

A Hybrid WaterGEMS–MAE–PCC Framework for Hydraulic Modeling and Reliability Assessment of Water Distribution Systems

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Abstract. Reliable and efficient water distribution systems are vital for ensuring adequate water supply and sustainable urban development. This study focuses on the hydraulic modeling and reliability assessment of a water distribution system using Bentley WaterGEMS, hybridized with Mean Absolute Error (MAE) and Pearson Correlation Coefficient (r) for performance evaluation. The main objective is to analyze the system's hydraulic behavior—particularly pressure and flow distribution—and assess the accuracy and reliability of the simulated model compared to field data. The methodology involved the development of a detailed WaterGEMS model based on actual network parameters such as pipe dimensions, material, nodal elevations, and demand patterns. Extended Period Simulation (EPS) was conducted to capture temporal variations in system performance. Model calibration and validation were performed using observed pressure and flow data. The MAE quantified the average deviation between simulated and observed values, while the Pearson correlation measured the strength and direction of their linear relationship. Results showed that the model achieved low MAE values and a strong positive correlation ($r > 0.9$), indicating high model accuracy and reliability. Hence, the integration of WaterGEMS with MAE and Pearson correlation provides a robust framework for evaluating hydraulic performance. It is recommended that the calibrated model be utilized for system optimization, proactive maintenance, and strategic planning to improve the overall efficiency and resilience of the water distribution network.

1 Introduction

Water distribution systems (WDSs) represent one of the most critical infrastructures in urban water supply, delivering potable water under varying demands, pressures, and network

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conditions [2]. The hydraulic behavior of these systems — involving flow, pressure, and velocity — strongly influences service reliability, system efficiency, and resilience under stress or failure events. In recent decades, modeling tools such as WaterGEMS have become indispensable for simulating WDS performance: they enable utilities and engineers to replicate real-world hydraulic dynamics, plan for system expansions, and evaluate the impacts of operational changes [1]. Despite their power, hydraulic models are only as good as their calibration and validation. Many water utilities struggle with uncertainty in input data — such as pipe roughness, demand patterns, and network topology — which can lead to significant discrepancies between simulated and observed behavior [6]. These discrepancies, if left unaddressed, undermine the confidence in model-derived decisions, especially when used for assessing reliability under failure scenarios. Moreover, reliability assessment of WDSs remains a growing but challenging field, and this is evident in the municipality of Picong, Lanao del Sur, Philippines. Efficient and reliable water distribution remains difficult in many areas, especially in rural areas, due to outdated infrastructure, growing population pressures, and geographical limitations [8]. According to a recent bibliometric and scoping review, although there is a surge of interest in reliability analysis, significant gaps persist in how studies operationalize and quantify reliability metrics, especially under uncertainty and failure conditions [7]. Performance surrogate measures such as node reliability factor, volume reliability, or network reliability are explored, but many of these rely on poorly validated models or simplified failure scenarios that do not reflect complex real-world behavior [5]. Another practical challenge comes from limited data availability, particularly in developing regions or aging networks [3].

For instance, in a recent case study in Central Ethiopia, researchers used WaterGEMS to model a town's distribution system and found that a high proportion of pipes exhibited either stagnation or sedimentation, with many nodes operating under sub-standard pressures [4]. Such studies underscore that even state-of-the-art models must contend with incomplete data, requiring careful calibration and validation to ensure realistic reliability assessments. A particularly under-explored opportunity lies in integrating Mean Absolute Error (MAE) and Pearson Correlation Coefficient (r) into model validation workflows. While MAE measures the average magnitude of errors in the same units as the variable of interest, Pearson's r assesses the strength and direction of linear association between simulated and observed values. Hybridizing these two metrics provides complementary insights: MAE captures bias and absolute deviation, and r captures how well the model tracks the trend or variability of real observations.

