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A GEOSPATIAL PLATFORM FOR VISUALIZING UNDERGROUND UTILITIES IN GROWING URBAN CENTERS

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ABSTRACT

Urban development in rapidly expanding cities, especially in developing countries, is often hindered by limited access to accurate and current information on underground infrastructure. This paper introduces a web-based dashboard developed to map and visualize subsurface utilities in Kampala, Uganda. To support the development of this system, a field survey was conducted to collect baseline data on existing underground assets, validate geospatial records, and assess on-the-ground conditions. Designed to address critical data gaps, the dashboard integrates this field-verified information with open-source web technologies and multilingual support, offering an interactive and accessible platform for planners, engineers, and city officials. By enabling non-intrusive identification and exploration of underground assets, the dashboard supports safer construction practices, reduces the risk of accidental utility damage, and improves coordination among stakeholders. Ultimately, this solution contributes to more efficient urban planning and lays the foundation for Kampala's transition toward sustainable smart city development.

1. INTRODUCTION

Unintentional damage to underground utilities during con-struction or excavation activities is a common occurrence, often leading to severe injuries and substantial financial losses (Al-Bayati & Panzer, 2019; Tanoli et al., 2019; Yadav et al., 2022). Underground Infrastructure (UI) includes essential assets such as water pipelines, sewer systems, electrical cables, and communication lines that are vital for societal functioning and economic activity (Goel et al., 2012). These utilities provide critical services including energy distribution, water supply, commu-nication, and sewage transportation.

Detecting and mapping buried infrastructure is essential to maintain safety and safeguard utility systems. Standard detection methods typically involve reviewing existing records, such as as-built plans or layout drawings, and employing professional locating services, including Subsurface Utility Engineering (SUE) (Al-Bayati et al. 2022; Lai, 2021). However, these records are often outdated, incomplete, or inaccessible, making effective utility mapping a persistent challenge (Jaw & Hashim, 2013; Li et al., 2015; Van Son et al., 2018)/

This issue is especially pronounced in rapidly urbanizing areas in developing countries, where demand for accurate and current underground utility data is growing (Esekhaigbe, 2020). In cities like Kampala, Uganda, UI information is often unavailable in a usable digital format, leading to inefficiencies in urban planning and

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construction (Doherty, 2021; Stewart, 2024); . The absence of accessible maps and digital infrastructure hampers coordination among stakeholders, increases the risk of accidental utility strikes, and contributes to long-term operational and structural problems (Arlinghaus, 1994; Chibuye, 2023).

To better understand these limitations and inform the design of a contextualized solution, a field survey was conducted with municipal authorities, engineers, utility providers, and construction professionals in Kampala. The survey aimed to assess current practices, identify bottlenecks in information sharing, and evaluate the specific needs of end-users regarding underground infrastructure data. Findings revealed a strong demand for a centralized, easily accessible platform that integrates spatial data with real-time updates, along with frustration over the lack of coordination among stakeholders and fragmented data sources.

Despite the known risks and the recognized importance of underground infrastructure (UI) data, existing solutions remain inadequate for developing contexts. These limitations are characterized by the absence of comprehensive digital underground maps, insufficient integration of geospatial data into urban planning tools, limited support for intuitive and re-mote access to subsurface information, and poor coordination among utility companies, engineers, and planners. Together, these challenges contribute to a significant knowledge and technology gap, which in turn increases the likelihood of infrastructure conflicts, service disruptions, and safety hazards during urban development activities.

To bridge this gap, this paper presents a novel web-based dashboard designed to map and visualize underground infras-tructure in developing urban contexts. The proposed system offers several contributions:

- Development of an interactive, web-based dashboard for visualizing underground utilities.
- Integration of geospatial data and open-source technolo-gies tailored to Kampala's infrastructure environment.
- Implementation of a modular framework enabling effi-cient monitoring and management of subsurface utilities.
- Demonstration of the dashboard's usability by urban planners, engineers, and municipal authorities to support safer and more coordinated construction practices.

By enhancing the accessibility and clarity of underground utility information, this system aims to support safer, more sustainable, and informed urban development in resource-constrained settings. The remainder of this paper is organized as follows: Section II reviews the related work; Section III outlines the methodology and system architecture; Section IV presents the results and discussion; and finally, Section V concludes the paper and highlights directions for future work.

