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Hydraulic Optimization through Iterative Design of the Existing Water Distribution System of Talaandig Tribe in Talakag, Bukidnon

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Abstract

Water is indispensable for biodiversity and human consumption. However, access to water security has become a prominent issue due to a skyrocketing population that strains water supply and water infrastructure. Talaandig tribe - an indigenous community in Talakag, Bukidnon, faces water scarcity that stems from a suboptimal water distribution system and inadequate water resources. Thus, this study seeks to evaluate the hydraulic efficiency of the community's existing water distribution network and propose a network optimization for a sustainable water distribution system within 15 years. The methods used involve qualitative and simulation-based research approaches. Researchers conducted focus group discussion with the Datu of the tribe in consonance with the topographic and reconnaissance data of the area to gather substantial information. Additionally, researchers conducted a topographic survey using Real-Time Kinematics. Thereafter, the data collected were entered in EPANET 2.0 via extended-period simulation and analysis. Results revealed negative pressure in most of the pipe networks of the existing system. Consequently, a network optimization was performed by designing a level II water distribution system. The design included the forecasted water demand of the population for 15 years which is equivalent to 2.623 lps. Moreover, projected climate change impacts, such as increased rainfall variability and heightened drought risk, may significantly affect the long-term sustainability and reliability of the Talaandig Tribe's water distribution system. These factors necessitate the integration of climate-resilient design choices within the optimization framework, ensuring adaptive capacity to fluctuating water availability and future hydrological uncertainties.

Keywords: EPANET 2.0, optimization, Talaandig Tribe, hydraulic efficiency, water demand

1. Introduction

Water is indispensable for public health (Bas, 2026). However, long-term security and access to water are affected by rapid urbanization and an exponential increase in population (Mishra *et al*., 2021). Hence, the result would be massive stress on water supply and water infrastructure. This problem is clearly evident in the Talaandig Tribe at Barangay Tagbak, Talakag, Bukidnon, as this indigenous community faces water scarcity due to the aging water distribution system and insufficient water resources. Several households complained of water shortages during the site visit, especially during peak-hour use. This problem poses a threat to the community, as water plays a pivotal role in their domestic, cultural, and livelihood uses.

In this context, an effective and sustainable water distribution infrastructure is needed to meet growing population-driven demand for water and to address rising levels of water contamination caused by sediment deposition. The piped distribution network, pumps, communal faucets, reservoirs, and other water facilities that make up this network's essential nodes enable the delivery of clean, efficient water to end users (Tanyimboh & Seyoum, 2020). Hence, hydraulic modeling software is highly relevant to the community's water distribution network design. EPANET 2.0 is an ideal hydraulic modeling software that simulates water flow through a network of pipes across a system of nodes, allowing civil engineers to identify potential issues such as low water pressure, friction loss, and sediment buildup (Masum *et al*., 2020). Moreover, EPANET 2.0 can simulate real-world case studies, such as increased water demand during peak consumption hours (Abhijith & Ostfeld, 2022).

The predictive ability of this software helps ensure that the system meets design requirements, prevents operational errors, and promotes sustainable water use. According to Shah and Patel (2023), this hydraulic modeling software supports decision-making for system designers, enabling them to develop comprehensive plans for water infrastructure, test and validate a wide range of network configurations, and gradually improve the system's hydraulic performance. This helps minimize risks and enhance the overall resilience of the water distribution system.

Similarly, Mehta *et al*. (2024) designed an efficient and reliable water supply system using EPANET 2.0, in which the model accurately simulated velocity and significantly reduced head loss by 66.46%. Conversely, Dongare *et al*. (2024) used EPANET 2.0 to identify areas of network leaks, substantial head loss, and negative pressures in the system. Based on the EPANET 2.0 simulation, the study recommended new pipelines, booster pumps, and the rehabilitation of existing water infrastructure to optimize the water distribution network.

However, projected climate change over the next 15–30 years—marked by increased drought frequency, rainfall variability, and more extreme weather events—is expected to intensify water scarcity and strain infrastructure, threatening the long-term water security of the Talaandig Tribe in Talakag, Bukidnon. Consequently, optimizing the existing water distribution system must incorporate climate-resilient strategies, including diversified water sources, adaptive storage design, and flexible operational management, to enhance system sustainability under future hydrological uncertainties (Intergovernmental Panel on Climate Change [IPCC], 2023; United Nations Educational, Scientific and Cultural Organization [UNESCO], 2022).

