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Original Research Article

Spatial Analysis and Optimization of Water Pipeline Distribution Networks in Maradun, Zamfara State

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KEYWORDS

Geographic Information System (GIS),
Water distribution network,
Pipeline infrastructure,
Spatial analysis,
Water supply,
Infrastructure planning,
Maradun,
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Sustainable urban development.

ABSTRACT

Inadequate water distribution infrastructure remains a major challenge to effective municipal planning and sustainable water supply in many developing regions. This study evaluates the existing water distribution pipeline infrastructure in Maradun, Zamfara State, Nigeria, and develops a geospatially optimized network expansion plan to address identified spatial and service-coverage deficiencies. Geographic Information System (GIS) techniques and spatial analysis were employed to map and assess key water infrastructure components, including the Bakolori Dam, centralized Water Treatment Plant (WTP), storage tanks, transmission lines, and existing distribution pipelines. The assessment revealed substantial spatial limitations in the existing distribution network, with pipeline coverage extending across only 1.00 km^2, equivalent to approximately 15% of the 5.53 km^2 metropolitan area. This limited coverage indicates significant disparities in access to municipal water infrastructure and highlights the need for systematic network expansion. Based on spatial optimization and infrastructure connectivity analysis, the study proposes an additional 28.648 km of distribution pipelines and 8.130 km of transmission lines to extend water services to currently underserved areas. The proposed geospatial network substantially improves the spatial reach and connectivity of the municipal water supply system and provides a practical framework for prioritizing infrastructure expansion. The study demonstrates the value of GIS-based spatial planning in identifying infrastructure gaps, optimizing pipeline networks, and supporting evidence-based decisions for sustainable urban water management. The proposed approach can serve as a scalable model for water infrastructure planning in Maradun and other rapidly developing communities in sub-Saharan Africa.

CITATION

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INTRODUCTION

Water is an essential yet finite natural resource that underpins human survival, public health, environmental sustainability, and socio-economic development. Its availability and reliable distribution are particularly important in densely populated urban and rapidly developing areas, where increasing demand places considerable pressure on existing water resources and infrastructure (Katko, 2015). Population growth and urban expansion are accompanied by the development of residential areas, road networks, commercial activities, and other urban services. These changes modify land-use patterns and the urban hydrological cycle, potentially altering infiltration, surface runoff, groundwater recharge, drainage patterns, and overall water availability (McGrane, 2016). Consequently, effective planning and management of urban water infrastructure are essential for ensuring equitable and sustainable access to potable water.

Access to safe and reliable potable water is a fundamental component of urban sustainability and public health. Nevertheless, many rapidly growing urban settlements in Nigeria continue to experience inadequate, aging, poorly documented, and spatially constrained water distribution infrastructure. These limitations often result in unequal access, intermittent supply, low network coverage, and inefficient utilization of available water resources (Amoo et al., 2025). The challenge is particularly pronounced in developing communities where population growth and physical expansion frequently outpace the development and upgrading of municipal infrastructure. Addressing these challenges requires not only increased water production but also effective spatial planning of transmission and distribution networks to ensure that available water resources reach underserved and emerging urban areas.

The development of urban water distribution systems has a long historical trajectory. Early water conveyance systems can be traced to the Bronze Age (approximately 3200–1100 B.C.), While subsequent civilizations, particularly the Romans, further developed and implemented these technologies on a much larger scale, constructing extensive aqueduct systems that conveyed water from distant sources to urban centres, with some Roman aqueducts extending over 100 km (Mala-Jetmarova et al., 2015). Modern water distribution systems have evolved considerably from these early networks and now incorporate complex arrangements of pipelines, storage reservoirs, pumping stations, treatment facilities, valves, and other hydraulic components. Collectively, these facilities constitute a substantial proportion of the physical infrastructure required to provide reliable water services. However, the complexity and extensive spatial distribution of modern water supply networks present significant challenges for effective planning, operation, maintenance, and risk management, particularly with respect to preventing localized contamination and minimizing service disruptions (National Research Council, 2006).

The fundamental technical objective of a water distribution network is to convey safe and acceptable-quality potable water to consumers in sufficient quantities and at appropriate pressures while maintaining operational reliability and economic efficiency. A well-designed network should provide adequate service pressure under normal operating conditions, accommodate variations in demand, and support emergency requirements such as fire protection where applicable (National Research Council, 2006). Achieving these objectives requires accurate knowledge of the spatial configuration of existing infrastructure, the location of water sources and treatment facilities, storage capacity, existing and projected demand, and the geographical distribution of served and unserved communities.