2. RELATED WORK

The detection, mapping, and management of underground utilities have been widely investigated within the field of in-frastructure engineering, particularly in light of the increasing frequency and cost of accidental utility strikes during con-struction activities (Huston et al., 2017; Wang & Yin, 2022). Prior research has consistently emphasized the severity of such incidents and the critical need for accurate detection methods to enhance safety and reduce economic losses (Al-Bayati & Panzer, 2019; Al-Bayati et al., 2022; Ssemakula et al., 2024; Yadav et al., 2022).

Subsurface Utility Engineering (SUE) has emerged as a formalized methodology combining surface geophysical techniques, such as electromagnetic sensing and ground-penetrating radar (GPR), with historical utility documentation to locate and characterize underground assets (Birken & Oristaglio, 2022;. Goel et al., 2012; Meis et al., 2020). For example, Al-Bayati et al. (2022) underscore the contribution of GPR in improving detection accuracy. Nevertheless, the widespread application of SUE remains constrained by several challenges: limited access to accurate records, high operational costs, and inadequate technical capacity, especially in developing countries. These barriers underscore the need for alternative or complementary approaches to critical infrastructure (CI) management and monitoring that are both cost-effective and context-appropriate.

Traditional record-based approaches, including reliance on as-built plans and city planning archives, are frequently un-reliable. Studies have shown that such documents are of-ten outdated, incomplete, or missing entirely—particularly in informal and rapidly expanding urban areas (Al-Bayati & Panzer, 2019; Mubiana, 2024; Rolan, 2017). This has led to significant inefficiencies in utility location and planning.

Several researchers have investigated the systemic challenges that developing nations face in managing underground infrastructure. Du et al. (2023) critically examine existing mon-itoring techniques, offering a case-based evaluation of their strengths and limitations. A key contribution of their work is the identification of fundamental scientific barriers to intelli-gent infrastructure systems, alongside the proposal of a unified monitoring architecture specifically designed for subterranean environments. In contrast, Esekhaigbe (2020) emphasize the lack of institutional capacity and digital infrastructure, which impedes accurate mapping and effective data sharing. Similarly, Goel et al. (2012) explore the socio-economic con-sequences of inadequate utility information, noting that such deficiencies significantly hinder the delivery of urban services. Collectively, the insights and methodologies presented in these studies provide a strong foundation for the development of more effective underground infrastructure management and monitoring strategies by addressing the critical gaps they identify.

In the Sub-Saharan African context, studies by Chibuye (2023), Azunre et al. (2022), and Haou et al. (2024) further point to a persistent lack of utility visibility in urban planning. These authors stress the consequences of uncoordinated development and advocate for integrated digital platforms that can support real-time utility management and inter-agency collaboration.

To address this, researchers have increasingly explored the integration of Geographic Information Systems (GIS) with modern web-based technologies. Arlinghaus (1994) and Li et al. (2024) were among the early proponents of using GIS for visualizing infrastructure data, highlighting its value for spatial reasoning. More recent work has advanced this by incorporating open-source tools into web-based dashboards to enable interactive visualization and real-time decision support for city planners. However, in cities like Kampala, Uganda, where data sys-tems are fragmented and digital infrastructure is still emerging, such technologies remain underutilized. Stewart (2024) and Doherty (2021) document the absence of unified utility datasets and call for innovations tailored to the local context, especially those that can function effectively in low-resource environments.

While existing literature demonstrates significant progress in utility detection, documentation, and visualization, particularly in high-income countries, there remains a clear gap in scal-able, context-sensitive solutions for underground infrastructure management in developing urban settings.

This study addresses that gap by proposing a cost-effective, web-based dashboard that leverages open geospatial data, interactive visualization tools, and user-friendly interfaces. Unlike existing SUE or GIS-based systems that often assume high technical and financial capacity, the proposed solution is specifically designed to support urban stakeholders in resource-constrained environments, with a focus on enhanc-ing safety, coordination, and decision-making in underground infrastructure management.