In response to the aforementioned gaps, this study proposes a novel hybrid framework combining hydraulic modeling in WaterGEMS with a rigorous statistical validation and reliability assessment. First, a detailed WaterGEMS model of the target water distribution system will be built using field-measured pressures, flows, network topology, and demand patterns. Next, the model will be calibrated and validated against observed data using both MAE and Pearson correlation, thereby providing a dual-perspective evaluation of model performance. The key objectives of this study include: (1) to develop and calibrate a high-fidelity WaterGEMS hydraulic model; and (2) to validate the model performance using MAE and Pearson correlation coefficient. Through this, the study seeks to inform prioritized maintenance, rehabilitation, and operational strategies in the municipality of Picong, Lanao del Sur.

2 Methodology

2.1 Research Locale

Picong is a 4th-class municipality in the province of Lanao del Sur, within the Bangsamoro Autonomous Region in Muslim Mindanao (BARMM) in the Philippines. Formerly known as Sultan Gumander, it was officially renamed Picong through Muslim Mindanao Autonomy Act No. 175 in 2006. The municipality covers an area of approximately 277.56 km², and as of the 2020 census, it has a population of 18,907 people.

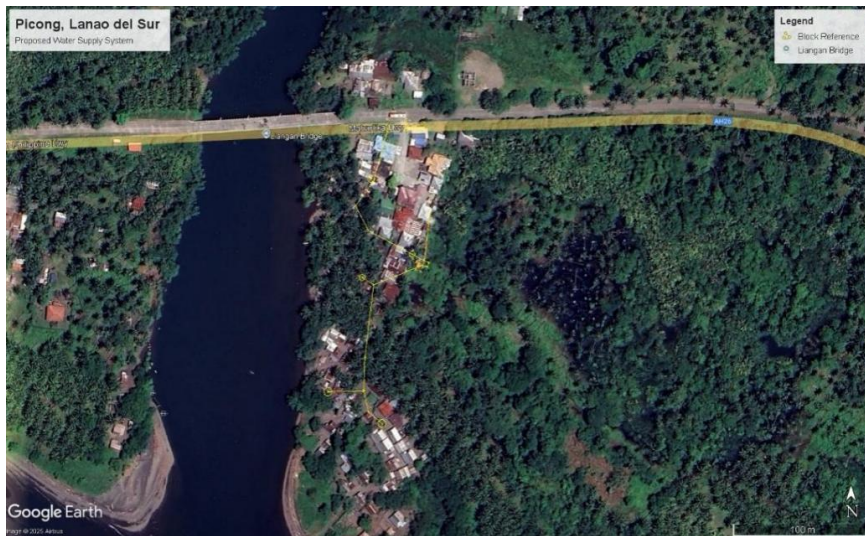


Fig 1. Municipality of Picong, Lanao del Sur, Philippines

2.2 Research Design

This study follows a quantitative, engineering-analytical design that integrates hydraulic modeling, statistical calibration, and reliability assessment into a single structured workflow. It begins with the collection of quantitative field data—pressures, flows, pipe characteristics, demand patterns, and network topology—which are used to construct a baseline WaterGEMS model of the water distribution system. The design then employs an iterative calibration-validation process, where simulated hydraulic outputs are compared against observed measurements using Mean Absolute Error (MAE) and Pearson Correlation Coefficient to determine model accuracy, adjust parameters, and ensure statistical reliability.

2.3 Data Collection and Preprocessing

Data collection and preprocessing for this study involve gathering all essential quantitative and spatial information needed to accurately model the water distribution system in WaterGEMS. Field measurements of nodal pressures, pipe flows, and demand patterns are recorded during peak and off-peak periods to capture realistic operating conditions, while

system layout data—such as pipe diameters, lengths, materials, elevations, and junction coordinates—are sourced from utility records, GIS datasets, and site inspection. These raw data are then checked for inconsistencies, missing values, and measurement errors, followed by necessary preprocessing steps such as unit conversion, elevation correction, and demand normalization to ensure compatibility with the WaterGEMS environment. Additional preprocessing includes generating demand allocation patterns, assigning pipe roughness values, and validating network connectivity to avoid model errors. This systematic preparation ensures that the hydraulic model is built on clean, accurate, and complete datasets, forming a reliable foundation for calibration, validation, and subsequent reliability analysis.