Community-led governance and participatory management enhance the durability and local acceptability of rural water systems by building social capital, enabling routine maintenance, and strengthening collective responses to shocks (Das *et al*., 2019). Integrating locally managed, nature-based options (rainwater harvesting, catchment protection) with technical upgrades has been shown to reduce vulnerability to droughts and extreme precipitation by diversifying sources and buffering supply variability. Importantly, heterogeneous risk awareness and local capacity mean that adaptation measures must be co-designed with communities and coupled with flexible operating rules and monitoring to be effective under nonstationary climate conditions (Franceschinis *et al*., 2021). Incentive structures and financing mechanisms that reward local stewardship and lower barriers to community participation significantly increase uptake of resilient practices and long-term service continuity (Piñeiro *et al*., 2020). For Talaandig Tribe systems, these findings imply that optimization should explicitly include community governance, source diversification, and adaptive operational policies as design variables to improve climate resilience and equity.

Thus, this research uses EPANET 2.0 in extended-period simulation to analyze fluid flow in the system's hydraulic network. Specifically, this study aimed to: evaluate the hydraulic performance of the existing water distribution network (a); optimize the existing water distribution system through iterative hydraulic modeling and design, utilizing Monte Carlo simulation to evaluate system performance under uncertainties and integrating climate resilience and adaptation strategies to enhance the system's reliability, efficiency, and capacity to withstand future climatic conditions (b).

2. Methodology

2.1 Study Area

The study was conducted in Barangay Tagbak, Talakag, Bukidnon, which is situated at approximately 8°1′ North, 124°41′ East (Figure 1). As of 2024, its current population is estimated to be around 2,385, which represented 2.86% of the total population in Talakag, Bukidnon.

Figure 1. Location of the study area

2.2 Focus Group Discussion with the Datu of the Tribe

The researchers conducted a focus group discussion with the head of the tribe in correlation to the design specifications of the existing water distribution system (Figure 2a). Based on the provided numerical data, the pipe diameter used was 25 mm and there are 3 existing Bestanks polyethylene water storage tank with a volume of 2000 liters. Other design parameters such as elevation and location of the potential water source were determined using topographic surveying via using a Hi-Target V200 Real-Time Kinematic (RTK) Global

Navigation Satellite System (GNSS) receiver (Hi-Target Surveying Instrument Co., Ltd., China) as shown in Figure 2b.

Figure 2. Focus group discussion with the head of the tribe (a); topographic surveying using RTK (b)

2.3 Network Modeling and Simulation Procedure

Figure 3 illustrates hypothetical data of a hydraulic simulation of a water distribution system modeled in EPANET 2.0 (Arandia & Eck, 2018). The network includes interconnected pipes, junctions, a reservoir, and demand nodes, with each element accurately positioned based on topographic survey data. According to the study of Shah and Patel (2023), the hydraulic simulation in EPANET 2.0 exhibits pressure readings at each node, denoted by color-coded values, and flow directions represented by arrows along the pipe networks. These visual outputs assist in detecting areas with negative pressures and high head loss, which are crucial for diagnosing system inefficiencies (Burkhart & Janke, 2023). Moreover, the simulation is the basis for evaluating various design scenarios and optimizing the network to meet hydraulic performance standards.

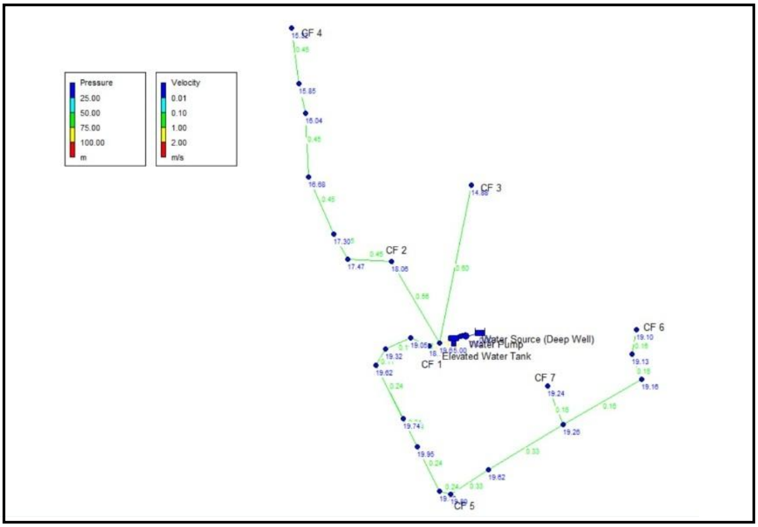

Figure 3. Hydraulic modeling and simulation in EPANET 2.0

2.4 Data Collection

Figure 4 shows the comprehensive methodology of optimizing the hydraulic model of the existing water distribution system. This methodology is correlated to the study of Dongare *et al*. (2024) wherein the location of the water source, population to serve, and forecasted water demand within a specific design period are considered in the hydraulic simulation. The study calculated the required water demand of the community in liters per capita per day (LPCD) based on the current and projected population of Talaandig tribe after 15 years. The computation considered factors such as per capita water consumption, population size, and peak factor - which is a multiplier used to account for water demand fluctuations during peak hours. The input data included the elevation, pipe length, pipe diameter, roughness coefficient, and water demand which are derived from real world measurements of the existing water distribution network. Moreover, the first step of the calibration procedure is defining parameter values. Through these initial design variables, EPANET 2.0 simulations are modeled and performed, and the results of hydraulic modeling are closely correlated to the actual data that were observed. If the model meets the service requirements, the algorithm is finished; if not, the parameters are refined through successive iterations.

