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Assessing The Performance of the 3-Districts Water Supply System Using Gis and Hydraulic Models

Sampson Osei

PhD Student, Selinus University of Science and Literature

https://orcid.org/0009-0009-8996-2997

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ABSTRACT

Purpose: This study aimed to evaluate the performance challenges of the 3-Districts Water Supply System (3-DWSS), a major rural–urban water scheme in Ghana, focusing on identifying hydraulic inefficiencies and structural limitations driven by population growth, elevation disparities, and aging infrastructure.

Methodology: An integrated Geographic Information System (GIS) and hydraulic modelling approach was employed. Spatial data, including pipeline alignments, elevation, community expansion, and nodal distributions, were processed in a GIS environment. EPANET 2.2 was used to simulate hydraulic performance under current and projected demand scenarios, assessing parameters such as pressure, velocity, flow, and head loss.

Findings: The analysis revealed that over 60% of system nodes operate below acceptable pressure thresholds, with some experiencing negative pressures, particularly in high-elevation and peripheral areas. Pipe diameters averaged 84 mm, contributing to excessive frictional losses and poor pressure delivery. Flow velocity analysis indicated both overburdened and stagnant sections, confirming imbalance in system design. Scenario modelling showed that upgrading pipelines to 160mm–220.6mm, expanding network coverage, and reconfiguring pump stations substantially improved hydraulic performance and service reliability.

Unique Contribution to Theory, Practice and Policy: The study demonstrates the effectiveness of combining GIS with hydraulic modelling for diagnosing and improving water supply systems in rapidly urbanizing rural contexts. It provides actionable recommendations, including targeted pipeline resizing, network expansion, operational optimization, and routine spatial-hydraulic assessments. These interventions offer scalable, evidence-based strategies to inform water infrastructure policy and planning in Ghana and similar settings.

Keywords: *GIS Integration, Hydraulic Modeling, Water Supply Optimization, Infrastructure Performance*

1. Introduction

Access to safe, reliable and equitably distributed potable water remains one of the most essential drivers of human development, public health and socio-economic transformation. In many developing countries, water supply systems continue to face severe pressure due to rapid population growth, settlement expansion, climate variability, ageing infrastructure, and operational inefficiencies. Ghana's rural–urban water systems are no exception. Although significant investments have been made in expanding water infrastructure, several schemes continue to experience suboptimal performance marked by low pressures, intermittent supply, and uneven service distribution. Studies in Ghana have documented various challenges including water losses, distribution inequities and insufficient hydraulic capacity in key transmission corridors (Ameyaw et al., 2020; Ampadu & Boakye, 2004). These gaps point to the need for modern analytical tools capable of providing detailed insights into both the spatial and hydraulic behaviour of complex water distribution networks.

The 3-Districts Water Supply System (3-DWSS), managed by the Community Water and Sanitation Agency (CWSA), is one of the largest multi-district water supply schemes in the Greater Accra and Volta Regions. Commissioned in 2008 and expanded in phases, the system currently serves an extensive and fast-growing population spread across Ada East, Ada West, Ningo-Prampram, Shai Osudoku, Central Tongu and North Tongu Districts as seen in Figure 1. The network includes transmission mains, booster stations, elevated reservoirs and over 296 km of distribution infrastructure. While the system was originally adequate for its design population, rapid growth and the emergence of new settlements have placed significant strain on its hydraulic capacity. Communities located at the network extremities and higher elevations frequently experience low pressures, inadequate flows, and inconsistent supply.

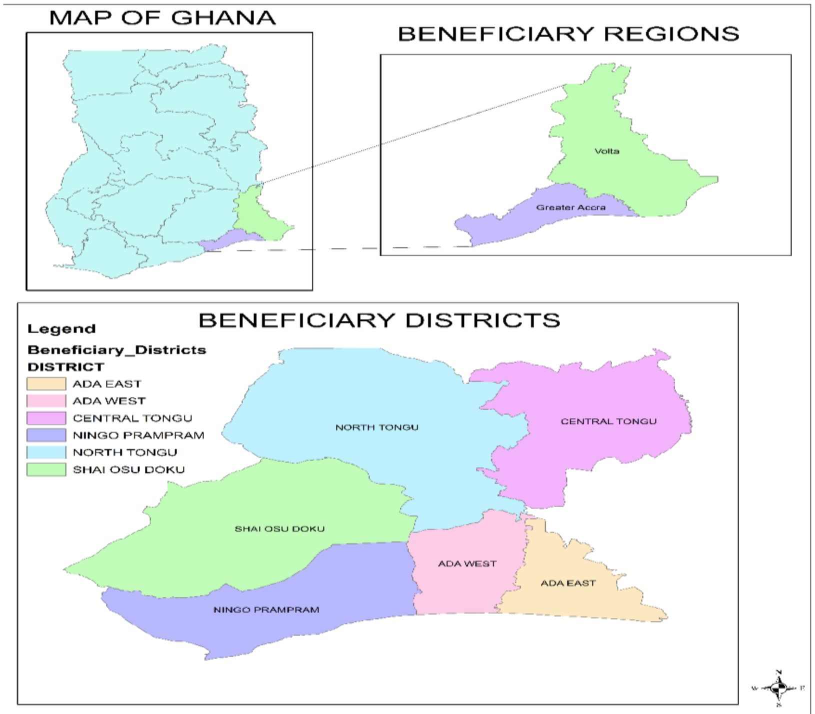

Figure 1: Map of the study area

Source: Researcher's Construct (2025)

These issues are exacerbated by spatial development occurring in areas previously not planned for in the initial layout, resulting in a mismatch between population distribution and water supply infrastructure.