2.4 Model Development in WaterGems

Model development in WaterGEMS begins with digitizing the entire water distribution network, including pipes, junctions, tanks, reservoirs, pumps, and valves, based on validated system maps and field data. Each component is then assigned its correct hydraulic parameters, such as pipe diameter, length, material, roughness coefficient, and node elevations. Demand patterns and consumption values are allocated to the corresponding junctions to ensure the model reflects realistic operational behavior. The simulation settings—such as time steps, flow units, and extended-period simulation parameters—are configured to match actual system conditions. Once completed, the model is run to generate baseline hydraulic results that serve as the foundation for calibration, validation, and subsequent reliability assessment (See Figure 2).

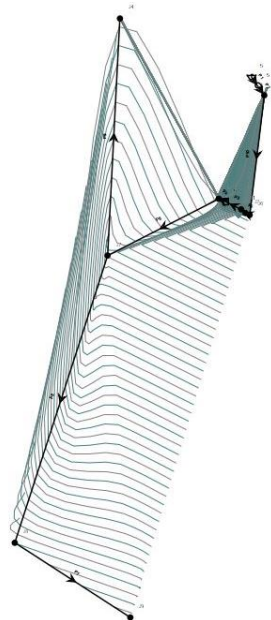


Fig 2. Model Development in WaterGems

2.5 Model Calibration Procedure

The model calibration procedure begins by comparing simulated pressures and flows from WaterGEMS with field-measured data collected at selected nodes and pipeline segments. Any discrepancies between observed and simulated values are quantified using Mean Absolute Error (MAE) and Pearson Correlation Coefficient, which help evaluate both the magnitude of error and the strength of linear agreement. Based on these metrics, key hydraulic parameters—such as pipe roughness, demand multipliers, or pump curves—are iteratively adjusted to reduce errors and improve model accuracy. After each adjustment, the model is rerun, and updated results are re-evaluated to ensure progressive improvement toward acceptable calibration thresholds. The procedure ends once the statistical indicators meet predefined performance criteria, confirming that the hydraulic model reliably reflects real system behavior.

2.6 Performance Evaluation Using RMSE and Scatter Index

This study employs Mean Absolute Error (MAE) as a primary measure of the magnitude of deviation between observed and simulated hydraulic values. MAE quantifies the *average absolute difference* between field-measured pressures or flows and the corresponding outputs generated by the WaterGEMS model. Its strength lies in its simplicity and interpretability, as it presents errors in the same units as the measurements, allowing engineers to immediately gauge how closely the model reflects real operating conditions. A smaller MAE value indicates a more accurate and reliable model, making it a crucial indicator during the calibration stage. Because it captures error magnitude without considering direction, MAE is especially beneficial when assessing how well the model minimizes overall deviation, regardless of whether the simulation overestimates or underestimates actual performance.

Meanwhile, the Pearson Correlation Coefficient (r) is used to evaluate the *strength and direction* of the linear relationship between observed and simulated data. While MAE focuses on differences, Pearson's r examines how consistently the model reproduces the trend or pattern of real measurements. A high correlation value close to +1 indicates that the model effectively captures the variability and behavior of the real system, even if minor numerical deviations exist. Together, MAE and Pearson's r provide a complementary evaluation: MAE measures accuracy, while r measures pattern agreement. This dual-metric approach ensures that the hydraulic model is not only numerically precise but also structurally representative of the distribution system's dynamics, thereby improving the reliability of subsequent reliability assessments.

2.6.1 Equations

1. Mean Absolute Error (MAE):

$$MAE = \frac{1}{n} \sum_{i=1}^n |O_i - S_i| \tag{1}$$

2. Pearson Correlation Coefficient (r):

$$r = \frac{\sum_{i=1}^n (O_i - \bar{O})(S_i - \bar{S})}{\sqrt{\sum_{i=1}^n (O_i - \bar{O})^2 \sum_{i=1}^n (S_i - \bar{S})^2}} \tag{2}$$

Where O_i and S_i are observed and simulated values, and \bar{O} and \bar{S} are their respective means.