In Maradun, Zamfara State, the availability of the Bakolori Dam as a major water resource provides an important foundation for municipal water supply. However, the presence of a substantial water source does not necessarily translate into equitable access to potable water. Spatial limitations in the existing distribution network, inadequate pipeline coverage, and insufficient connectivity between major water facilities and expanding urban settlements can significantly constrain the effective utilization of available water resources. Furthermore, conventional infrastructure planning approaches may not provide the spatial precision required to identify service gaps, determine priority areas for expansion, and optimize pipeline routing and facility connectivity (Sani, 2024). Consequently, there is a need for systematic spatial assessment capable of integrating existing infrastructure with the geographical characteristics and expansion patterns of the urban area.

Geographic Information Systems (GIS) provide an effective framework for addressing these challenges. GIS enables the integration, visualization, management, and analysis of geographically referenced information, making it particularly useful for water infrastructure planning and management. Through spatial analysis, GIS can be used to map existing pipelines and water facilities, identify underserved areas, assess network coverage, evaluate spatial relationships among infrastructure components, and support the development of alternative expansion scenarios. It therefore provides policymakers, urban planners, engineers, and other stakeholders with an effective spatial decision-support framework for infrastructure planning, network assessment, and efficient allocation of water resources (Amoo et al., 2025).

Against this background, this study applies GIS-based spatial analysis to evaluate the existing water distribution infrastructure in Maradun and develop an optimized expansion strategy for improving municipal water coverage. Specifically, the study seeks to:

Map and inventory the existing water pipeline infrastructure and associated facilities, including water treatment plants, storage tanks, transmission lines, and distribution pipelines;

Quantify the existing water service deficit by determining the spatial extent of pipeline coverage relative to the total metropolitan area; and

Develop an optimized pipeline expansion network capable of extending water services to currently underserved areas and improving the spatial efficiency and connectivity of the municipal water distribution system.

The study is expected to provide a GIS-based planning framework that can support informed investment decisions, prioritize infrastructure expansion, and promote more equitable and sustainable access to potable water in Maradun. More broadly, the approach demonstrates how geospatial technologies can contribute to evidence-based urban water infrastructure planning in rapidly developing communities across Nigeria and other sub-Saharan African regions.

MATERIALS AND METHODS

Study Area

The study focuses on Maradun, a prominent region located in Zamfara State, Nigeria. The geographic coordinates of the primary infrastructure network sit roughly between 6˚10'0''E to 6˚11'40''E longitude and 12˚30'50''N to 12˚33'20''N latitude. The primary water feedstock for the municipality is drawn directly from the adjacent Bakolori Dam water body.

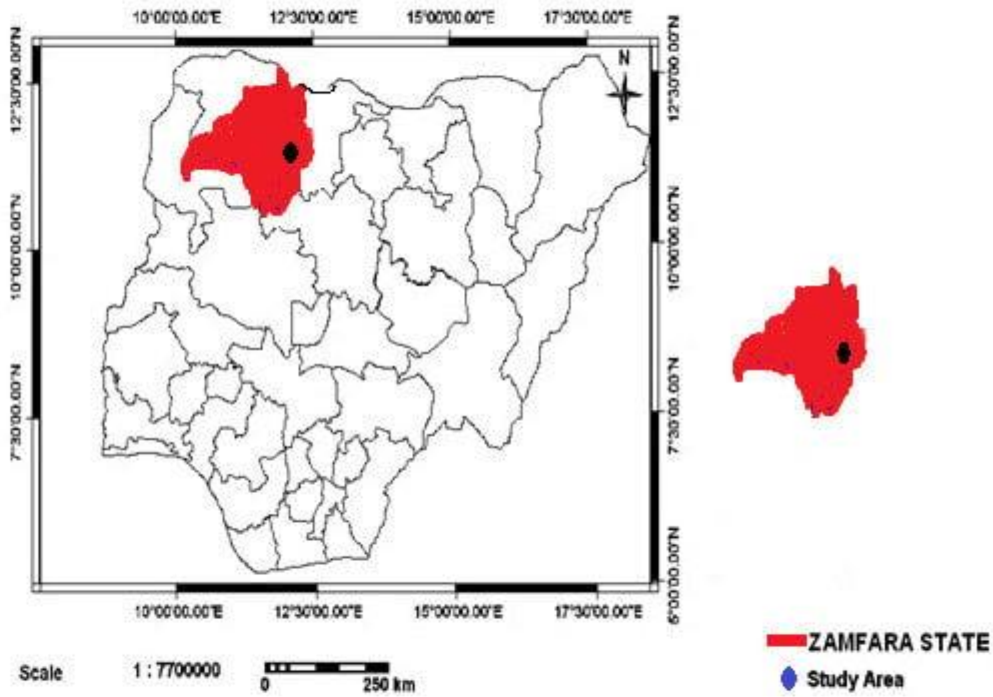

Figure 1: Map showing the study area (Maradun)

