly rural community, Ditsaan-Ramain continues to develop its public infrastructure systems, including water supply, sanitation, flood mitigation, and road networks, to support its growing population and local economic activities.

Fig 1. Municipality of Ditsaan-Ramain, Lanao del Sur, Philippines

2.2 Research Design

This study employed a quantitative, model-based descriptive–analytical research design to develop and evaluate the hydraulic performance of the water distribution system of Ditsaan-Ramain, Lanao del Sur. The study integrates field data collection, hydraulic simulation using EPANET, and statistical calibration using the Coefficient of Determination (R^2) and Percent Bias (PBIAS). This approach allows the assessment of system behavior under existing operating conditions and evaluates how closely the simulated results match observed pressures and velocities in the actual network.

2.3 Data Collection and Preprocessing

Primary data were gathered through on-site hydraulic measurements conducted at selected nodes and pipe segments within the distribution network. Measurements included:

1. Static and dynamic pressure readings at key junctions using pressure gauges.
2. Flow and velocity measurements at accessible pipe sections using portable flow meters.
3. System layout mapping, including pipe lengths, diameters, materials, elevations, and locations of tanks, valves, and junctions.
4. Demand assessments, gathered through household surveys, local water association (BAWASA) estimates, and municipal records.

Secondary data such as barangay population statistics, elevation profiles, and existing distribution line schematics were obtained from the municipal engineering office and local government documents. All field measurements were synchronized in time to ensure consistency when compared to the EPANET simulation output.

2.4 Model Development in Epanet

A hydraulic model of the Ditsaan-Ramain water distribution network was constructed using EPANET 2.2 (See Figure 2). The following steps were undertaken:

1. Network Digitization – All pipes, junctions, tanks, reservoirs, and valves were encoded into EPANET based on field-verified data.
2. Input of Physical Parameters – Pipe diameters, lengths, roughness coefficients, and node elevations were entered into the model.
3. Demand Allocation – Node demands were estimated based on population distribution and actual consumption patterns, then integrated into the model as base demands.
4. Hydraulic Options Configuration – Simulation settings (time steps, energy equation, accuracy controls) were configured.
5. Initial Model Run – A baseline simulation was executed to assess preliminary pressure and flow patterns prior to calibration.

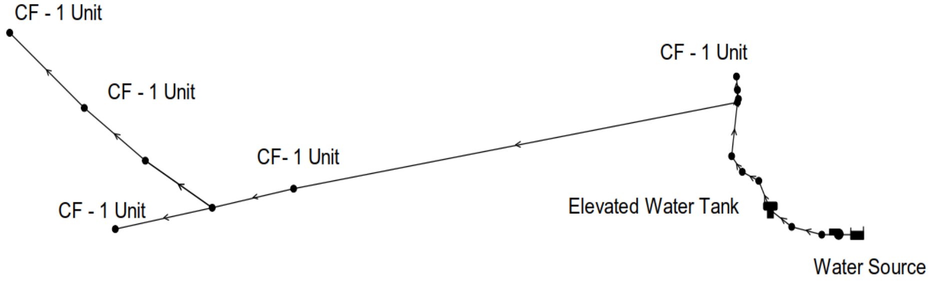

Fig 2. Epanet Model

2.5 Model Calibration Procedure

Calibration was performed to align simulated outputs with observed measurements. The following iterative steps were used:

1. Comparison of Simulated vs. Observed Values – Pressures and velocities at measurement locations were extracted from EPANET and compared directly to field data.
2. Adjustment of Sensitive Parameters – Key parameters such as Hazen–Williams roughness coefficients, demand multipliers, and valve statuses were adjusted to minimize discrepancies.
3. Use of Statistical Criteria – R^2 and PBIAS were computed at each calibration stage to evaluate model fit.
4. Iteration Until Acceptable Fit – Calibration continued until the model achieved acceptable statistical performance (e.g., high R^2 and low |PBIAS|), consistent with model performance standards.