Integrated modelling tools such as Geographic Information Systems (GIS) and hydraulic simulation engines have become indispensable for diagnosing such complex system-wide challenges. GIS supports the compilation, analysis and visualization of spatial infrastructure data, allowing utilities to map pipelines, facilities, demand centres and topographic conditions with high accuracy. Meanwhile, hydraulic models like EPANET simulate the dynamic behaviour of water within a network, providing insights into pressures, flows, velocities, head losses and demand satisfaction across different nodes and pipes. While each tool is individually useful, research increasingly demonstrates that combining GIS and hydraulic modelling provides a more powerful and decision-relevant assessment framework. Globally, these integrated tools have been applied to optimize pipe sizing, evaluate system reliability, minimize energy use, identify district metering areas, and support long-term expansion planning (Behzadian & Kapelan, 2015; Hou et al., 2011; Giustolisi & Berardi, 2009). Despite these demonstrated benefits, the adoption of integrated GIS–hydraulic assessment remains limited in many water utilities in Ghana, especially within rural and peri-urban schemes.

The 3-DWSS has not previously undergone a comprehensive, model-based evaluation combining both spatial and hydraulic perspectives. Operational challenges have been identified anecdotally through field observations and consumer feedback, but these do not provide sufficient clarity on the underlying causes or the extent of network deficiencies. A systematic assessment is required to determine whether pipe diameters are adequate for present and future demands, whether storage and pumping arrangements support equitable distribution, and where the most critical pressure-deficient or high-demand areas are located. Understanding these issues is essential for guiding targeted investments, reducing system stress, ensuring fair service distribution, and improving reliability across all beneficiary communities within the catchment.

This study therefore applies an integrated GIS and hydraulic modelling approach to assess the performance of the 3-Districts Water Supply System. Building on detailed spatial datasets including pipeline alignments, elevation profiles, reservoir locations, demand node distributions and population projections, GIS is used to construct a complete spatial representation of the system. Hydraulic simulations are then carried out using EPANET to evaluate pressures, flows, velocities and head losses under existing conditions as well as potential future scenarios. The integration of both tools allows the hydraulic outputs to be visualized spatially, enabling a clearer and more intuitive interpretation of system behaviour across different districts. The study aims to generate evidence-based insights that support operational planning, infrastructure rehabilitation, service expansion and long-term investment decisions.

Through this integrated assessment, the paper contributes to enhancing the decision-making capacity of water utilities, particularly in Ghana where such modelling approaches are still emerging. By highlighting areas of hydraulic stress, spatial inequity and infrastructure inadequacy, the study provides a strong foundation for prioritizing interventions that can significantly improve service reliability. Moreover, the study establishes a replicable framework that can be adopted for evaluating other rural–urban water supply systems within the country. In an era where water utility management must become more data-driven and forward-looking, the application of GIS and hydraulic models offers a practical pathway toward sustainable system performance and equitable distribution of safe water.

2. Methodology

The methodological framework adopted for this study was designed to comprehensively assess the performance of the 3-Districts Water Supply System (3-DWSS) through an integrated application of Geographic Information Systems (GIS) and hydraulic modelling. This approach enabled the combination of spatial infrastructure analytics with hydraulic behavior simulation to diagnose pressures, flows, pipe adequacy, demand patterns, and system vulnerabilities. The methodology was structured into four major components: data acquisition and preprocessing, development of a GIS spatial model, construction and calibration of a hydraulic simulation model using EPANET, and integration of GIS and hydraulic outputs for performance assessment. Each component is described in detail below.

The methodological sequence followed aligns with the procedures commonly applied in modern water supply system assessments internationally, and is consistent with approaches adopted by several authors who have evaluated complex water distribution networks (Hou et al., 2011; Behzadian & Kapelan, 2015; Araujo et al., 2006). These methods were adapted to suit the data availability, operational context and infrastructure characteristics of the 3-DWSS.

2.1 Data Acquisition and Preparation

The first stage of the methodology involved the acquisition, validation and preprocessing of spatial, hydraulic and demographic datasets. The accuracy of both GIS and hydraulic modelling relies substantially on the quality of input data; therefore, extensive effort was made to compile detailed and reliable datasets from multiple sources. The data sources included:

- As-built drawings and pipeline layout maps obtained from the Community Water and Sanitation Agency (CWSA). These documents provided information on pipeline routes, diameters, materials, system elevations, reservoir locations, and transmission main alignments.
- GPS surveys of key infrastructure components such as booster stations, elevated tanks, distribution nodes and terminal points. These were conducted to validate and supplement existing spatial data, particularly where records were outdated or incomplete.
- Topographic maps and digital elevation models (DEMs) used to capture elevation changes that significantly influence hydraulic behavior within the network.
- Operational records including pumping hours, flow meter readings, storage tank levels, system input volumes, and supply schedules across different districts.
- Population datasets and community settlement information obtained from district planning authorities and recent census updates, used to estimate spatially distributed water demand.
- Field observations and site inspections conducted to verify infrastructure conditions, identify undocumented pipes, confirm flow directions and understand operational constraints.