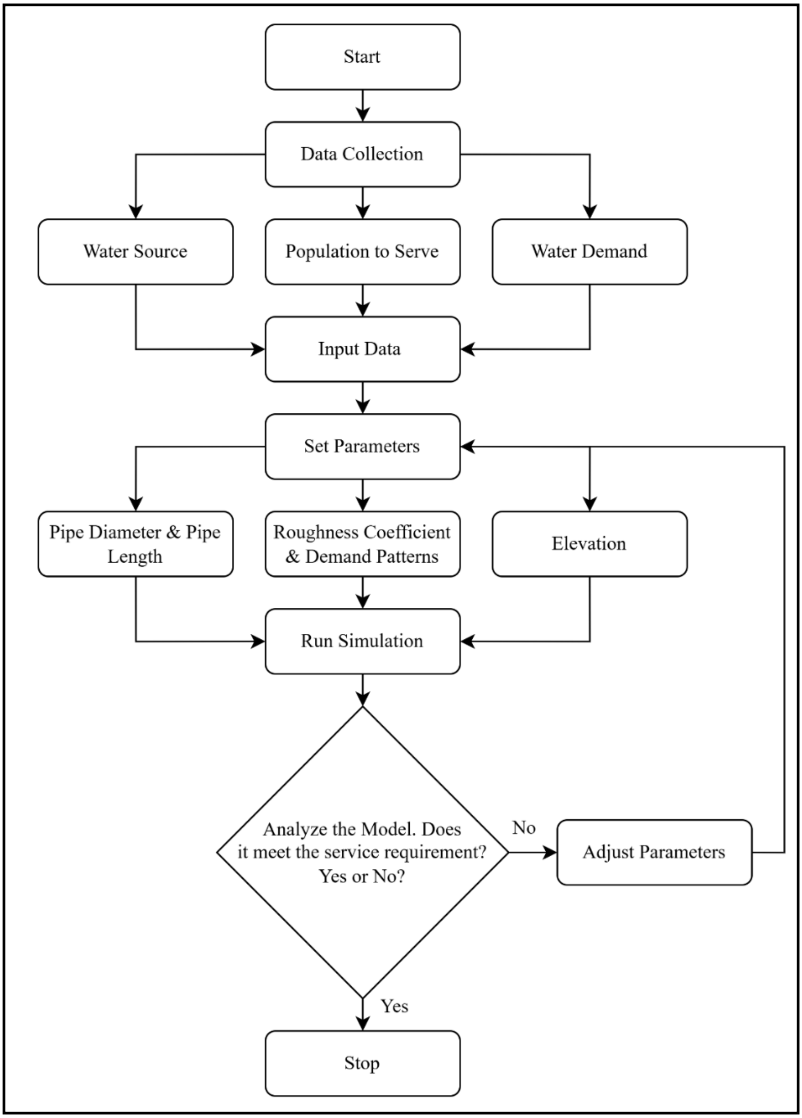

Figure 4. Flowchart of research methodology

Moreover, this study incorporated the following algorithm in modeling and simulation to achieve the optimized data of the existing water distribution system:

1. Calculate the forecasted population of the community after 15 years. This refers to the estimated number of inhabitants during the design

horizon of the existing water distribution system. This ensures that the system can meet the water demand of the community from year 2025 to 2040. Thus, this study used the geographical increase method shown in Equation 1:

$$P_t = P_o(1+r)^n \quad (1)$$

where P_t *is* the projected future population; P_o is the present population; *r is* the annual growth rate; *n* is the number of years of the design period.

2. Determine the average daily demand. This refers to the average quantity of water consumed daily over a year. The value of non-revenue water used was 15%, which is in accordance with the design manual for rural water supply for level II (Department of Public Works and Highways [DPWH], 2023). Moreover, the formula used is shown in Equation 2:

$$ADD = \frac{P_t \times WCR}{1-NRW} \quad (2)$$

where *ADD* is the average daily demand; P_t is the projected future population; *WCR* is the water consumption rate measured in liters per capita per day; *NRW* is the non-revenue water.