Materials, Hardware and Software Used

The study utilized a combination of field equipment, geospatial software, and general-purpose computer applications for data acquisition, processing, spatial analysis, mapping, and documentation. The materials and tools employed in the study included:

1. Global Positioning System (GPS) receiver – used for field acquisition and recording of the geographic coordinates of existing water infrastructure, including pipelines, storage facilities, treatment plants, and other relevant features.
2. ArcGIS Desktop 10.3 – used for spatial data management, georeferencing, digitization, geospatial analysis, pipeline network mapping, spatial queries, and production of thematic maps.
3. ERDAS IMAGINE 9.2 – used for processing and analysis of remotely sensed imagery and preparation of spatial datasets required for the study.
4. Google Earth – used for visual interpretation of satellite imagery, identification of urban features, preliminary assessment of infrastructure locations, and verification of selected spatial features.
5. Microsoft Excel – used for data organization, tabulation, basic statistical calculations, measurement of pipeline lengths and areas, and preparation of datasets for subsequent GIS analysis.
6. Microsoft Word – used for data documentation, organization of the research report, presentation of results, and preparation of tables and other textual materials.
7. Laptop computer – used as the primary computing platform for data storage, processing, GIS analysis, mapping, statistical analysis, and report preparation.

The procedural steps used in the research are summarized in Figure 2.

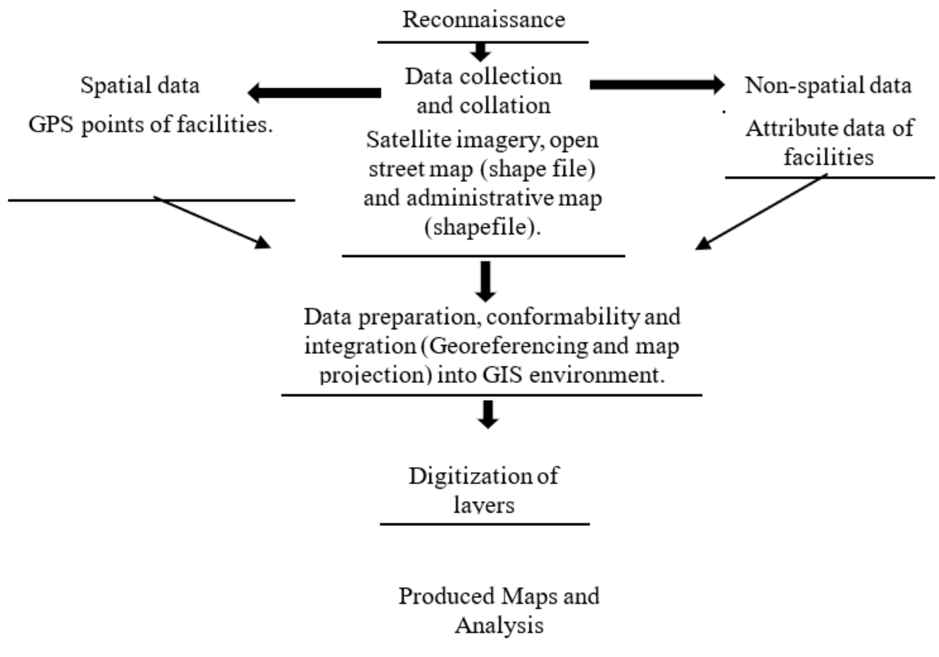

Figure 2: A flow diagram of the steps used in carrying out the work

Data Collection and Processing Procedures

The study adopted a systematic geospatial data acquisition and processing workflow comprising reconnaissance, data collection and collation, data preparation and integration, digitization, spatial analysis, and map production.

Reconnaissance Survey

An initial reconnaissance survey was conducted to obtain a general understanding of the spatial organization and existing condition of the water supply infrastructure in Maradun. The survey involved preliminary visits to major water facilities, including storage tanks, treatment facilities, transmission infrastructure, and distribution networks. The information obtained during this stage was used to identify relevant data requirements, determine accessible locations, and develop an appropriate field data collection strategy.