All datasets were checked for internal consistency, georeferenced to a common coordinate system (UTM Zone 31N, WGS84), and digitized where necessary. Attribute tables were developed for each infrastructure element, capturing information such as pipe diameter, length, material, service function, and elevation. Missing data points were reconstructed using field measurements and engineering judgment based on similar system segments.

2.2 Development of the GIS Spatial Model

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The GIS spatial model served as a foundation for visualizing and analyzing the entire water supply network. The model captured the full geometric configuration of the network, enabling interrogation of pipe alignments, node distributions, service zones, elevation gradients, and community growth patterns.

The GIS environment was built using ArcGIS software, wherein the following layers were created:

- Transmission mains and distribution pipelines digitized according to as-built drawings, validated using GPS coordinates.
- Storage reservoirs, including their elevations, capacities and spatial relations to supply zones.
- Booster pump stations and their operational linkages to downstream supply areas.
- Demand nodes, representing community clusters, public institutions, and service points.
- Elevation layers, including DEMs to support hydraulic gradient analysis.
- Administrative district boundaries, to contextualize service coverage across Ada East, Ada West, Ningo-Prampram, Shai Osudoku, Central Tongu and North Tongu.

Spatial queries and analyses were performed to determine pipeline lengths, classify pipes by diameter, and identify settlement expansions beyond the original design footprint of the system. GIS was also used to identify isolated pockets of development lacking formal network connections, which later informed scenario modelling. This spatial database formed the backbone of the hydraulic model, with all nodes and pipes assigned coordinates, elevations and attribute parameters directly derived from the GIS dataset.

2.3 Hydraulic Model Development Using EPANET

The hydraulic modelling component was conducted using EPANET 2.2, a widely used software package for simulating hydraulic and water quality behavior in pressurized pipe networks. The EPANET model was designed to reflect the current operational configuration of the 3-DWSS, replicating its transmission mains, distribution pipelines, tanks, pumps and nodes.

2.3.1 Network Representation

Each pipeline in the network was represented as a pipe element within EPANET, assigned with:

- diameter
- length
- material-based roughness coefficient
- elevation
- connectivity to upstream and downstream nodes

Reservoirs were represented as storage tanks with specified elevations, minimum and maximum water levels, and inlet/outlet pipe configurations. Pumping stations were modeled using pump curves provided by CWSA or otherwise approximated from pump specifications based on installations manuals. Valves were included where flow control structures were identified in the field.

2.3.2 Demand Allocation

Water demand was allocated to nodes based on population distribution patterns from district census data and verified community service population figures from CWSA operational records. Demand was estimated using average per capita consumption values of the CWSA design guideline, 2010 and adjusted for institutional, commercial and public-use components within more urbanized areas.

Daily demand patterns were incorporated through demand multipliers, accounting for morning and evening peaks consistent with rural–urban consumption behavior in Ghana.

2.3.3 Model Calibration

Calibration was undertaken to ensure that model outputs closely matched field-measured flows and pressures. Field measurements included:

- pressure readings at selected nodes
- flow readings at transmission mains
- tank filling and drawdown rates

Where discrepancies arose, parameters such as pipe roughness, demands and pump operation schedules were refined iteratively until model results conformed reasonably with field conditions. This calibration process enhanced the confidence level of subsequent scenario simulations.

2.4 Integration of GIS and Hydraulic Models

Following construction and calibration of the hydraulic model, GIS was used to visualize and interpret hydraulic outputs spatially. EPANET simulation results such as pressure distribution, node head, pipe flow rates, velocities and head losses were exported and imported back into GIS. These were joined to the spatial pipeline and node layers, enabling thematic maps that revealed the spatial distribution of hydraulic performance.

This integration allowed for clearer identification of:

- pressure-deficient zones, typically located in remote areas, high-elevation communities or terminal ends of the network
- overloaded transmission segments exhibiting high velocities and head losses
- pipeline bottlenecks where undersized diameters restrict flow to downstream communities

- areas experiencing intermittent or inadequate supply due to limited hydraulic conveyance capacity
- spatial patterns of inequality, correlating service levels with population distribution and elevation

GIS visualization also allowed the model to be used interactively with stakeholders, supporting decision discussions on where to prioritize rehabilitation or expansion efforts.

2.5 Scenario Modelling

To assess potential improvement strategies, several scenarios were simulated using the calibrated hydraulic model. These included:

1. Pipe resizing scenarios, where undersized pipelines were replaced with larger diameters to observe improvements in downstream pressures.
2. Network expansion scenarios, simulating new distribution lines to underserved communities identified through GIS analysis.
3. Pumping and storage enhancement scenarios, evaluating the impact of increased pump capacities or additional storage on system performance.
4. Population growth scenarios, projecting demand increases based on anticipated growth rates across the six districts.

Each scenario was analyzed for its effect on pressures, flows, nodal demand satisfaction, and system reliability. Comparisons between existing and improved scenarios provided critical insights into which interventions produced the most significant hydraulic benefits at the lowest infrastructure cost.

3. Results and Discussion

The integration of GIS and hydraulic modelling provided a comprehensive and coherent assessment of the performance of the 3-Districts Water Supply System (3-DWSS). The following discussion presents the findings from both spatial and hydraulic analyses, highlighting pressure patterns, flow behavior, demand distribution, and scenario-based improvements.

3.1 Spatial Analysis of the Water Supply Network

The GIS spatial model revealed the full geometric configuration of the 3-DWSS, including transmission mains, distribution pipelines, reservoirs, and standpipes. As shown in Figure 2, the system layout follows a linear pattern extending from the Aveyime Treatment Plant through several districts, branching into multiple smaller delivery pipelines as it approaches remote communities.