3. Determine the maximum daily demand. This denotes the highest volume of water consumed by end-users within a 24-hour extended-period simulation. It is computed using the formula shown in Equation 3:

$$MDD = 1.3ADD \quad (3)$$

where *MDD* is the maximum daily demand; ADD is the average daily demand.

Furthermore, the optimized parameters include the roughness coefficient values, node elevation data, pipe diameter, pipe length, and demand patterns. These parameters were modelled in EPANET 2.0 for hydraulic simulation. If the model meets the service requirements based on the design criteria for rural water supply for the level II water distribution network, the process is finished;

if not, the design parameters are changed iteratively until the simulation meets the design criteria.

4. Determine the pump horsepower. It is computed using the formula shown in Equation 4:

$$PHP = \frac{Q \times TDH}{75 \times PE} \quad (4)$$

where PHP is the pump horsepower; Q is the discharge; *TDH* is the total dynamic head; *PE* is the pump efficiency which is equivalent to 80%.

2.5 Mathematical Formulation of WDS Optimization

Decision Variables. The decision variables considered in the optimization are expressed in Equation 5:

$$X = \{D_i, Q_j, H_j, V_k \quad (5)$$

where:

D_i= diameter of pipe i
Q_j= flow through pump j
H_j= pump head for pump j
V_k= volume of storage tank k

Objective Function. The optimization seeks to minimize total cost while maintaining hydraulic performance, as shown in Equation 6:

$$Minimize\ Z(X) = \alpha \cdot Cost(X) - \beta \cdot Reliability(X) \quad (6)$$

where $\alpha$and $\beta$are weighting factors.

Constraints:

1. The hydraulic constraints governing pressure and flow across all nodes and pipes are defined by Equations 7 and 8:

$$P_{\min} \leq P_n(\mathrm{X}) \leq P_{\max}, \forall n \in \text{Nodes} \quad (7)$$

$$Q_{\min} \leq Q_i(\mathrm{X}) \leq Q_{\max}, \forall i \in \text{Pipes} \quad (8)$$

2. Pump operational limits are imposed through Equation 9:

$$H_{\min} \leq H_j \leq H_{\max}, Q_{\min} \leq Q_j \leq Q_{\max}, \forall j \in \text{Pumps} \quad (9)$$

3. Design Constraints:

   Pipe diameters and tank volumes are restricted to standard available sizes, as expressed in Equation 10:

$$D_i \in \{D_1, D_2, \dots, D_m\}, V_k \in \{V_1, V_2, \dots, V_l\} \quad (10)$$

4. Mass Balance (Continuity Equation):

   Flow continuity across all nodes is enforced by the mass balance equation (Equation 11):

$$\sum_{i \in Inlets} Q_i - \sum_{i \in Outlets} Q_i = 0, \forall Nodes \quad (11)$$

The optimization model is developed under the following assumptions:

- Steady-state or pseudo steady-state hydraulic conditions
- Known demand patterns or probabilistic demand distributions
- Neglecting water quality effects (hydraulics-only optimization)
- Constant pipe roughness and pump efficiency

2.6 Sensitivity Analysis

This study used sensitivity analysis of water demand driven by three interacting processes: climate variability (seasonal and interannual shifts that amplify demand in hot/dry months), migration-driven population change (temporary and permanent in-/out-flows), and behavioral increases in per-capita use during heat or drought.

To capture this, we ran Monte-Carlo simulation that perturbed seasonal demand multipliers, net population change, and baseline per-capita use. Analyses focused on how these uncertainties change key performance metrics — system reliability, deficit volume, frequency of restrictions — and on identifying whether effects are additive or interactive (for example, whether population influx during drought produces disproportionate increases in failure risk). The approach highlights which drivers most influence outcomes and which interventions (demand management, source diversification, or storage) yield the biggest resilience gains.

The optimization algorithm incorporates extreme weather scenarios by evaluating system performance under representative droughts, intense rainfall, and combined climate–migration stress events, ensuring decisions are robust across a range of plausible futures. Both structural (e.g., modular storage, redundant pipelines) and operational (e.g., adaptive allocation rules, demand restrictions) variables are included, allowing the system to adjust dynamically under stress. This scenario-based, resilience-focused approach ensures the optimized design balances cost, reliability, and adaptability, maintaining service continuity even during rare but high-impact events.

