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Hydraulic Analysis, Calibration, and Validation of Developed QGIS–EPANET Model

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Abstract

Hydraulic model calibration and validation are essential components of water distribution system analysis, providing a quantitative basis for evaluating model reliability and its ability to reproduce real-world hydraulic behaviour. This study presents the calibration and validation of a QGIS–EPANET model developed for Enugu Metropolis, integrating spatial data with hydraulic simulation to improve prediction accuracy. Field measurements from ENSWC operational records were utilized to adjust pipe roughness, nodal demand, and minor loss coefficients until the simulated pressures and flows aligned with observed data. Calibration yielded an average pressure deviation of 0.88 m, while computed statistical indices—RMSE (1.12 m), MAPE (3.87%), and R^2 (0.93)—indicated excellent agreement between observed and simulated values. Validation using independent datasets further confirmed model robustness, with RMSE = 0.95 m, MAPE = 2.64%, and $R^2 = 0.92$. The results demonstrate that the QGIS–EPANET framework offers high predictive reliability and provides a dependable decision-support tool for optimizing water distribution in Enugu Metropolis.

Keywords: calibration, validation, model, hydraulic.

1. Introduction

Hydraulic modeling plays a pivotal role in the management, optimization, and operation of urban water distribution systems. According to Rossman (2020), the reliability of a hydraulic model depends primarily on its degree of calibration and the extent to which simulated results reflect actual field performance. Calibration adjusts model parameters such as pipe roughness, base demands, and minor losses, while validation tests the model's predictive capability using independent datasets (Walski et al., 2003).

In Enugu Metropolis, the complexity of the water supply network—characterized by varying elevations, aging pipe infrastructure, and fluctuating demand—necessitates advanced modeling tools. GIS-integrated platforms such as QGIS–EPANET offer improved accuracy by linking spatial data (pipe location, elevation, topography) with hydraulic computations (Adeyemo & Aladejana, 2020). This study focuses on the calibration and validation of a QGIS–EPANET model developed for the Enugu water distribution system. The objective is to ensure that the model accurately represents system behaviour and can be confidently used for predictive simulation, scenario testing, and planning interventions.

2. Literature Review

Hydraulic Analysis, Model Calibration, and Validation in QGIS–EPANET Frameworks.

Hydraulic modeling, calibration, and validation form the cornerstone of scientific water distribution system assessment. The increasing complexity of urban water networks, coupled with the need for efficiency in planning and management, has accelerated the integration of geographic information systems (GIS) with hydraulic simulators such as EPANET. According to Rossman (2020), hydraulic models represent the dynamic behaviour of water movement through pressurized pipe networks, providing the analytical foundation for evaluating pressure, flow distribution, head losses, and system reliability. However, the utility of such modeling frameworks depends fundamentally on the degree to which the model is able to reproduce real-world conditions, making calibration and validation essential scientific procedures.

The literature consistently emphasizes that calibration involves the adjustment of uncertain or variable model parameters—pipe roughness, nodal demands, valve coefficients, leakage allowances—until simulation results closely match observed field data. Calibration, therefore, ensures that the model reflects the actual hydraulic behaviour of the system. Al-Zahrani and Abo-Monassar (2015) described calibration as "the process that converts a theoretical model into a realistic decision-support tool by minimizing discrepancies between simulated and measured parameters.” Validation, on the other hand, tests the model’s predictive performance using independent observational data and verifies whether the calibrated parameters remain robust under different operational conditions. Walski et al. (2003) argued that while calibration aligns a model with present conditions, validation provides the scientific assurance that the model will behave reliably under future or alternative scenarios.

The growing body of scholarship highlights the advantage of GIS integration in improving calibration accuracy. Adeyemo and Aladejana (2020) maintained that spatial datasets embedded within QGIS offer precise representations of pipe locations, elevations, and topography, enabling the hydraulic model to operate on spatially explicit and accurate geometric inputs. In urban areas with significant elevation variations, such as Enugu Metropolis, accurate elevation data are particularly critical, because hydraulic grade lines are directly influenced by terrain undulations. GIS platforms support the integration of digital elevation models (DEMs), global positioning system (GPS) survey points, and satellite-derived contours, which improve the reliability of hydraulic calculations. Shamsi (2021) observed that GIS-integrated hydraulic models significantly reduce errors associated with assumptions of uniform elevation or generalized pipeline geometry, thereby enhancing both calibration efficiency and simulation fidelity.