Data Collection and Collation

Data collection was organized into two major categories: spatial and non-spatial data.

Spatial Data

Spatial datasets comprised the geographic coordinates of existing water infrastructure obtained using a Global Positioning System (GPS) receiver, satellite imagery, OpenStreetMap (OSM) shapefiles, and available administrative boundary maps. The spatial data provided the geographic framework for mapping the existing water infrastructure and assessing its relationship with the spatial extent of the Maradun metropolitan area.

Non-Spatial Data:

Non-spatial data consisted of attribute information associated with the identified water infrastructure. These data included facility type, storage tank capacity, operational status, and other relevant descriptive information. For example, storage facilities with capacities of approximately 120,000 L and 400,000 L were recorded and incorporated into the GIS database.

Data Preparation, Georeferencing and Integration

The collected datasets were subjected to preprocessing before integration into the GIS environment. Satellite imagery and other spatial datasets were georeferenced where necessary, and appropriate coordinate reference systems and map projections were assigned to ensure spatial consistency. GPS coordinates, satellite imagery, OpenStreetMap shapefiles, and administrative boundaries were subsequently integrated within the GIS environment. This process ensured accurate spatial alignment and minimized positional discrepancies among the different datasets.

Digitization and Generation of GIS Layers

Relevant features identified from the prepared spatial datasets were digitized within the GIS environment. Existing water pipelines, storage tanks, treatment facilities, transmission lines, administrative boundaries, road networks, and other relevant features were converted into appropriate vector layers. Point, line, and polygon feature classes were created according to the geometric characteristics of each feature. The resulting GIS database provided a structured and editable representation of the existing water infrastructure.

Spatial Analysis and Map Production

The digitized datasets were subjected to spatial analysis to evaluate the distribution and coverage of the existing water supply infrastructure. Pipeline lengths, facility locations, storage capacities, and the spatial extent of existing service coverage were determined. Spatial overlay and proximity analyses were subsequently employed to identify underserved areas and assess potential routes for network expansion. Based on the results of these analyses, proposed transmission and distribution pipeline networks were developed to improve spatial coverage and connectivity. The final outputs included maps showing the existing pipeline network, locations and capacities of storage facilities, treatment infrastructure, existing service coverage, and proposed pipeline expansion areas.

RESULTS AND DISCUSSION

Empirical Assessment of the Existing Water Infrastructure Coverage

The GIS-based spatial analysis revealed a substantial disparity between the geographical extent of Maradun metropolis and the existing municipal water distribution infrastructure. The total mapped metropolitan area was approximately 5.53 km^2, whereas the active pipeline network provided spatial coverage of only approximately 1.00 km^2. Based on these measurements, the existing pipeline network covers approximately 18.1% of the metropolitan area, leaving approximately 81.9% of the area outside the mapped formal pipeline network (Figure 3).

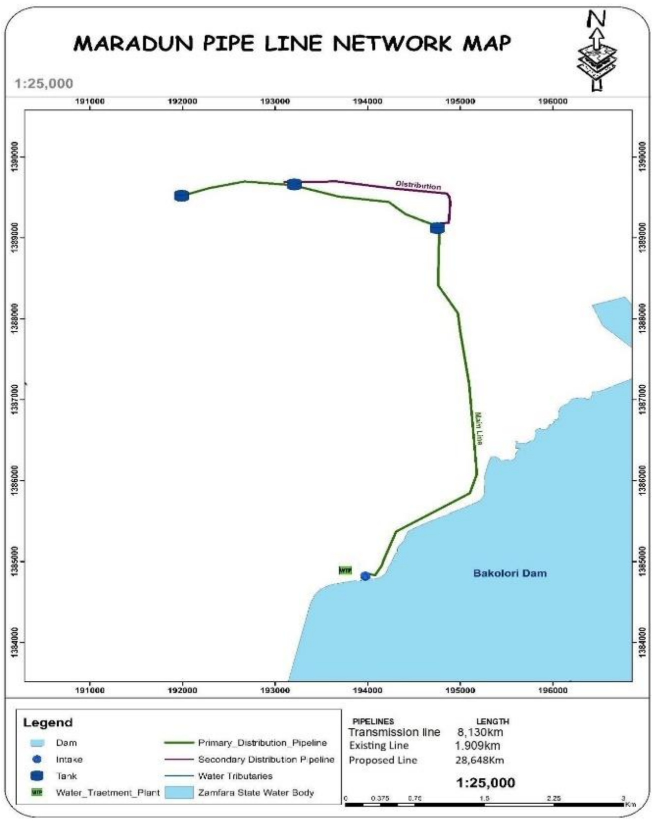

Figure 3: Map showing existing Pipeline network and spatial distribution of tanks and other facilities

The result demonstrates a pronounced spatial deficit in the municipal water distribution system. The existing network is concentrated within a relatively restricted corridor of the metropolis, while substantial portions of the western and northwestern sectors remain outside the direct reach of the mapped pipeline infrastructure. This pattern indicates that the geographical expansion of Maradun has progressed considerably beyond the existing water-distribution footprint.