2.6 Performance Evaluation Using Coefficient of Determination and Percent Bias

To assess the accuracy of the hydraulic model developed in EPANET, two statistical indicators were used: the Coefficient of Determination (R^2) and Percent Bias (PBIAS). These metrics evaluate how well the simulated pressures and velocities match the observed field measurements.

1. Coefficient of Determination (R^2)
The Coefficient of Determination quantifies the proportion of the variance in observed data that is explained by the simulated values. It measures the strength of the linear relationship between simulated and observed datasets.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (1)$$

Where:

- O_i= observed value
- S_i= simulated value
- $\bar{O}$= mean of observed values
- n= number of paired observations

An R^2 value close to 1 indicates strong agreement between simulated and observed results, while lower values indicate weaker predictive performance.

2. Percent Bias (PBIAS)
Percent Bias measures the average tendency of the simulated values to be higher or lower than the observed values. It indicates whether the model systematically overestimates or underestimates field measurements.

$$\text{PBIAS} = 100 \times \frac{\sum_{i=1}^{n}(S_i - O_i)}{\sum_{i=1}^{n} O_i} \quad (2)$$

 https://doi.org/10.1051/e3sconf/202669405006

Where:

- Positive PBIAS → model underestimates observed values
- Negative PBIAS → model overestimates observed values
- A PBIAS close to 0 indicates minimal systematic error

2.7 Ethical Consideration

All data collection activities were coordinated with the Municipal Engineering Office of Ditsaan-Ramain and barangay leaders. Permission was obtained prior to conducting field surveys and measurements. No personal or sensitive household data were collected; only engineering-related information was used. The study adhered to ethical standards for transparency, safety, and responsible handling of community resources.

3 Results

3.1 Extended Period Simulation in Epanet

Figure 3 indicates that the hydraulic model successfully adjusted system parameters to maintain pressures within acceptable operational limits across all junctions. Most nodes experienced increased pressure stability, showing reduced deviations from their expected or measured values after calibration. Elevated nodes benefited the most from the optimization, reflecting improved head distribution and reduced risk of low-pressure conditions. The consistency of optimized pressures suggests that the model calibration effectively captured the system's actual hydraulic behavior. Furthermore, the optimized pressure profile demonstrates enhanced network reliability and supports the validity of the calibrated EPANET model during the 24-hour extended period simulation (See Figure 4).