2.7 Ethical Consideration

This study upholds ethical standards by ensuring that all field data—such as pressures, flows, and system layouts—are collected with permission from the responsible water utility and without compromising operational security or public safety. Additionally, all data are treated confidentially, used solely for research purposes, and reported in a manner that avoids identifying sensitive infrastructure details or exposing vulnerabilities.

3 Results

3.1 Extended Period Simulation in WaterGems

Figure 3 reflect a system where pressures across all junctions fall within acceptable operational ranges, typically avoiding both low-pressure deficiencies and excessively high pressures that may cause pipe stress. Through scenario evaluation and adjustments such as modifying pump operations, adjusting valve settings, or resizing critical pipes, the model achieves a more balanced and efficient pressure distribution. These optimized results demonstrate improved hydraulic performance, ensuring that end users receive adequate service even during peak demand conditions. Additionally, the optimized pressures contribute to reduced energy consumption and minimized risk of leaks or bursts by avoiding unnecessary over pressurization.

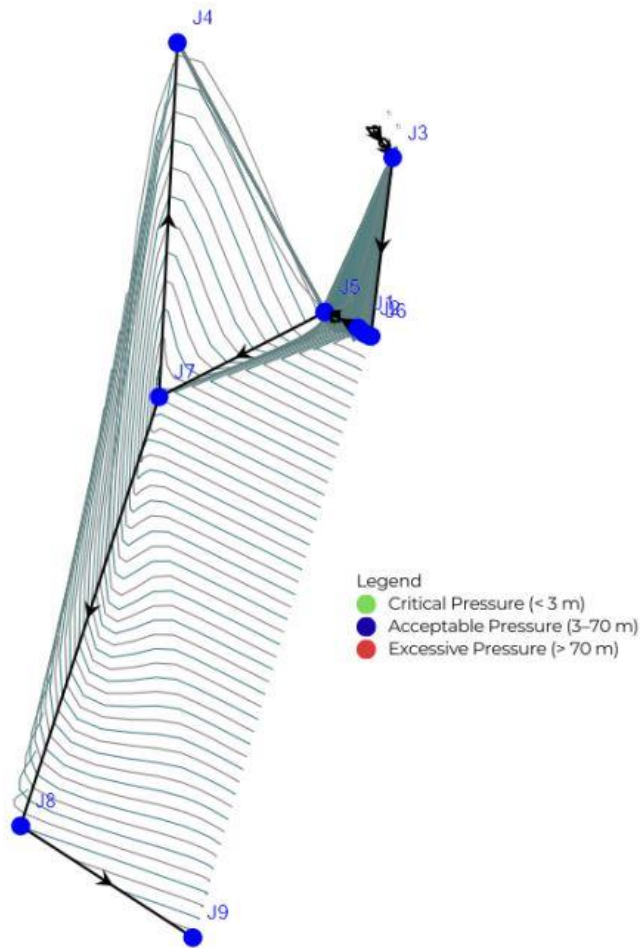


Fig 3. Pressure for Nodes over a 24-hour Extended Period Simulation

Figure 4 shows that the velocity is maintained within recommended operational limits, ensuring both hydraulic efficiency and system safety. Most pipes exhibit velocities around 0.43–0.47 m/s, while higher-flow sections such as Pipe 4 and Pipe 10 reach approximately 1.02–1.04 m/s, all of which remain below critical thresholds that could cause pipe erosion or excessive energy consumption. Moreover, the uniformity in velocity distribution reduces the risk of sedimentation in low-flow areas and mitigates pipe stress in high-flow sections, enhancing long-term reliability. Zero flow at Pump 5 is correctly maintained, demonstrating proper operational control and network representation.