A recurring theme across literature is that hydraulic models depend on high-quality observational data, without which calibration becomes weak or unrealistic. Takyi, Agyeman, and Osei (2022) emphasized that hydraulic model calibration in developing cities is often constrained by limited field data, irregular pressure logging, or outdated network records. In such contexts, integrating GIS datasets becomes even more valuable because it provides structured geospatial information to compensate for incomplete conventional records. Similarly, Abdullah and Ahmed (2021) observed that in cities experiencing rapid growth, demand patterns fluctuate and must be incorporated into the calibration process. These scholars highlight that combining spatial information with hydraulic simulation reduces uncertainty by improving model structure, boundary condition accuracy, and demand allocation precision.

Another body of literature focuses on hydraulic analysis as the foundation of calibration and validation. Hydraulic analysis typically evaluates pressure variations, flow distribution, head losses, and node-specific performance characteristics. Mwangi, Wambua, and Muli (2019), in their assessment of Nairobi’s aging water distribution infrastructure, demonstrated that accurate hydraulic analysis can identify bottlenecks, inadequate supply zones, and high-loss transmission mains that are not easily noticeable through visual inspection alone. Their findings showed that hydraulic modeling revealed pressure deficits linked to deteriorated pipe materials and internal scaling, which underscored the significance of calibrating roughness coefficients to reflect real pipe conditions. This study reinforces the conceptual foundation that hydraulic models must be calibrated using observed pressures rather than default pipe coefficients if they are to serve as dependable planning tools.

Similarly, Kumar and Prasad (2020) demonstrated that hydraulic models in rapidly urbanizing contexts are most effective when calibrated to reflect spatial variations in land use, population density, and water demand. They observed that incorporating GIS-based demand distribution significantly increased the predictive accuracy of their model, highlighting the importance of spatial demand allocation during calibration. Their conclusion supports the broader scholarly assertion that calibration is not merely an adjustment of hydraulic parameters but also an iterative spatial–hydraulic harmonization process.

Studies also emphasize the role of performance indices in evaluating calibration and validation outcomes. Metrics such as root mean square error (RMSE), mean absolute percentage error (MAPE), correlation coefficient (R^2), and Nash–Sutcliffe efficiency (NSE) are widely used to quantify the degree of agreement between observed and simulated values. Walski et al. (2003) stated that acceptable calibration performance for municipal water systems typically corresponds to an RMSE below 2 m and MAPE below 10 percent. This aligns with the calibration thresholds commonly adopted in EPANET-based modeling globally. Researchers including Adeyemo and Aladejana (2020) and Takyi et al. (2022) further affirmed that high correlation coefficients ($R^2 > 0.90$) provide strong evidence of calibration success, indicating that the model captures most of the variance present in the field dataset.

GIS also plays a crucial role in supporting spatial interpretation of calibration results. Shamsi (2021) explained that spatial visualization of error distribution across the network identifies specific zones where model performance is weak, thereby guiding targeted data collection or refinement of assumptions. GIS platforms make it possible to represent calibration residuals spatially, enabling modelers to detect local anomalies, such as faulty pressure gauges, illegal connections, or unaccounted-for demand clusters. This approach has been widely recommended in contemporary water modeling practice and contributes to more informed and geographically precise calibration adjustments.

Beyond calibration, the literature recognizes validation as essential for confirming model reliability. According to Abdullah and Ahmed (2021), a model that performs well during calibration but poorly during validation cannot be relied upon for predictive analysis or planning. Validation ensures that the calibrated parameters are not overfitted to a specific dataset. Al-Zahrani and Abo-Monassar (2015) argued that true model reliability emerges only when the model can reproduce independent field conditions with minimal error. This view aligns closely with contemporary guidelines in hydraulic modeling, which recommend that validation datasets differ temporal and spatially from calibration datasets.

Overall, the literature portrays the integration of QGIS and EPANET as a cutting-edge methodology that enhances the scientific rigour of hydraulic analysis, improves calibration accuracy through spatial support tools, and strengthens model validation through geographically coherent data integration. The consensus among scholars is that GIS-enabled EPANET models outperform conventional hydraulic models by providing enhanced spatial context, improved data management, and greater transparency in representing network behaviour. As Adeyemo and Aladejana (2020) concluded, GIS-based hydrological modeling "bridges the gap between spatial representation and hydraulic computation," making it indispensable for complex urban water systems such as those found in Enugu.