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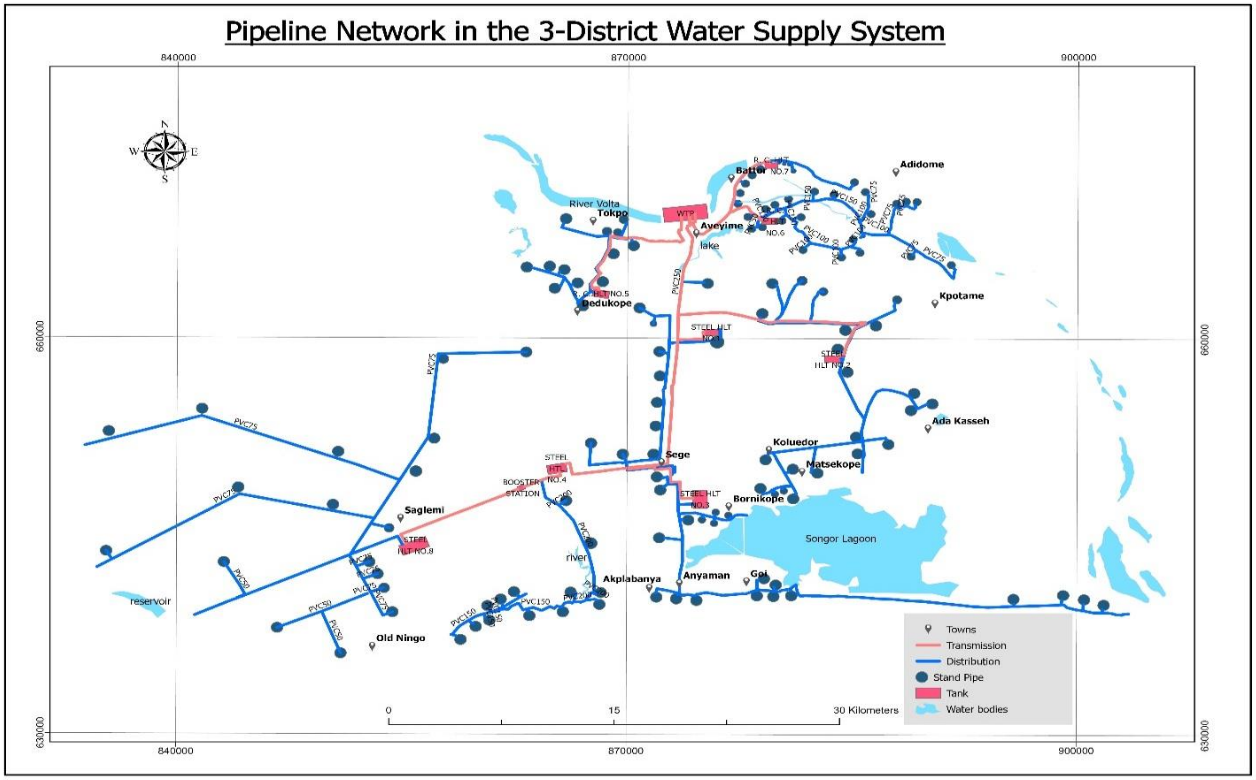

Figure 2: GIS model of the 3-Districts Water Supply System

Source: Researcher's Construct (2025)

The pipeline diameter distribution, illustrated in Figure 3 shows a progressive reduction in pipe size from 180 mm at the distribution mains to between 45 and 63 mm in terminal branches. This variation plays a major role in supply imbalances, as smaller diameters restrict the volume of water reaching distant communities. In several rural communities, long stretches of small piping are observed which is a structural characteristic that significantly influences downstream hydraulic behavior.

Figure 1B integrates population density (1 dot = 400 people) with pipeline infrastructure typologies transmission (red), distribution (blue), standpipes (cyan), tanks (magenta), and towns across the 3-District Water Supply System (3DWSS). It effectively demonstrates how geospatial intelligence can drive equity in water access by aligning infrastructure development with demographic concentration. This integrated approach reflects a service-oriented planning model where infrastructure is not only designed for current demand but also to accommodate future growth, echoing principles outlined in UN-Habitat's Water for Cities Programme (UN-Habitat, 2010). The southern and central corridors of the map show higher population concentrations (denser black dots) and a corresponding denser pipeline layout. Conversely, the northern fringes, despite notable population presence, exhibit sparse or no visible pipeline extension. This spatial imbalance signals a significant service coverage gap between urbanized zones and peri-urban or rural settlements, a pattern also observed in the hydraulic audits of Accra (Nyarko & Odai, 2008). This mismatch aligns with Giné-Garriga et al. (2017), who assert that in developing regions, infrastructure often lags behind settlement growth, leading to service exclusion for emerging communities.