3. METHODOLOGY AND ARCHITECTURE

This section outlines the methodology employed in the design and implementation of the proposed system. It focuses on the core components: the characterization of the under-ground water network and the development of the web-based application

3.1 Characterization of the Underground Water Network

The subsurface water distribution network was characterized within the spatial boundaries of the utility provider's service area. This process involved a comprehensive mapping of the network's structural elements, identification of system vulnerabilities, and evaluation of hydraulic performance metrics.

The analysis focused on key components such as transmission mains, distribution and service lines, control valves, pipe materials, and installation depths. The primary goals were to identify operational inefficiencies, assess infrastructure risks, and emphasize flow rate analysis to inform the design of effective monitoring and management strategies.

Accurately extracting and integrating this information was essential for building a web-based utility management platform that accurately mirrors the physical infrastructure in the field. To achieve this, a multi-faceted methodological framework was adopted, combining field data collection, spatial analysis using Geographic Information Systems (GIS), and hydraulic simulation through EPANET. The following sections describe the step-by-step procedures applied in the systematic characterization of the water distribution system.

3.1.1 Identification of Water Network Components

The initial step in characterizing the water distribution system involved the systematic identification and categorization of its key structural elements. These components are detailed in the following subsections.

a) **Trunk Mains:** Trunk mains are the primary pipelines responsible for transporting water from the main source to the wider distribution network. Designed with large diameters, these conduits are built to handle high flow volumes and form the central backbone of the system. Their accurate identification and assessment are crucial for evaluating the network's hydraulic capacity and overall structural integrity.

b) **Distribution mains:** These secondary pipelines de-liver water from the trunk mains to localized service zones. Typically, smaller in diameter than trunk mains, distribution lines facilitate water conveyance to various sectors within the service area. An in-depth assessment of these lines is critical to ensure their capacity aligns with expected flow demands and pressure requirements throughout the network.

Figure 1. Depth Profile of a Typical Service Pipe

c) **Service connections:** Service lines represent the terminal segment of the water distribution chain, connecting distribution mains to individual premises or end-users. These pipes are generally of smaller diameter and are vital for the final delivery of water. The structural condition and material composition of service connections substantially affect both water quality and system efficiency. The depth profile of a representative service pipe is illustrated in Figure 1.

d) **Control valves:** Control valves are strategically in-stalled throughout the network to facilitate flow regulation, operational flexibility, and system maintenance. These components are critical for isolating sections during repair activities, managing pressure zones, and optimizing distribution efficiency. Figure 2 provides an illustration of representative valve installations within the network.

e) **Pipeline materials:** The selection of pipe material significantly influences the performance, durability, and maintenance requirements of the network. Common materials include polyvinyl chloride (PVC), high-density polyethylene (HDPE), and galvanized steel, each exhibiting unique characteristics with respect to hydraulic efficiency, mechanical strength, and resistance to corrosion and biofouling.

f) **Burial depth:** The depth at which pipelines are installed is a critical factor affecting their structural protection and operational accessibility. Shallow-buried pipelines are more susceptible to mechanical damage from surface activities, while deeply buried pipelines may pose logistical challenges for inspection and repair. Figure 3 also illustrates the burial depth of a 1-inch diameter pipe as an example.

Therefore, understanding these components is crucial for identifying potential vulnerabilities and inefficiencies within the network. Each component plays a vital role in the overall performance of the water network, making detailed analysis essential for developing a comprehensive understanding of the proposed system.