The finding has important implications for sustainable urban water planning. Access to safe and reliable drinking water depends not only on the availability of water resources but also on the ability of infrastructure to convey treated water to areas of demand. The World Health Organization identifies safely managed drinking water as an essential public-health requirement and emphasizes that water should be available when needed, accessible, and free from contamination (WHO, 2023). More recent WHO/UNICEF monitoring also demonstrates that significant inequalities in drinking-water access persist globally, with urban and low-income populations continuing to experience important service gaps (WHO & UNICEF, 2025).

It is important to distinguish spatial infrastructure coverage from population-level access. The finding that approximately 81.9% of the metropolitan area lies outside the mapped pipeline network does not necessarily mean that 81.9% of the population lacks access to potable water. Residents outside the formal pipeline network may obtain water from boreholes, wells, water vendors, or other sources, while some residents within the mapped coverage area may not have direct household connections. Therefore, the 81.9% figure should be interpreted specifically as an urban land-area infrastructure coverage deficit.

This distinction is particularly important because contemporary water-supply planning increasingly recognizes the need to identify not merely the presence of infrastructure but also its spatial relationship with population, demand, and service accessibility. The WHO/UNICEF Joint Monitoring Programme reports that inequalities in drinking-water services remain substantial and that the number of people lacking safely managed drinking-water services has continued to increase in some urban and low-income settings (WHO & UNICEF, 2025).

The GIS results therefore establish that the major challenge in Maradun is not simply the availability of a water resource, but the limited spatial reach and connectivity of the existing distribution infrastructure. This finding provides the basis for evaluating the topology and attributes of the existing network and developing an appropriate expansion strategy.

Existing Network Topology and Infrastructure Attributes

The spatial configuration of Maradun's existing water supply network is strongly anchored by the Bakolori Dam, which serves as the principal raw-water source for the municipal water supply system. Raw water from the dam is conveyed to the associated Water Treatment Plant (WTP), located within the southern portion of the study-area corridor. Following treatment, water is conveyed towards the urban settlement through the existing transmission network.

The GIS inventory identified a predominantly linear and corridor-oriented network topology. The principal transmission pipeline extends approximately 8.130 km from the treatment facility towards the developed portion of Maradun. A secondary distribution pipeline of approximately 1.909 km branches from the primary line to serve localized areas. Consequently, the mapped existing transmission and secondary distribution pipelines have a combined length of approximately 10.039 km. Thus, the existing mapped pipeline network comprises approximately 10.039 km of transmission and distribution infrastructure (Figure 4).

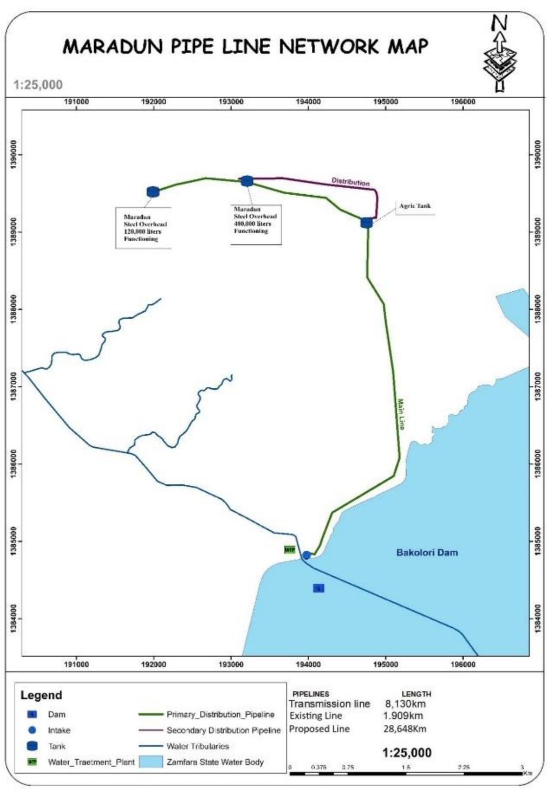

Figure 4: Map showing existing Pipeline network and tagged attribute data spatial distribution of tanks and other facilities

The predominantly linear structure has implications for the operational flexibility and resilience of the network. Water distribution systems are spatially organized networks in which connectivity, redundancy, and the availability of alternative flow paths influence operational efficiency, reliability, and vulnerability to failure (Yazdani & Jeffrey, 2011). Networks with limited redundancy may have greater dependence on individual transmission corridors, making service continuity more sensitive to failures, maintenance activities, or disruptions affecting critical links.