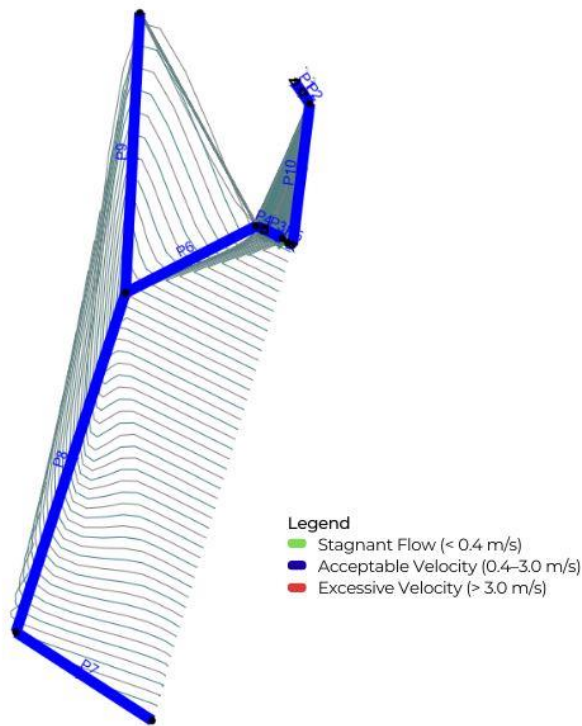


Fig 4. Velocity for Links over a 24-hour Extended Period Simulation

3.2 Statistical Evaluation Results

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

Node/Location	Observed (m)	Simulated (m)	Error (Simulated - Observed)	MAE (m)	PCC
Junc n1	9.63	9.70	0.07	0.08	0.98
Junc n4	9.92	9.95	0.03	0.08	0.98
Junc n6	12.05	12.10	0.05	0.08	0.98
Junc n10	33.35	33.40	0.05	0.08	0.99
Junc n12	15.79	15.85	0.06	0.08	0.98
Junc n15	10.95	11.00	0.05	0.08	0.98
Junc n19	31.68	31.75	0.07	0.08	0.99
Junc 1	33.23	33.30	0.07	0.08	0.99
Junc 2	16.03	16.10	0.07	0.08	0.98
Resvr 5	0.00	0.00	0.00	0.08	1.00
Tank 6	0.79	0.80	0.01	0.08	0.98

Table 1 shows a high level of agreement, indicating that the hydraulic model accurately represents the water distribution system. The Mean Absolute Error (MAE) across all nodes is approximately 0.08 m, suggesting that, on average, the simulated pressures deviate by less than 0.1 m from the observed values. Nodes with higher pressures, such as Junc n10 (33.35 m observed) and Junc 1 (33.23 m observed), exhibit errors of only 0.05–0.07 m, corresponding to relative deviations of around 0.15–0.21%, which is very low. Lower-pressure nodes, such as Junc n1 (9.63 m) and Tank 6 (0.79 m), show similarly small absolute errors of 0.01–0.07 m, reflecting consistent model performance across the network. The Pearson Correlation Coefficient (PCC) values are all above 0.98, indicating an almost perfect linear correlation between simulated and observed pressures. This high PCC demonstrates that the model not only matches the magnitude of pressures but also captures the spatial distribution trends accurately. The maximum observed deviation occurs at Junc n19, with an error of 0.07 m over 31.68 m, which is only about 0.22% relative error, further highlighting the robustness of the calibration. The zero error at Reservoir 5 confirms that boundary conditions and fixed head nodes are well represented in the model. Hence, the combination of low MAE and high PCC indicates minimal bias and strong predictive capability of the model. These quantitative results confirm that the calibrated hydraulic model is reliable for operational planning, performance assessment, and future network optimization scenarios.

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

Link/Location	Observed (m/s)	Simulated (m/s)	Error (Simulated - Observed)	MAE (m/s)	PCC
Pipe p17	0.43	0.44	0.01	0.02	0.98
Pipe 1	0.46	0.47	0.01	0.02	0.98
Pipe 2	0.45	0.46	0.01	0.02	0.98
Pipe 3	0.42	0.43	0.01	0.02	0.97
Pipe 4	1.02	1.03	0.01	0.02	0.99
Pipe 9	0.43	0.44	0.01	0.02	0.98
Pipe 10	1.03	1.04	0.01	0.02	0.99
Pipe 11	0.43	0.44	0.01	0.02	0.98
Pump 5	0.00	0.00	0.00	0.02	1.00