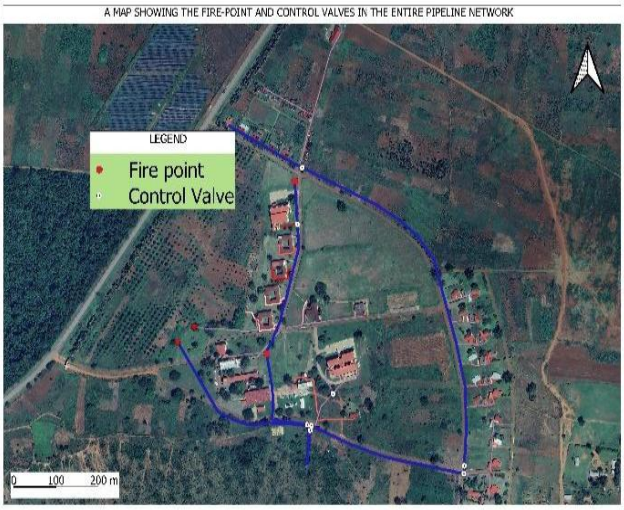


Figure 2. Configuration of the Control Valve

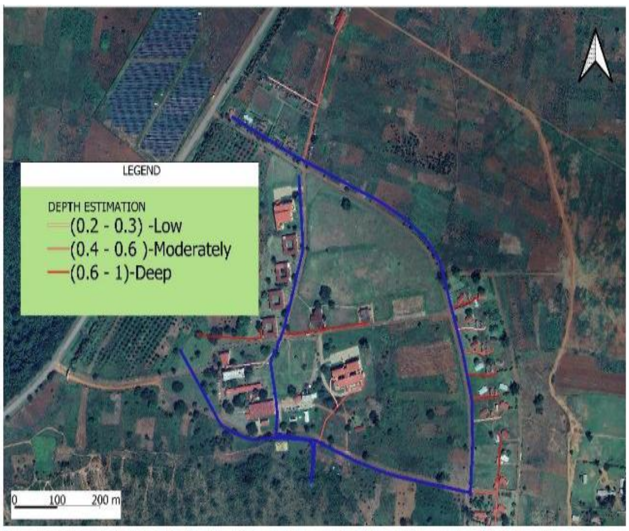


Figure 3. The Depth of a 1-inch Diameter Pipe

3.1.2. Field Survey and Inspection

Field surveys were carried out to collect direct, on-site data regarding the water distribution network. These surveys encompassed the following key activities:

a) **Material identification:** This involved the physical inspection of pipelines to determine the types of materials used in different sections of the network. Identifying these materials is crucial for evaluating the durability and long-term performance of the system.

b) **Pipeline diameter measurement:** Pipeline diameters were measured to better understand the system's flow capacity. Precise diameter data is vital for hydraulic modelling and performance analysis, as it directly influences the rate of water transport.

c) **Pipeline depth measurement:** The depth at which pipelines are buried was recorded to assess their susceptibility to external damage. Shallow pipelines may be more prone to disruption from surface activities, while deeper installations can pose challenges for maintenance and repair.

d) **Network mapping:** Using a handheld GPS device, the geographic coordinates of key infrastructure elements such as valves, junctions, distribution points, taps, and storage tanks were logged. This geospatial data was used to develop an accurate map of the network, aiding in the identification of areas requiring further attention or intervention.

Overall, the field surveys yielded essential data for subsequent analysis, forming the foundation for an accurate and comprehensive representation of the water network and highlighting areas for potential maintenance or improvement.

3.1.3 Quantum Geographic Information Systems (GIS) Analysis

QGIS was employed to conduct a spatial analysis of the water distribution network. Data collected during field surveys, along with existing maps and documentation, were digitized and incorporated into the QGIS environment to enable comprehensive geospatial analysis. The primary tasks involved were:

a) **Digitization of the pipeline network:** The physical and paper-based representations of the pipeline network were converted into digital formats using polylines to accurately depict the network's spatial layout. This digitization enhanced the precision of structural analysis and improved visualization of the system's connectivity and performance.
b) **Mapping of key infrastructure components:** Critical elements such as valves, distribution points, and storage tanks were digitized as point features within the GIS platform. This mapping was essential for identifying network control points and gaining insights into the system's distribution mechanisms.
c) **Spatial integration and analysis:** The digitized pipeline data was layered with additional spatial datasets, including building footprints, road networks, and boundaries of the study area. This integration facilitated a detailed spatial understanding of the network, enabling the detection of patterns, infrastructure interactions, and potential areas of vulnerability.

The GIS-based analysis proved vital for contextualizing the water network within its surrounding environment. It offered a spatial perspective that supported the identification of performance issues and informed strategic, data-driven decisions aimed at optimizing the network and guiding targeted interventions.