Additionally, the study employed Monte Carlo Simulation to account for uncertainties in the existing water distribution system and to evaluate the robustness of the proposed hydraulic optimization. In the study, 10,000 simulation iterations were performed using EPANET 2.0, with hydraulic simulations automated through Python. The uncertain parameters, particularly nodal water demand and pipe roughness coefficients, were represented using appropriate probability distributions based on available field measurements and assumed engineering variability. Random samples were generated using a pseudo-random sampling procedure with a fixed random seed to ensure reproducibility. For each iteration, the sampled parameters were incorporated into the hydraulic model, and key performance indicators such as nodal pressure, pipe velocity, and system reliability were evaluated against the established design criteria in consonance with the guidelines for the Design of Rural Water Supply Systems for Level II as the primary reference for the assessment and hydraulic design of the existing water distribution system. The simulation was considered sufficiently converged when the estimated mean and standard deviation of the principal hydraulic performance indicators exhibited less than 1% relative change over successive batches of simulations. The resulting probability distributions and reliability estimates were then used to assess the performance of each iterative design alternative, with the design satisfying the required hydraulic constraints and demonstrating the highest overall system reliability selected as the optimized configuration.

3. Results and Discussion

3.1 Hydraulic Performance of Existing Water Distribution System

Figure 5 shows hydraulic inefficiency via a 24-hour extended-period simulation in EPANET 2.0. Table 1 outlines the existing design specifications of the water distribution system in Barangay Tagbak, Talakag, Bukidnon. The hydraulic simulation recorded negative pressures in most of the nodes. This is attributed to high elevations relative to the water source and undersized pipe networks. Additionally, negative pressures are ascribed to closed links in some parts of the network and the absence of booster pumps (Rashed *et al*., 2024). Moreover, it has been observed that a significant drop in water flow in pipes causes a decrease in velocity.

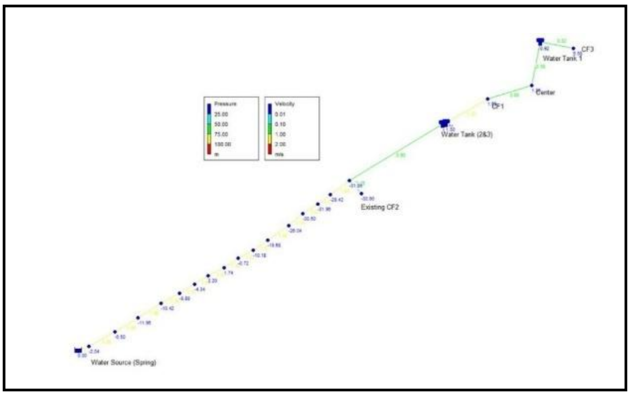

Figure 5. Hydraulic simulation of the existing water distribution network

Table 1. Existing design specifications of the water distribution system

Network Table - Nodes			Network Table - Links			
Node ID	Elevation (m)	Pressure (m)	Link ID	Diameter (mm)	Flow	Velocity (m/s)
J1	1458	-2.04	P1	25	0.52	1.06
J2	1459	-6.5	P2	25	0.52	1.06
J3	1461	-11.96	P3	25	0.52	1.06
J4	1456	-10.42	P4	25	0.52	1.06
J5	1451	-8.88	P5	25	0.52	1.06
J6	1443	-4.34	P6	25	0.52	1.06
J7	1433	2.2	P7	25	0.52	1.06
J8	1430	1.74	P8	25	0.52	1.06
J9	1429	-0.72	P9	25	0.52	1.06

J10	1435	-10.18	P12	25	0.52	1.06
J11	1441	-19.58	P13	25	0.52	1.06
J12	1444	-26.04	P14	25	0.52	1.06
J13	1445	-30.5	P15	25	0.08	0.16
J14	1443	-31.96	Pipe to Existing CF2	25	0.42	0.85
J15	1436	-28.42	Pipe to CCF	25	0.65	1.32
J16	1436	-31.89	P to C1	25	0	0.01
J to Existing CF2	1435	-30.9	P25	25	-0.44	0.9
J CF1	1365	1.59	P26	25	0.19	0.38
J Center CF	1363	1.36	P27	25	0.16	0.32
J CF3	1357	6.58	P to CF3	25	0.52	1.06
R18	1458	0	P30	25	0.52	1.06
Tank 24	1373	1.5	Pump 17	25	0.52	1.06
Tank 25	1373	1.5	Pump 11	25	0.52	1.06
Tank 26	1363	0.92	-	-	-	-

3.2 Projected Water Demand

The forecasted water demand from 2025 to 2040 is 2.623 lps, which is computed based on the estimated population increase from 2385 (current year) to 3210 in 2040. The annual growth rate of 2% and non-revenue water of 15% for the level II water distribution system were also considered (DPWH, 2023). Moreover, this water demand will aid in simulating flow dynamics and system responses that cater to the community's water needs within 15 years. It enhances the adaptability of the water supply system regardless of droughts and urban sprawl.

3.3 Optimization of the Existing Water Distribution System

Figure 6 shows the hydraulic efficiency of the existing water distribution network. Table 2 outlines the optimized design specifications of the system through an iterative adjustment of parameters such as pipe diameters and elevation of existing water tanks and the inclusion of a pressure-reducing valve, booster pump, and centrifugal pump. The optimization of these parameters ensures an efficient pressure, velocity, and head loss across the 24-hour extended period simulation in EPANET 2.0.