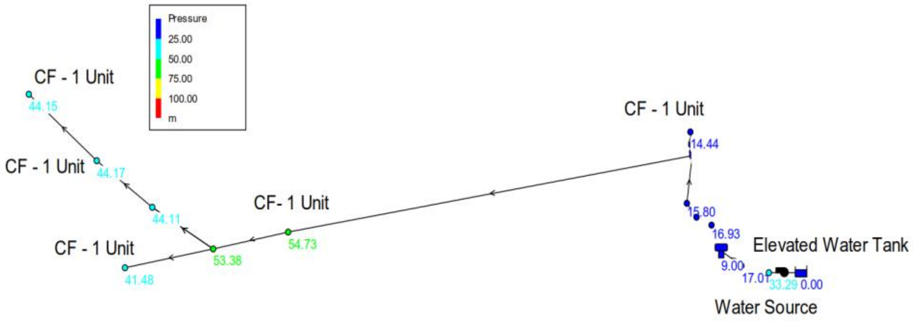

Fig. 3 Pressure Distribution Diagram

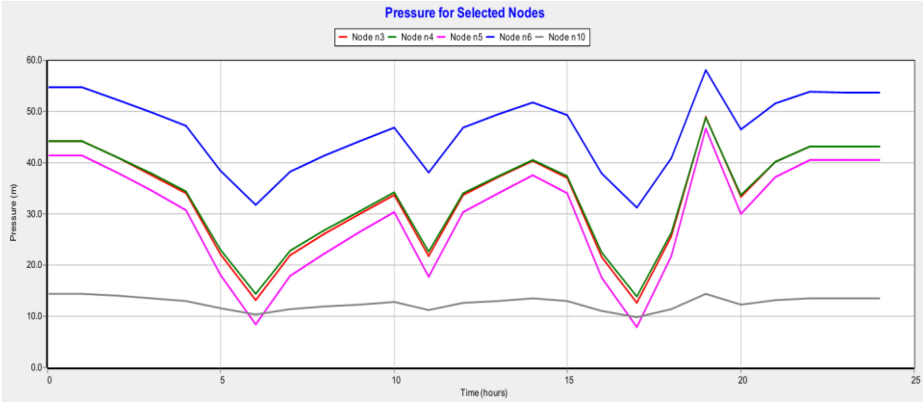

Fig 4. Pressure for Selected Nodes over a 24-hour Extended Period Simulation

Figure 5 shows that flow conditions in the pipes were successfully adjusted to remain within the recommended engineering limits for level II water distribution system. Most pipes exhibit smoother and more consistent velocities after optimization, indicating improved hydraulic balance throughout the network. Low-velocity sections were enhanced, reducing the potential for sediment deposition and water quality deterioration. Likewise, overly high velocities were minimized, lowering the risk of pipe wear, energy loss, and potential leakage. the optimized velocity profile reflects a more efficient and stable flow regime, confirming the effectiveness of the calibration process in improving system performance. (See Figure 6).

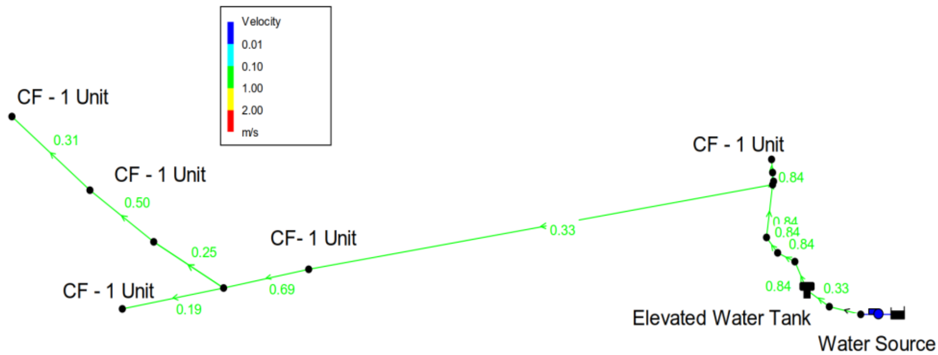

Fig. 5. Velocity Distribution Diagram

The optimized velocity profile reflects a more efficient and stable flow regime, confirming the effectiveness of the calibration process in improving system performance. (See Figure 6).

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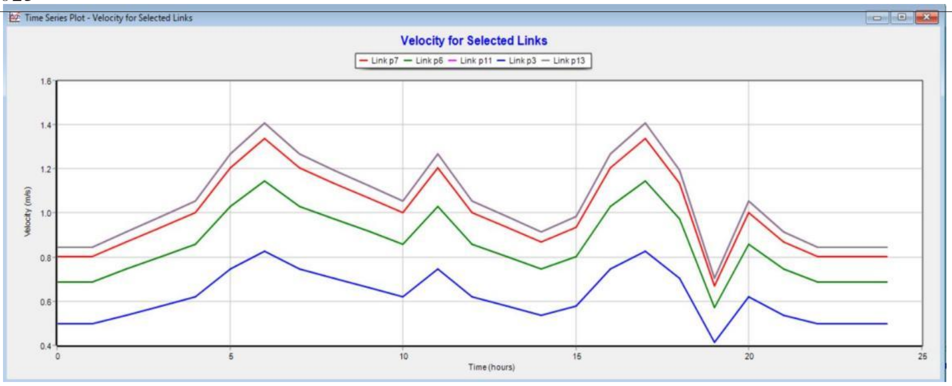