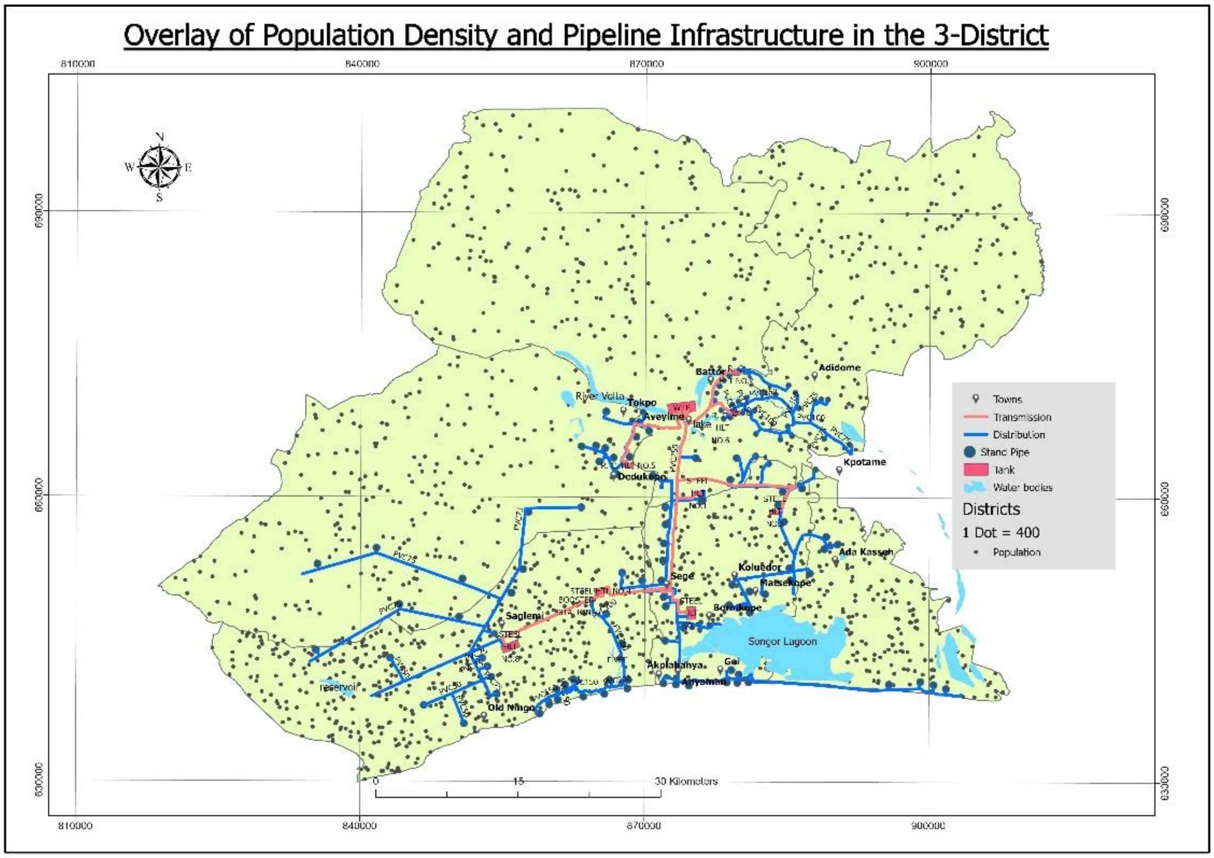

Figure 3: Overlay of Population Density and Pipe Network of 3-District water system

Source: Researcher's Construct (2025)

3.2 Hydraulic Simulation Results

Hydraulic model in Figure 4 provided insights into flows, pressures, velocities, and head losses throughout the system.

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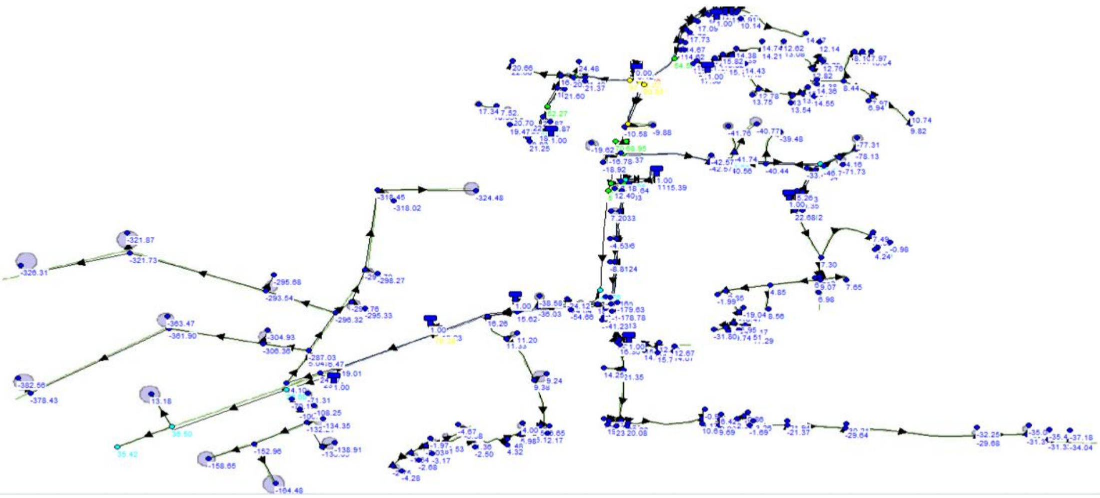

Figure 4: Observed Hydraulic layout of the 3-Districts Water Supply System

Source: Researcher's Construct (2025)

3.2.1 Pressure and Headloss Distribution

The pressure distribution in Figure 2 reveals widespread deficiencies across the network. While areas located nearer to the primary distribution pipelines maintain acceptable pressures (5m-13m), most of the upstream and distant communities experience significantly low and negative pressures. More than 60% of demand nodes record pressures below 10 m, and terminal nodes located in remote sections of Central Tongu and North Tongu, Ningo Prampram and Ada East and West show pressures dropping to as low as –0.5 m. These negative pressures indicate situations where water cannot reach certain nodes during peak demand, or worse, situations where contaminated water from the surroundings may enter the pipes if leakage points exist.