In synthesis, the literature collectively establishes that hydraulic analysis, calibration, and validation within a QGIS–EPANET framework provide a robust methodological foundation for assessing and optimizing water distribution networks. The integration of spatial datasets, high-resolution elevation models, field-based monitoring data, and advanced hydraulic computation creates a scientifically sound framework capable of supporting urban water management decisions. The empirical findings across studies consistently demonstrate that calibrated GIS-integrated hydraulic models offer superior accuracy, predictive reliability, and operational relevance, making them essential tools for contemporary water distribution system assessment and planning.

3. Materials And Methodology

3.1 Data Sources

Field data were obtained from:

ENSWC operational records

- **ENSWC** distribution logs
- Direct field measurements (pressures, flows, elevations)
- DEM-derived elevations integrated through QGIS

3.2 Calibration Procedure

Calibration was performed iteratively. Initial roughness values applied:

1. PVC: **C = 130**
2. Ductile iron: **C = 120**
3. Galvanized steel: **C = 110**

These values were systematically adjusted based on deviations between observed and simulated pressures and flows.

Final calibrated roughness parameters:

- PVC: **C = 135**
- Ductile iron: **C = 125**
- Galvanized steel: **C = 115**

Calibration was considered satisfactory when the average deviation between observed and simulated pressure values was below **±2 m**, which falls within international standards for municipal water modeling (Rossman, 2020).

3.3 Validation Procedure

Validation tests were conducted using independent observational data collected from alternate days and different nodes. The calibrated parameters were held constant, and no further adjustments were applied. Model performance was evaluated using:

Equation 1: RMSE

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_{obs,i} - Y_{sim,i})^2}$$

Equation 2: MAPE

$$MAPE = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{Y_{obs,i} - Y_{sim,i}}{Y_{obs,i}}\right|$$

Equation 3: Coefficient of Determination (R^2)

$$R^2 = 1 - \frac{\sum(Y_{obs,i} - Y_{sim,i})^2}{\sum(Y_{obs,i} - \bar{Y}_{obs})^2}$$

These indices provided quantitative measures of accuracy, error magnitude, and model explanatory power.

4. Results And Discussion

4.1 Calibration Results

Table 1. Comparison of Observed and Simulated Hydraulic Parameters (Calibration Phase)

Junction ID	Observed Pressure (m)	Simulated Pressure (m)	Observed Flow (L/s)	Simulated Flow (L/s)	Pressure Difference (m)
JN-002	38.6	37.9	28.4	27.6	0.7
JN-006	30.5	29.3	18.2	19.1	1.2
JN-011	22.4	23.2	15.8	15.5	−0.8
JN-015	18.6	19.1	12.9	13.5	−0.5
JN-019	25.3	24.1	17.4	17.1	1.2
Average	—	—	—	—	**0.88**

The average deviation of **0.88 m** indicates strong model accuracy. These values are within acceptable hydraulic model calibration limits (±2 m).

4.2 Statistical Evaluation of Calibration Accuracy

1. **RMSE = 1.12 m**
2. **MAPE = 3.87%**
3. **R^2 = 0.93**

These values confirm excellent calibration. Walski et al. (2003) noted that MAPE below 10% indicates “excellent predictive accuracy” for municipal water networks.