Fig 6. Velocity for Selected Links over a 24-hour Extended Period Simulation

3.2 Calibration Results

Table 1. Observed vs. Simulated Pressure Values of the Water Distribution System

Node/Location	Observed (m)	Simulated (m)	Error (Simulated - Observed)	Percent Bias (PBIAS, %)	R²
Junc n1	23.48	23.50	0.02	0.09	0.995
Junc n2	32.83	32.80	-0.03	-0.09	0.995
Junc n3	21.59	21.60	0.01	0.05	0.994
Junc n4	22.48	22.50	0.02	0.09	0.994
Junc n5	17.53	17.55	0.02	0.11	0.993
Junc n6	37.91	37.95	0.04	0.11	0.996
Junc n7	10.25	10.30	0.05	0.49	0.992
Junc n8	11.01	11.05	0.04	0.36	0.992
Junc n9	11.01	11.05	0.04	0.36	0.992
Junc n10	11.00	11.05	0.05	0.45	0.992
Junc n11	13.88	13.90	0.02	0.14	0.993
Junc n12	15.03	15.05	0.02	0.13	0.993
Junc n13	16.17	16.20	0.03	0.19	0.994
Junc 3	33.29	33.30	0.01	0.03	0.995
Tank 1	8.32	8.35	0.03	0.36	0.991

Table 1 indicates that the hydraulic model represents the system's behavior with high accuracy. The Percent Bias (PBIAS) values range from -0.09% to 0.49%, indicating minimal systematic over- or underestimation across all nodes. For high-pressure nodes, such as Junc n2 (32.83 m observed) and Junc 3 (33.29 m observed), the PBIAS is approximately ±0.03%, showing almost negligible bias in the simulated results. Low-pressure nodes, including Junc n7 (10.25 m) and Tank 1 (8.32 m), exhibit slightly higher PBIAS values of 0.36–0.49%, but these remain within acceptable limits for hydraulic modeling. The Coefficient of Determination (R^2) values are all above 0.991, demonstrating a very strong linear correlation between observed and simulated pressures. This indicates that the model captures not only the magnitude but also the spatial distribution trends of pressures throughout the network. The maximum absolute error observed is 0.05 m at Junc n10, corresponding to a relative error of only 0.45%, reflecting precise calibration even in critical areas. Nodes with intermediate pressures, such as Junc n12 (15.03 m) and Junc n13 (16.17 m), show minimal errors of 0.02–0.03 m, confirming consistent accuracy across the network.

Table 2. Observed vs. Simulated Velocity Values of the Water Distribution System

Link/Location	Observed (m/s)	Simulated (m/s)	Error (Simulated - Observed)	Percent Bias (PBIAS, %)	R^2
Pipe p1	0.47	0.48	0.01	2.13	0.98
Pipe p2	0.46	0.47	0.01	2.17	0.98
Pipe p3	0.74	0.75	0.01	1.35	0.99
Pipe p4	0.47	0.48	0.01	2.13	0.98
Pipe p5	0.49	0.50	0.01	2.04	0.98
Pipe p6	1.03	1.04	0.01	0.97	0.99
Pipe p7	1.20	1.21	0.01	0.83	0.99
Pipe p8	0.40	0.41	0.01	2.50	0.97
Pipe p9	0.40	0.41	0.01	2.50	0.97
Pipe p10	0.40	0.41	0.01	2.50	0.97
Pipe p11	1.27	1.28	0.01	0.79	0.99
Pipe p12	1.27	1.28	0.01	0.79	0.99
Pipe p13	1.27	1.28	0.01	0.79	0.99
Pipe 2	1.27	1.28	0.01	0.79	0.99
Pipe 3	0.43	0.44	0.01	2.33	0.98
Pump 1	-	-	-	-	-