Head loss distribution confirms that frictional losses increase dramatically along long-distance pipelines. Pipe segments feeding Central and North Tongu experience high cumulative head loss mostly due to small pipe sizes and high demand levels. These losses contribute directly to the low-pressure issues observed at terminal nodes. The combination of structural pipeline limitations and elevation differences explains the severe hydraulic stress identified in several communities

3.2.2 Velocity and Flow Behavior

Velocity distribution along the pipelines as shown in Figure 2 indicates that several transmission mains experience high velocities, sometimes exceeding 2.5 m/s, reflecting an overloaded condition that increases the risk of pipe bursts. In contrast, low velocities (<0.3 m/s) are found in distant terminal areas, suggesting potential stagnation, sediment deposition, and water quality deterioration.

The 3-Districts Water Supply System operates on six high lift that convey water through an 88.846 km transmission pipeline to the eight (8) high level tanks and a booster station. Each pump is rated with a flow capacity of 120 m³/h; however, the pumps operate under different head conditions. Specifically, three of the pumps are designed to operate at a total dynamic head of 120 meters, while the remaining three operate at a lower head of 90 meters. Despite the uniform flow capacities, the varying head conditions significantly influence the combined hydraulic output.

According to the results from the hydraulic simulation model based on actual field conditions, the total effective flow delivered by all six pumps is approximately 426 m³/h. This output is considerably lower than the theoretical combined flow of 604.26 m³/h, which was simulated under idealized conditions where all six pumps were assumed to operate uniformly at 120 m³/h with a consistent head of 120 meters. The observed discrepancy of 178.26 m³/h between the actual and ideal scenarios highlights the critical influence of differential pump head ratings and pipeline characteristics such as pipe diameter, and frictional losses.

3.3 Demand Distribution Characteristics

The nodal demands in the observed system range from 0.01 m³/day (min) to 3.5 m³/day (max). From a hydraulic perspective, the inadequacy of the observed system becomes evident when subjected to both current and 15-year projected demands. Results indicate that under the current diameter of pipes are unable to carry the current and projected demand flows and hence, the system exhibits negative pressures at critical nodes, signaling a failure to meet minimum pressure requirements as stipulated in many design standards (AWWA, 2012). This phenomenon explains why numerous communities remain underserved, despite the operation of high-lift pumps that inject water into the pipelines. The problem is not the absence of supply but the hydraulic incapacity of the network to deliver water due to undersized pipes and high frictional losses and also confirmed by Mays, 2000 and Walski et al., 2003).

3.5 Scenario Modelling Results

Several improvement scenarios were simulated to evaluate potential interventions.

3.5.1 Scenario 1: Pipeline Resizing

Pipeline upgrades simulated in Figure 5 show substantial improvements. Resizing critical segments from 63–90 mm to 160–220 mm increased minimum pressures from –0.5 m to approximately +15 m. Flow distribution also improved, reducing the hydraulic imbalance observed in the base scenario. Pipe diameter plays a critical role in determining the hydraulic efficiency of water distribution systems. The diameter of a pipeline directly affects both the flow capacity and head loss due to friction. Larger diameters reduce frictional resistance and, consequently, the energy required to transport water over long distances.

According to the Darcy-Weisbach equation, head loss due to friction (hf) is inversely proportional to the fifth power of the pipe diameter (D) for a given flow rate (Q):

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Hf= $F.L.\frac{V^2}{\mathrm{D}2g}$

This relationship implies that even a modest increase in pipe diameter can lead to a substantial reduction in head loss, thereby improving flow efficiency as reported by Mays, 2000. Smaller diameter pipes require higher pressure heads to maintain the same flow rate, increasing pumping energy requirements and operational costs. Conversely, oversized pipes may result in unnecessarily high capital expenditures and issues such as sediment deposition due to reduced flow velocities (Bhave & Gupta, 2006).