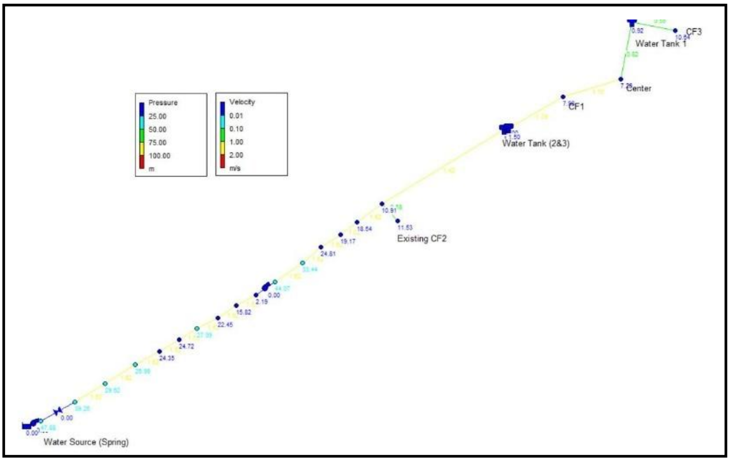

Figure 6. Optimized hydraulic simulation in EPANET 2.0

Table 2. Optimized design specifications

Network Table - Nodes			Network Table - Links			
Node ID	Elevation (m)	Demand (LPS)	Link ID	Length (mm)	Ø in mm	Roughness
J1	1458	-	Pipe 1	50.92	25	130
J2	1459	-	Pipe 2	50.92	25	130
J3	1461	-	Pipe 3	50.92	25	130
J4	1456	-	Pipe 4	50.92	25	130
J5	1451	-	Pipe 5	50.92	25	130
J6	1443	-	Pipe 6	50.92	25	130
J7	1433	-	Pipe 7	50.92	25	130
J8	1430	-	Pipe 8	50.92	25	130
J9	1429	-	Pipe 9	50.92	25	130
J10	1435	-	Pipe 12	50.92	25	130
J11	1441	-	Pipe 13	50.92	25	130
J12	1444	-	Pipe 14	50.92	25	130
J13	1445	-	Pipe 15	50.92	25	130
J14	1443	-	Pipe to Existing CF2	5.75	13	110
J15	1436	-	Pipe to CCF	48.99	32	130

J16	1436	-	Pipe to CF1	77.04	32	130
J to Existing CF2	1435	0.29	Pipe 25	0.00001	25.4	130
J CF1	1365	0.87	Pipe 26	586.54	25.4	130
J Center CF	1363	0.87	Pipe 27	43.07	32	130
J CF3	1357	0.59	Pipe to CF3	45.42	19	130
R18	1458	-	Pipe 30	50.92	25	130
Tank 24	1373	-	Pump 17	-	-	-
Tank 25	1373	-	Pump 11	-	-	-
Tank 26	1363	-	Valve 10	-	12	-

Figure 7 illustrates the optimized data for pressure and velocity distribution within the system, highlighting an efficient network where pressure and velocity are maintained within the design criteria and standards across all critical nodes. The minimum pressure head recorded in the system was 7.28 meters. Conversely, the maximum pressure head reached 15.73 meters. Both pressure values align with the established design criteria for rural water supply for the level II water distribution network. Additionally, the velocity of flow in pipes demonstrates an efficient system performance, as the velocity distribution remained between 0.4 m/s and 3.0 m/s (Table 3). This range is ideal for minimizing friction losses and preventing sediment deposition. These velocities indicate that the pipe diameters and layout of the system were fully optimized to accommodate the projected water demand of the community over the next 15 years without inducing turbulent flow or irregular velocity fluctuations, especially during peak usage hours. The correlation between velocity and pressure also indicates that pipes with moderate pressure correlate to critical nodes with increasing velocity of flow. This setup shows that the network configuration is dependable and robust by reducing mechanical stress in the system.