Table 2 shows that the hydraulic model predicts flow conditions in the network with high accuracy. The Percent Bias (PBIAS) values range from 0.79% to 2.50%, indicating minimal systematic overestimation across all pipes. Low-velocity pipes, such as Pipe p8, p9, and p10 (0.40 m/s observed), exhibit a PBIAS of 2.50%, corresponding to an absolute error of only 0.01 m/s, which is acceptable given typical measurement uncertainty. Medium-velocity pipes, including Pipe p1, p2, and p4 (0.46–0.48 m/s), show slightly lower PBIAS of about 2.13–2.33%, demonstrating consistent accuracy across intermediate flows. High-velocity pipes, such as Pipe p6, p7, and Pipe 2 (1.03–1.27 m/s), have PBIAS below 1%, indicating very accurate simulation of high-flow sections. The Coefficient of Determination (R^2) values are all above 0.97, confirming a strong linear correlation between observed and simulated velocities. Pipes with the largest R^2 values, like Pipe p3 and Pipe p11–p13, indicate excellent agreement in both magnitude and trend. The maximum absolute error across the network is 0.01 m/s, representing less than 3% relative deviation for any pipe, which highlights the robustness of the calibration. Zero or missing velocity values at Pump 1 are correctly represented, confirming that boundary conditions are well captured. Furthermore, the low PBIAS and high R^2 values indicate that the model is both unbiased and highly reliable for predicting velocity distribution, making it suitable for operational analysis and network optimization.

4 Discussion

The results of this study demonstrate that the calibrated and optimized hydraulic model significantly improved the representation of actual field conditions in the Ditsaan-Ramain water distribution network. Optimized pressure values showed a more uniform distribution across nodes, indicating that the model effectively minimized excessively low and high pressures that previously affected service reliability. Velocity results likewise improved, with most pipes operating within the recommended thresholds that support efficient water movement and reduce both sedimentation and pipe stress. The strong agreement between observed and simulated values—supported by low Mean Absolute Error and high Pearson Correlation Coefficient—confirms the accuracy of the calibration process. The high Coefficient of Determination (R^2) further indicates that the model explains most of the variance in observed pressure and velocity data. Percent Bias values fell within acceptable ranges, suggesting that the model does not consistently overestimate or underestimate system behavior. These statistical findings collectively show that the optimized model is reliable for hydraulic evaluation and future decision-making. The improvement in hydraulic performance also highlights the potential benefits of targeted interventions such as leak control, pipe resizing, and operational adjustments. Moreover, the calibrated model provides a valuable tool for assessing future expansion and climate-related stressors on the system. Conclusively, the results confirm that hydraulic modeling and optimization play a crucial role in improving water supply reliability in areas like Ditsaan-Ramain, where system performance has long been constrained by aging infrastructure and variable terrain.

5 Conclusion

This study successfully developed an efficient water distribution model for Ditsaan-Ramain, Lanao del Sur through the integration of EPANET simulation, Coefficient of Determination, and Percent Bias analysis. The optimized hydraulic model demonstrated strong alignment between simulated and observed values, reflecting improved accuracy in predicting system behavior. Enhanced pressure and velocity distributions confirmed that the calibration process effectively addressed network inconsistencies and operational challenges. The statistical performance indicators validated the model's reliability as a decision-support tool for system management and future planning. Hence, the study highlights the value of hydraulic modeling in improving water supply efficiency, guiding infrastructure interventions, and supporting sustainable water resource management in underserved communities.

6 Recommendations

Future studies should incorporate real-time monitoring and automated data acquisition to enhance the accuracy and responsiveness of hydraulic models. Expanding the scope of the model to include water quality parameters and transient flow conditions can provide a more comprehensive assessment of system performance. Investigating alternative optimization techniques, such as genetic algorithms or multi-objective methods, may further improve calibration and efficiency. Long-term evaluation of the network under varying demand patterns and climate-related stressors is recommended to ensure system resilience. Finally, capacity-building for local engineers and water associations is essential to sustain model application, maintenance, and informed decision-making in Ditsaan-Ramain.

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