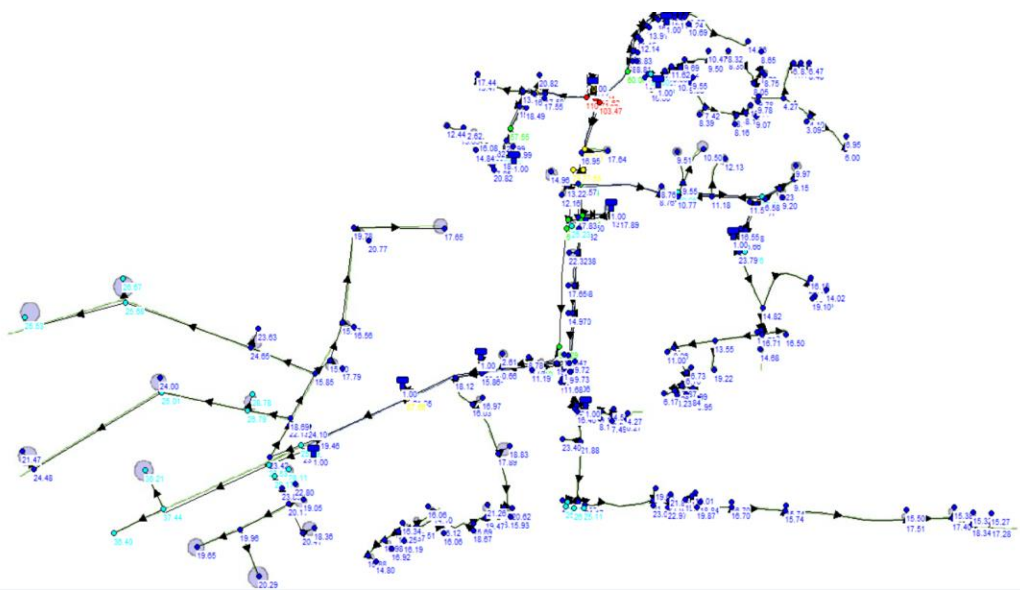

Figure 5: Ideal Simulated Hydraulic layout of the 3-Districts Water Supply System

Source: Researcher’s Construct (2025)

In simulation studies and practical design scenarios, it has been consistently observed that undersized pipes lead to significant frictional losses, which in turn reduce the effective discharge at the network’s endpoints (Todini, 2000). For example, Vairavamoorthy and Lumbers (1998) demonstrated that increasing the diameter of critical segments in a transmission line significantly improves hydraulic performance without proportionally increasing cost, provided the optimization is strategically applied.

Moreover, Ostfeld et al. (2012) emphasized in their benchmark study on water distribution system design that pipe sizing must be optimized alongside pump selection to achieve a cost-effective and energy-efficient system. When pipe diameters are not appropriately matched with pump capacities, the system may suffer from reduced throughput and increased energy consumption.

The performance of the simulated ideal model, which features increased pipe diameters, shows a marked improvement in nodal demands and corresponding positive pressure values throughout the network. This improvement validates the hypothesis that enlarging pipe diameters can significantly enhance distribution efficiency by reducing frictional losses and maintaining adequate pressure levels, even during peak demand periods.

Again, these findings align with several studies in the domain of water distribution system optimization. For instance, Fujiwara and Khang (1990) demonstrated through multi-objective optimization that enlarging critical pipe segments is essential for achieving demand satisfaction without compromising pressure stability. Similarly, Ostfeld et al. (2008) in their Battle of the Water Networks (BWN) study emphasized that network resilience and pressure management improve significantly when pipe diameters are appropriately matched to demand patterns and population growth projections.

In the context of the 3-District Water System, the flow discrepancy between the observed and ideal simulations can, in part, be attributed to differences in pipe diameters along the 88.846 km transmission and 296.168 km of distribution pipeline. Smaller diameter sections likely contribute to elevated frictional losses, thereby reducing the net flow output despite the rated pump capacities. The positive pressures and enhanced nodal demands observed in the ideal simulated model further justify network upgrades to align with future service reliability expectations and urban growth trends.

3.5.2 Scenario 2: Pump Reconfiguration

This phenomenon is consistent with findings from several other studies in the field of water distribution system optimization. For instance, Cheung et al. (2005) observed that in multi-pump operations, disparities in pump head can lead to flow imbalances and suboptimal performance due to hydraulic interference. Similarly, Todini (2000) emphasized the role of dynamic head variation and pipe hydraulic resistance in reducing system efficiency, especially in extended transmission systems. Moreover, Diao et al. (2013) also demonstrated through EPANET-based simulations that the non-uniform operation of pumps in series or parallel configurations can result in significant reductions in flow capacity, primarily due to pressure head mismatches and increased energy losses

3.5.3 Scenario 3: Future Demand Growth

The Figures 6 and 7 illustrates observed and ideal simulated nodes are spatially superimposed on distribution layout with corresponding demand concentrations at each service point, offering a granular view of localized demand behavior.

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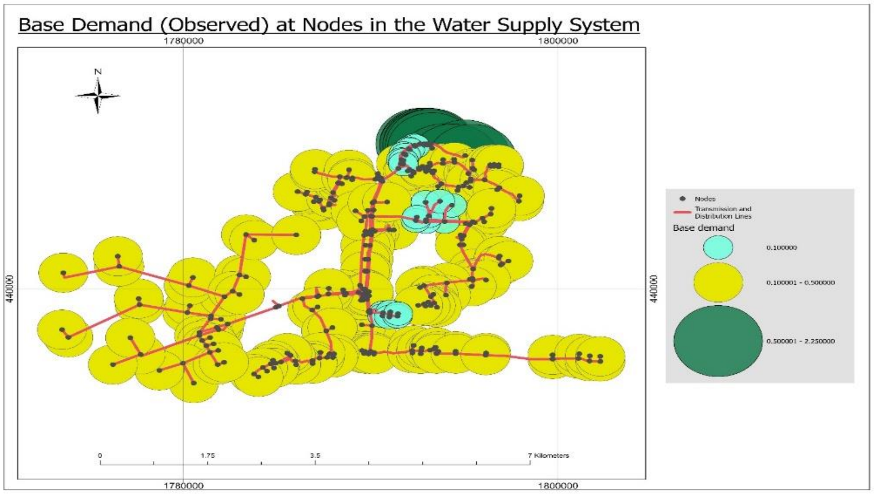

Figure 6: Nodal Base demand (Observed) within water system

Source: Researcher's Construct (2025)

Mapping indicated base demand at node level provides critical insights into spatial heterogeneity in water demand, a vital parameter for, hydraulic modeling calibration, infrastructure sizing, demand forecasting, pressure zoning and storage tank placement. The observed clustering of high-demand nodes in the north-central portion of the network suggests zones of high population density or industrial/commercial activity. This is in line with findings by Behzadian et al. (2009), who emphasize the need for geospatial differentiation of demand patterns for optimized pressure and flow regulation. Moreover, the presence of low-demand nodes (cyan) at the network periphery indicates sparsely populated areas or under-served zones, which is critical for planning future network expansion and demand-driven pipe resizing (Muranho et al., 2014).