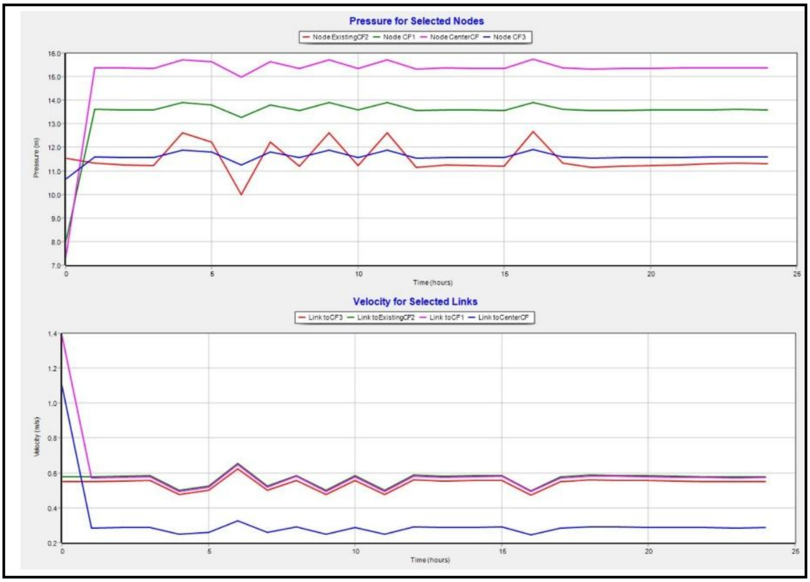

Figure 7. Optimized pressure and velocity distribution via a 24-hour extended period simulation

Table 3. Optimized results of velocity across critical nodes

Time Series	Link to CF2	Link to CF1	Link to Center CF	Link to CF3
Time (hrs.)	Velocity (m/s)			
0:00	0.58	1.39	1.10	0.55
1:00	0.58	0.57	0.30	0.55
2:00	0.58	0.58	0.30	0.55
3:00	0.58	0.58	0.30	0.56
4:00	0.50	0.50	0.30	0.48
5:00	0.52	0.52	0.30	0.50
6:00	0.66	0.65	0.32	0.62
7:00	0.52	0.52	0.30	0.50
8:00	0.59	0.58	0.30	0.56
9:00	0.50	0.50	0.30	0.48
10:00	0.58	0.58	0.30	0.56
11:00	0.50	0.50	0.30	0.48
12:00	0.59	0.58	0.30	0.56
13:00	0.58	0.58	0.30	0.55
14:00	0.58	0.58	0.30	0.56
15:00	0.59	0.58	0.30	0.56
16:00	0.50	0.49	0.30	0.47
17:00	0.58	0.57	0.30	0.55

18:00	0.59	0.58	0.30	0.56
19:00	0.59	0.58	0.30	0.56
20:00	0.58	0.58	0.30	0.56
21:00	0.58	0.58	0.30	0.55
22:00	0.58	0.57	0.30	0.55
23:00	0.58	0.57	0.30	0.55
24:00	0.58	0.57	0.30	0.55

Additionally, the system reveals a controlled variation in pressure regardless of demand fluctuations (Table 4). In elevated areas, it has been observed that pressure gradually increases with rising demand in peak hour usage. However, the pressure remained within the acceptable design standard (3 m to 70 m), and there were no steep spikes in pressure since the system incorporated modifications in pipe diameters to avoid pipe leakage and sediment deposition. Moreover, the pressure distribution diagram reflects an efficient hydraulic performance since the system's pressure corresponds proportionally to demand oscillations without compromising the established design criteria across critical nodes.

Table 4. Optimized results of pressure across critical nodes

Time Series	Node Existing CF2	Node CF1	Node CF	Node CF3
Time (hrs.)	Pressure (m)			
0:00	11.53	7.98	7.28	10.64
1:00	11.33	13.60	15.38	11.59
2:00	11.26	13.58	15.36	11.57
3:00	11.22	13.58	15.35	11.57
4:00	12.62	13.89	15.72	11.89
5:00	12.22	13.81	15.62	11.80
6:00	10.00	13.27	14.99	11.25
7:00	12.22	13.81	15.62	11.80
8:00	11.19	13.57	15.34	11.56
9:00	12.62	13.89	15.72	11.89
10:00	11.22	13.58	15.35	11.57
11:00	12.62	13.89	15.72	11.89
12:00	11.15	13.56	15.33	11.55
13:00	11.26	13.58	15.36	11.57
14:00	11.22	13.58	15.35	11.57
15:00	11.19	13.57	15.34	11.56
16:00	12.66	13.90	15.73	11.89
17:00	11.33	13.60	15.38	11.59
18:00	11.15	13.56	15.33	11.55
19:00	11.19	13.57	15.34	11.56

20:00	11.22	13.58	15.35	11.57
21:00	11.26	13.58	15.36	11.57
22:00	11.30	13.59	15.37	11.58
23:00	11.33	13.60	15.38	11.59
24:00	11.30	13.59	15.37	11.58