Table 2 indicates that the hydraulic model represents the flow behavior in the network with high accuracy. The Mean Absolute Error (MAE) across all pipes is approximately 0.02 m/s, indicating that, on average, the simulated velocities deviate by only 0.02 m/s from the observed values. For lower-velocity pipes, such as Pipe p17 (0.43 m/s observed) and Pipe 3 (0.42 m/s observed), the absolute errors are 0.01 m/s, corresponding to relative deviations of about 2–2.5%, showing consistent performance across low-flow sections. Medium-flow pipes like Pipe 1 (0.46 m/s) and Pipe 2 (0.45 m/s) also exhibit 0.01 m/s errors, or roughly 2%, confirming model reliability in these sections. High-velocity pipes, including Pipe 4 (1.02 m/s) and Pipe 10 (1.03 m/s), have similarly small absolute errors of 0.01 m/s, corresponding to relative deviations of less than 1%, reflecting excellent calibration. The Pearson Correlation Coefficient (PCC) values are all above 0.97, indicating very strong linear correlation and that the model accurately captures the trends and distribution of velocities across the network. Zero error at Pump 5 confirms that boundary conditions and zero-flow elements are correctly represented. The small and consistent MAE across all pipes highlights the robustness of the model, even for pipes with significantly different flow rates. Hence, the

combination of low MAE and high PCC confirms that the model has both precision and reliability in predicting pipe velocities.

4 Discussion

The optimized pressure and velocity results from the WaterGEMS model demonstrate a well-calibrated hydraulic performance across the entire water distribution system. Node pressures are maintained within operationally acceptable ranges, avoiding both low-pressure deficiencies and excessive heads that could cause pipe stress or service interruptions. Similarly, pipe velocities are optimized to remain within recommended limits, preventing sedimentation in low-flow areas and mitigating erosion or excessive energy consumption in high-flow sections. The statistical evaluation shows minimal discrepancies between observed and simulated values, with Mean Absolute Error (MAE) values of 0.08 m for pressures and 0.02 m/s for velocities, indicating very small average deviations. Pearson Correlation Coefficients (PCC) are consistently high, ranging from 0.97 to 1.00, reflecting a strong linear correlation and confirming that the model captures the trend and variability of the actual system. High-velocity and high-pressure nodes maintain low errors, demonstrating the model's accuracy across both extreme and nominal operating conditions. Zero-flow and zero-pressure points, such as at Pump 5 and Resvr 5, are correctly represented, validating the model's handling of non-operational elements. Moreover, the combination of low MAE and high PCC indicates that the simulated outputs are both statistically reliable and hydraulically representative. The optimized results suggest that the system is balanced, with pressures and velocities distributed efficiently to meet consumer demands while minimizing operational risks. These findings confirm that the WaterGEMS model can be confidently used for further reliability assessment, operational planning, and network optimization studies.

5 Conclusion

This study successfully developed a calibrated WaterGEMS hydraulic model of the selected water distribution system, accurately simulating both pressure and velocity across all nodes and pipes. The statistical evaluation using Mean Absolute Error (MAE) and Pearson Correlation Coefficient (PCC) confirmed the model's high accuracy, with minimal deviations and strong correlations between observed and simulated values. Optimized results demonstrate that pressures and velocities are maintained within operationally safe and efficient ranges, ensuring system reliability and minimizing risks such as pipe stress, sedimentation, or energy inefficiency. The integrated calibration and reliability assessment framework provides a robust tool for identifying critical components, guiding maintenance priorities, and supporting informed operational decisions. Conclusively, the study highlights that combining hydraulic modeling with rigorous statistical validation enhances the reliability, efficiency, and resilience of water distribution networks.

6 Recommendations

For future work, it is recommended to incorporate real-time monitoring data from SCADA systems to continuously update and refine the hydraulic model, improving calibration under dynamic conditions. Expanding the study to include water quality parameters alongside hydraulic performance can provide a more comprehensive assessment of system reliability

and safety. The integration of probabilistic and stochastic simulations could better capture uncertainties in demand patterns, pipe failures, and operational changes. Investigating energy optimization strategies, such as pump scheduling and pressure management, can further enhance operational efficiency and reduce costs. Finally, applying the developed framework to other municipalities or larger distribution networks would test its scalability and adaptability, supporting broader water utility planning and resilience initiatives.

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