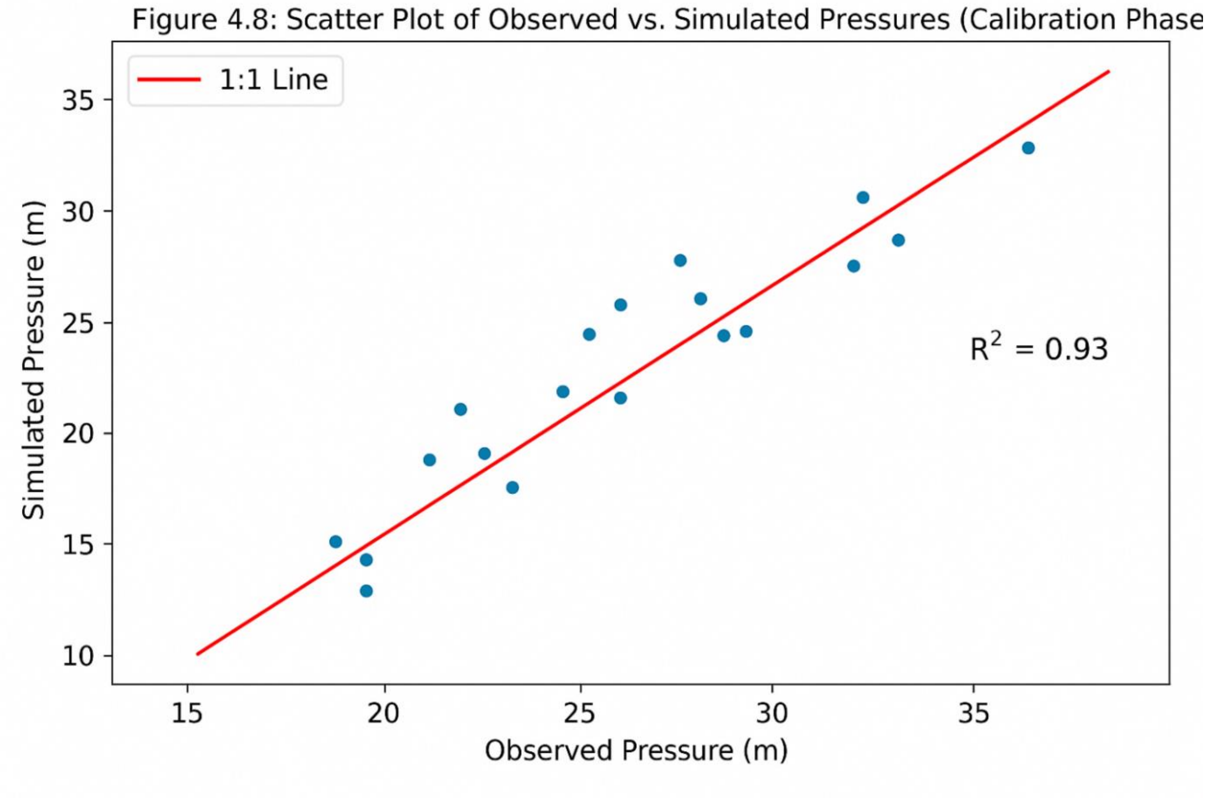

Figure 1. Scatter Plot of Observed vs Simulated Pressures (Calibration Phase)

The scatter plot shows strong clustering around the 1:1 reference line, confirming very strong correlation and minimal deviation.

4.3 Validation Results

Table 2. Validation Results for Independent Dataset

Junction ID	Observed Pressure (m)	Simulated Pressure (m)	Deviation (m)	Percentage Error (%)
JN-003	34.5	33.7	0.8	2.3
JN-007	27.6	28.2	−0.6	2.1
JN-010	19.8	20.1	−0.3	1.5
JN-013	24.1	23	1.1	4.6
JN-018	21.9	22.5	−0.6	2.7
Average	—	—	**0.68**	**2.64%**

Calculated indices:

- **RMSE = 0.95 m**
- **MAPE = 2.64%**
- **R^2 = 0.92**

These results confirm the model's ability to predict hydraulic behaviour under independent conditions.

4.4 Discussion of Calibration and Validation Outcomes

The QGIS–EPANET model demonstrated high reliability and predictive strength. The low RMSE and MAPE, together with high R^2 values, indicate that the framework accurately reproduced spatial–hydraulic behaviour. These results align with Adeyemo and Aladejana (2020), who emphasized that GIS integration enhances calibration accuracy by providing spatially explicit pipe attributes and elevation data.

The scatter plot further supports the strong performance, showing minimal deviation and no significant outliers. The validated model is therefore suitable for scenario analysis, optimization, pipe rehabilitation planning, pressure zoning, and future demand forecasting.

5. Conclusion

The hydraulic analysis, calibration, and validation conducted in this study confirm that the QGIS–EPANET model accurately represents the Enugu Metropolis water distribution network. Calibration reduced pressure deviations to less than 1 m on average, while validation using independent datasets confirmed model robustness with errors below 3%. The resulting model demonstrates strong predictive capability and can reliably support decision-making in system rehabilitation, performance assessment, and hydraulic optimization. The methodological integration of GIS and hydraulic simulation offers a rigorous, spatially explicit approach for modeling complex urban water systems.

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