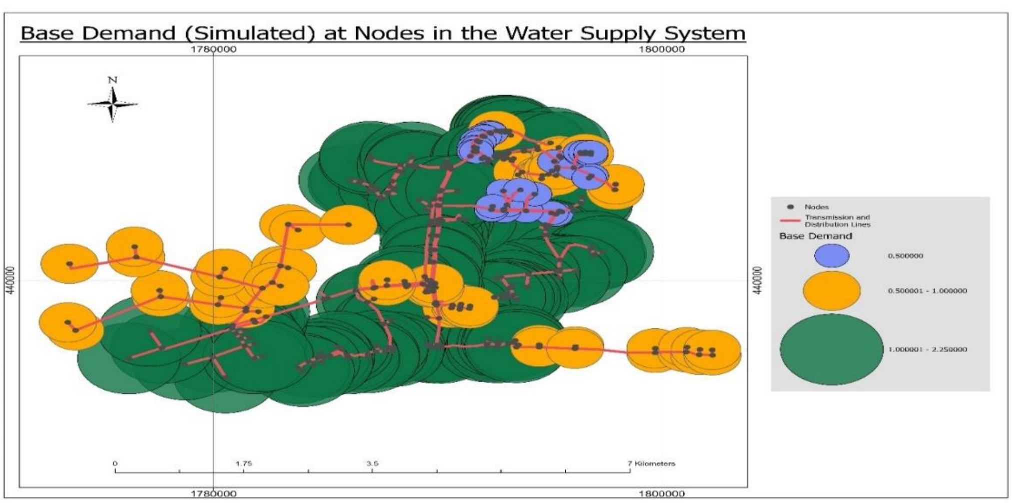

Figure 7: Nodal Base demand Simulated within water system, Source: Researcher's Construct (2025)

The map also reveals a radial-branch topology in the pipe layout, indicative of distribution strategy where main pipelines feed into localized distribution arms. Such design supports efficient transport over long distances while accommodating nodal variation in demand. According to Walski et al. (2003), radial systems are advantageous for minimizing head loss along primary conduits while ensuring hydraulic efficiency. The model extends existing knowledge by integrating observed consumption data into a spatially referenced hydraulic model, enhancing the model's realism, calibration fidelity, and decision-making potential.

Several global studies have leveraged similar spatial analyses to improve water distribution planning: A study by Tanyimboh & Templeman (2010), emphasized the importance of node-based demand simulation in pressure-deficit regions which is similar to the 3DWSS nodel-level base demand mapping. Tanyimboh & Templeman (2010), Diao et al. (2013), Wambua et al. (2020) and Jain et al. (2014) also used observed demand clusters in Beijing and Nairobi to optimize pipe rehabilitation. This helped to identify undersupplied informal settlements using mapping in enabled zone-based pressure management. In all these cases, demand-based node classification formed the basis for future asset prioritization, leakage detection, and non-revenue water (NRW) mitigation. The map connotes analytical narrative, providing a template for data-driven system optimization. The observed base demand map of 3DWSS offers futuristic contributions both in diagnostic and predictive utilities to identify where service levels may be inadequate or over-supplied as well as provision of information on dynamic modeling of future demand scenarios under growth, climate variability, or infrastructure shifts.

4. Conclusion

This study utilized an integrated Geographic Information Systems (GIS) and hydraulic modelling approach to evaluate the 3-Districts Water Supply System (3-DWSS) in Ghana, revealing structural, operational, and hydraulic weaknesses that traditional methods could not detect. The analysis uncovered significant issues, including undersized pipelines, elevation-related pressure drops, and imbalanced flow conditions, all contributing to unreliable supply and distribution inequities across the six service districts. Rapid population growth and expansion beyond the original design footprint further strain the system, particularly in high-elevation and peripheral areas. Hydraulic simulations showed over 60% of system nodes operate below acceptable pressure levels, with some experiencing negative pressures. Scenario modelling demonstrated that strategic interventions such as pipeline resizing and pump reconfiguration could markedly improve system performance, but projected future demands underscore the urgency for upgrades. Overall, the study highlights the value of a GIS-hydraulic framework in diagnosing and improving rural–urban water systems and offers a replicable model for similar systems in developing regions.

5.Recommendations

To enhance the performance and long-term sustainability of the 3-Districts Water Supply System (3-DWSS), the study recommends several key interventions. These include resizing critical pipelines to reduce pressure drops and friction losses, and expanding the network to serve newly developed communities beyond the original system design. Optimizing pump operations through better scheduling, pressure control, and automation is also advised to improve distribution efficiency. The study emphasizes the need for regular GIS and hydraulic assessments to keep pace with changing settlement patterns and demands. Additionally, establishing a formal asset management framework will support strategic maintenance and infrastructure upgrades. Finally, incorporating community input into planning processes will help validate system models and promote more inclusive and effective service delivery.

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