3.4 Sensitivity Analysis

The Monte Carlo simulation results highlight the varying hydraulic and reliability responses of the water distribution system under different stress conditions. During the dry-year scenario, the average node pressure dropped to 22.5 m and average flow declined to 920 m³/day, resulting in a system reliability of 85%. This indicates that prolonged drought and a 20% increase in per-capita demand significantly strain the network, primarily due to reduced source yield and increased consumer usage. In contrast, the wet-year scenario exhibited higher hydraulic performance with an average node pressure of 28.0 m, flow of 1,080 m³/day, and reliability reaching 98%. These values suggest favorable operating conditions, although the risk of localized overflow or contamination may increase due to excessive runoff and system surcharging. Under the power outage scenario, when pumping stations were offline for 12 hours, the system's performance deteriorated sharply with pressures falling to 15.0 m, flows decreasing to 600 m³/day, and reliability dropping to 70%. This emphasizes the network's dependence on pumping infrastructure and the limited effectiveness of gravity-fed and storage-based supply in sustaining service levels. The combined stress scenario (drought plus outage) yielded the most critical outcomes, with pressures and flows reducing to 12.0 m and 550 m³/day respectively, and reliability plummeting to 60%. This compounded stress highlights the system's vulnerability under concurrent climatic and operational disruptions, underscoring the necessity for enhanced contingency measures such as emergency storage, redundancy in pumping capacity, and adaptive operational protocols to maintain service continuity during extreme events (Figure 8).

Moreover, the reliability of the Talaandig Tribe water distribution system was significantly enhanced through targeted technical upgrades, including pump and pipeline improvements, optimized network layout, and pressure management strategies. These interventions reduced the vulnerability of critical nodes and ensured more consistent delivery of water under varying operational and climate conditions. Beyond immediate technical improvements, adaptation to climate change and long-term sustainability were integrated into the system design by considering strategies that enhance resilience to both supply and demand shocks.

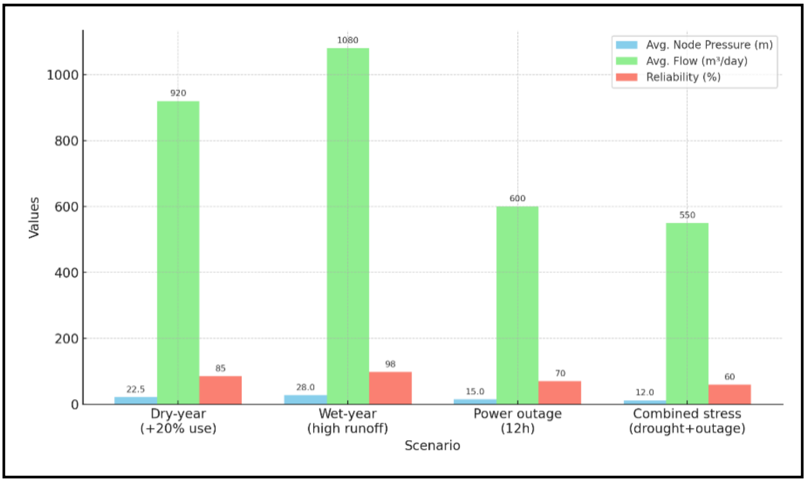

Figure 8. Monte Carlo simulation results across scenarios

Key adaptation measures include the implementation of rainwater harvesting systems at household and community levels, multipurpose storage reservoirs to buffer seasonal variability, and demand management programs to optimize consumption and reduce wastage. Emergency water sources, such as auxiliary wells or connection to regional water networks, provide redundancy in case of droughts or infrastructure failure. The system design also incorporates flexibility for integration with regional water systems, enabling resource sharing during extreme conditions. These measures align with best practices for resilient rural water supply as highlighted by the World Health Organization [WHO] (2022) and the Global Water Partnership & United Nations Children's Fund [GWP & UNICEF, 2017], (2017), emphasizing the importance of diversified water sources, adaptive management, and community participation in sustaining reliable water services under changing climatic and socio-economic conditions.

4. Conclusions and Recommendation

The study revealed hydraulic inefficiency of the existing water distribution network as most critical nodes recorded negative pressure. This is attributed to undersized pipe networks and the absence of valves and pumps in elevated topographies. During optimization, the forecasted water demand is 2.623 lps, which is not enough to cater to the scant water resources of the community from the year 2025 to 2040. Moreover, the optimized water distribution system includes the iterative adjustment of pipe diameters and elevation of some water infrastructures, as well as the inclusion of a pressure-reducing valve, booster pump, and centrifugal pump.

Furthermore, ensuring the sustainability and resilience of the Talaandig Tribe water distribution system requires a strong emphasis on climate change adaptation. Continuous monitoring of system performance, combined with proactive contingency planning, is essential to respond effectively to extreme weather events, droughts, or operational disruptions. Moreover, the system should undergo iterative design updates informed by evolving climate projections and changing community water needs, ensuring that both current and future demands are met reliably. By integrating adaptive management strategies and long-term planning into the water system's operation, the community can maintain dependable service, safeguard public health, and enhance the sustainability of water resources in the face of climate variability and socio-economic changes.

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