Two major elevated storage facilities were identified: the 120,000-L Maradun Steel Overhead Tank and the 400,000-L Maradun Steel Overhead Tank. Together, the two reservoirs provide a combined nominal storage capacity of approximately 520 m^3.

The existence of these storage facilities represents an important strength of the existing water-supply system because storage can provide operational buffering between water production and consumption and can help accommodate temporal variations in demand. However, the spatial concentration of the storage facilities within the existing service corridor limits their potential contribution to improving access in peripheral parts of the metropolis. Consequently, infrastructure capacity must be considered together with infrastructure location, network connectivity, and spatial demand distribution.

The topology of the existing system further suggests that the network has evolved primarily as a supply corridor from the treatment facility towards established areas rather than as a fully integrated urban distribution grid. This type of configuration may be adequate for a relatively compact settlement but becomes increasingly restrictive as urban development expands laterally. Yazdani and Jeffrey (2011) demonstrated that network structure and connectivity are closely associated with the robustness and vulnerability of water-distribution systems, highlighting the importance of connectivity and redundancy in network planning.

The findings therefore indicate that Maradun possesses important foundational infrastructure, including a major water source, treatment facility, transmission pipeline, and storage reservoirs, but these components are not yet spatially integrated sufficiently to provide broad metropolitan coverage. The challenge is consequently one of distribution reach, network connectivity, and spatial equity, rather than water-resource availability alone.

Optimized Pipeline Expansion Network

To address the identified 81.9% spatial coverage deficit, a GIS-based pipeline expansion model was developed to extend the municipal water network into currently underserved sections of Maradun. The proposed network seeks to transform the predominantly linear existing configuration into a more spatially distributed and interconnected system.

The proposed expansion comprises three principal infrastructure components.

First, the existing 8.130-km transmission corridor is retained as the principal conveyance route from the WTP into the urban area. Retaining this infrastructure preserves the existing investment and provides the foundation for subsequent distribution expansion.

Second, the existing 1.909-km secondary distribution network is integrated into the proposed system. This approach avoids unnecessary duplication and allows the existing distribution corridors to function as components of the expanded network.

Third, approximately 28.648 km of new distribution pipelines are proposed to extend the network into currently underserved areas. These proposed extensions constitute the major intervention in the spatial optimization model because they substantially increase the reach of the distribution system beyond its existing corridor.

The proposed network therefore introduces a considerably more extensive spatial configuration than the existing system. The new distribution corridors branch from the established network and extend towards the western, northwestern, and other underserved sections of the metropolis. Overlay analysis using satellite imagery indicates that the proposed routes penetrate existing and emerging residential areas, creating opportunities for future connections to households, public facilities, commercial areas, and other demand centres.

The proposed configuration represents a transition from a predominantly linear network towards a more interconnected urban distribution structure. Such integration can improve network flexibility by increasing connectivity and, where hydraulically feasible, providing alternative pathways for water conveyance. Network redundancy and connectivity are recognized as important characteristics in assessing the reliability and resilience of water-distribution systems (Yazdani & Jeffrey, 2011).

The proposed 28.648 km of new distribution pipelines represents a substantial increase over the existing 1.909 km secondary distribution network is approximately 15.0%.

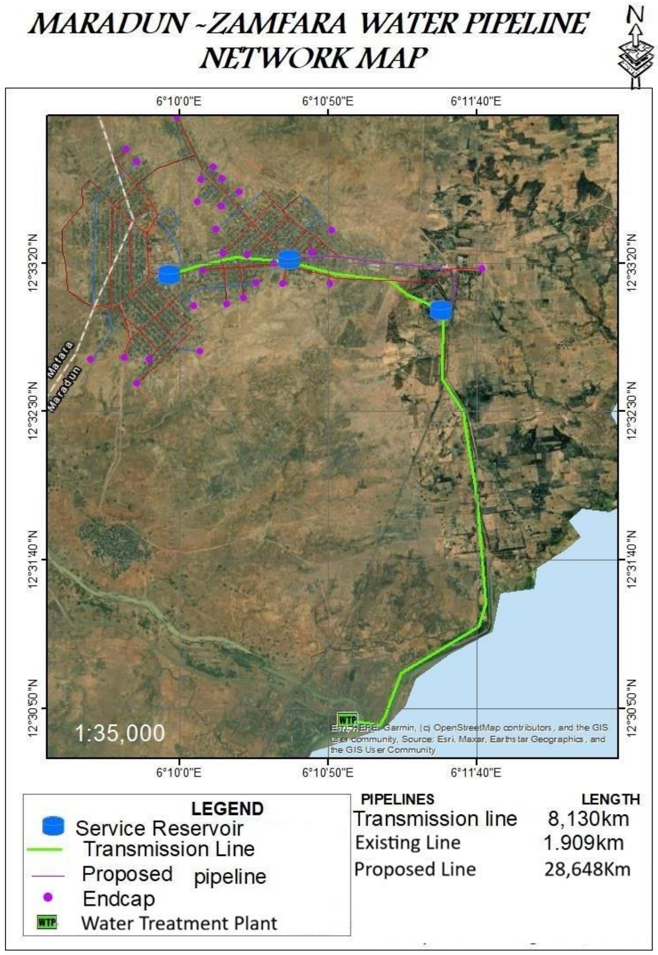

Figure 5: Satellite image showing proposed Pipeline

Thus, the proposed new distribution network is approximately 15 times the length of the existing secondary distribution network. This magnitude of expansion illustrates the scale of intervention required to overcome the spatial limitations identified through the GIS analysis.

The expansion should nevertheless be regarded as a GIS-based spatial planning model rather than a final hydraulic design. The proposed routes identify strategically suitable corridors for network extension, but detailed hydraulic modelling will be necessary to determine appropriate pipe diameters, design flows, pressure requirements, pumping requirements, storage requirements, valve locations, and peak-demand performance. Water-distribution design requires consideration of both network topology and hydraulic performance; consequently, spatial optimization should ultimately be integrated with hydraulic simulation before construction.

Geospatial Implications of the Proposed Expansion

The spatial overlay of the proposed pipeline network with satellite imagery demonstrates a substantial improvement in the geographical reach of municipal water infrastructure. Whereas the existing network is concentrated around the principal transmission corridor, the proposed network extends laterally into previously underserved western and northwestern portions of Maradun.

The proposed branches are distributed along existing and emerging urban corridors, providing potential opportunities for service connections to residential areas and other demand centres. The reduction in spatial separation between potential consumers and the formal water network is particularly important in rapidly expanding settlements, where urban development can occur faster than infrastructure provision. Figure 5 shows the Satellite image of the proposed Pipeline.

The proposed expansion therefore addresses the coverage problem at its spatial origin. Rather than focusing solely on increasing treatment or storage capacity, the model prioritizes network extension, connectivity, and accessibility. This is important because increasing the production or storage capacity of a water system without extending the distribution network would not necessarily improve access in areas located outside the existing service corridor.

The proposed network also provides a framework for phased infrastructure implementation. Expansion priorities can subsequently be refined using population distribution, settlement density, road accessibility, projected water demand, proximity to existing infrastructure, and future land-use development. Such integration would enable planners to identify priority areas where new infrastructure would provide the greatest service benefit.

The GIS-based approach is consistent with the broader objective of achieving universal and equitable access to safe and affordable drinking water under Sustainable Development Goal 6.1. The WHO identifies universal and equitable access to safely managed drinking water as a core global development objective, while recent WHO/UNICEF evidence highlights persistent inequalities in water-service access and the need for continued infrastructure investment (WHO, 2023; WHO & UNICEF, 2025).

Implications for Municipal Water Infrastructure Planning

The findings have several implications for water infrastructure planning in Maradun and comparable developing urban centres.

First, the analysis demonstrates that water-resource availability does not necessarily translate into water-service accessibility. The Bakolori Dam provides a major water resource, while the WTP and storage facilities provide essential components of the municipal supply system. Nevertheless, the limited spatial extent of the distribution network constrains the extent to which these facilities can provide services across the metropolitan area. This reflects a broader challenge in which water-service inequalities can persist even where water resources and basic infrastructure are present (WHO & UNICEF, 2025).

Second, the results demonstrate the importance of incorporating spatial analysis into infrastructure planning. GIS made it possible to quantify the existing network coverage, identify underserved areas, evaluate the spatial relationships among water facilities, and develop proposed expansion corridors. This provides planners with geographically explicit evidence for prioritizing infrastructure investments.

Third, the proposed expansion demonstrates the value of integrating existing infrastructure with new development. Rather than replacing the existing 10.039-km pipeline system, the proposed model incorporates the existing transmission and secondary distribution infrastructure while adding 28.648 km of new distribution pipelines. This approach supports progressive expansion while preserving existing infrastructure investments.

Fourth, the findings emphasize the need for integrated hydraulic and spatial planning. GIS is particularly useful for determining where infrastructure should be located, but hydraulic modelling is necessary to establish whether the proposed system can deliver adequate quantities of water at acceptable pressures. Future design stages should therefore incorporate hydraulic simulation under average, peak, and emergency demand conditions. Network-based approaches that explicitly consider connectivity, redundancy, and vulnerability can further strengthen such planning (Yazdani & Jeffrey, 2011).

Finally, the GIS database generated in the study provides a foundation for future infrastructure asset management. As additional pipelines, storage facilities, treatment infrastructure, and service connections are constructed, the database can be updated to maintain an accurate representation of the municipal water system. Continuous spatial updating can support maintenance planning, network monitoring, future expansion, and evidence-based investment decisions.

Overall Discussion of the Findings

Overall, the results demonstrate a substantial mismatch between the spatial extent of Maradun metropolis and the reach of its existing municipal water distribution infrastructure. The existing network covers approximately 1.00 km^2 of the 5.53 km^2 metropolitan area, corresponding to approximately 18.1% spatial coverage, while approximately 81.9% of the metropolitan land area remains outside the mapped pipeline network.

The existing system comprises an 8.130-km transmission pipeline and a 1.909-km secondary distribution network, giving a combined mapped pipeline length of 10.039 km. These facilities are supported by two elevated storage reservoirs with a combined nominal capacity of approximately 520,000 L. Although these components provide an important foundation for municipal water supply, their spatial concentration and predominantly linear network structure constrain the geographical reach of the system.

The proposed GIS-based intervention introduces approximately 28.648 km of new distribution pipelines, while retaining and integrating the existing infrastructure. The proposed network extends towards the western and northwestern sections of the metropolis and establishes a more spatially distributed framework for future water-service connections.

The findings demonstrate that GIS can serve as an effective decision-support tool for diagnosing infrastructure deficits and developing spatially informed expansion strategies. The approach is particularly valuable because it enables infrastructure coverage to be quantified objectively and allows proposed interventions to be visualized against existing urban development.

However, the proposed network should undergo detailed hydraulic, engineering, economic, environmental, and social assessment before implementation. Hydraulic modelling should establish pipe sizes, flow rates, pressure levels, storage requirements, and pump capacities, while economic assessment should determine construction and operational costs. In addition, population distribution and household water-access data should be incorporated in future studies to determine the actual population-level service deficit.

Thus, the proposed network represents a strategic spatial framework for sustainable water infrastructure expansion in Maradun, rather than a substitute for detailed engineering design. Its principal contribution is the demonstration of how GIS-based spatial analysis can identify service gaps, optimize infrastructure connectivity, integrate existing assets, and provide an evidence-based basis for future municipal water development.

CONCLUSION

The spatial analysis of Maradun's water infrastructure demonstrates a significant mismatch between the availability of a major raw-water resource, the Bakolori Dam, and the spatial reach of the existing municipal distribution network. Although the existing system comprises an approximately 8.130-km transmission line, a 1.909-km secondary distribution network, and two storage reservoirs with a combined capacity of about 520,000 L, the active pipeline network covers only 1.00 km^2 of the 5.53 km^2 metropolitan area, representing approximately 18.1% spatial coverage and leaving about 81.9% of the metropolitan land area outside the mapped pipeline network. The GIS-based expansion model addresses this spatial deficit by integrating the existing infrastructure with approximately 28.648 km of proposed distribution pipelines and an 8.130-km transmission backbone, thereby providing a more extensive and interconnected framework for extending municipal water services into underserved areas. The study demonstrates the effectiveness of GIS-based spatial analysis as a decision-support tool for identifying infrastructure gaps, optimizing pipeline expansion, improving network connectivity, and supporting equitable and sustainable urban water planning. Nevertheless, the proposed network constitutes a strategic spatial planning framework and should undergo detailed hydraulic, engineering, economic, environmental, and social assessment before implementation to ensure its long-term technical and operational viability.

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