3.1.4. Hydraulic Performance Analysis Using EPANET

EPANET software was utilized to develop a comprehensive simulation model for assessing the hydraulic performance of the water distribution network. Essential input parameters included pipeline diameters, lengths, material types, and estimated flow rates. The model enabled the simulation of various operational scenarios, helping to detect potential system weaknesses, such as areas experiencing low flow or significant pressure losses. Results from the simulations were crucial for producing risk maps and informing strategic decisions for system upgrades.

Hydraulic performance analysis is vital for understanding the network's behaviour under diverse operating conditions. By simulating different scenarios, the analysis helped uncover inefficiencies and highlighted areas at risk of failure, thereby supporting the formulation of targeted solutions to enhance system efficiency, reliability, and resilience.

3.1.5 Vulnerability and Risk Assessment

The concluding phase of the water network characterization involved evaluating infrastructure-related data, including net-work maps, asset inventories, and condition reports. This assessment aimed to identify segments of the network most prone to failure or inefficiency. Based on the analysis, risk maps were created to visually represent areas of concern and prioritize maintenance and upgrade efforts.

Conducting a vulnerability and risk assessment is critical for maintaining the long-term reliability of the water supply system. By identifying high-risk zones, the process enables the implementation of targeted mitigation strategies. The resulting risk maps served as essential tools for guiding infrastructure investment decisions, maintenance planning, and overall system resilience enhancement

3.2. Development and Integration of a Web-based Water Pipe Network Monitoring and Management System with Real-time Notification Capabilities

A functional prototype of the system was developed to support automation and real-time monitoring. Custom programming was undertaken to implement the necessary computational logic, enabling the efficient execution of the system's core features and ensuring seamless operation.

3.2.1. System Architecture

The utility network monitoring and management system is designed using a three-tier architecture, which organizes the system into three distinct layers: the data layer, the application layer (backend), and the presentation layer (frontend). Each layer has a specific function and interacts with the others to ensure optimal performance and maintainability.

To ensure scalability and remote accessibility, the system is deployed on Amazon Web Services (AWS). The data layer is managed using Amazon RDS, which handles the database services, while the application layer is hosted on an Amazon Elastic Compute Cloud (EC2) instance running a Django-based web application. When a user initiates a request through a web browser, it is routed to the client-side service, which forwards it to the application server. The server then processes the request and communicates with either the database server or the geospatial data server, depending on the nature of the query.

A variety of tools, technologies, and development practices were employed throughout the implementation, as outlined in the following sections.

3.2.1.1. Tools and Technology

A range of open source tools and libraries was utilized during system development, with a focus on technologies suitable for web-based geospatial applications.

QGIS, a desktop Geographic Information System (GIS) ap-plication supported by the Open Source Geospatial Foundation (OSGeo), was used for creating and analysing geographic features. QGIS supports various vector data formats, such as CSV, and provides core GIS functionalities including spatial analysis, geometry processing, geoprocessing, and data visualization and management.

Spatial data storage was managed using PostgreSQL, an open source object-relational database system. The database was enhanced with spatial capabilities using phpPgAdmin, enabling support for geographic objects, coordinate systems, and map projections. Although it primarily handles text-based formats like CSV, PostgreSQL facilitates the import and export of vector data through both command line tools and graphical interfaces, making it well suited for WebGIS development.

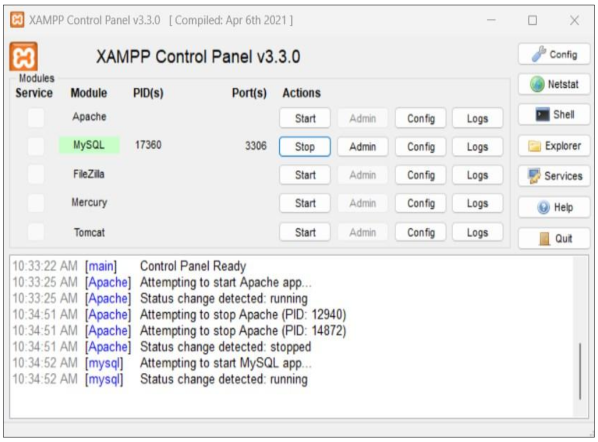
For web-based mapping, a Java-based open source map server was employed to deliver essential services for rendering and editing spatial data within a service-oriented architecture. On the client side, OpenLayers, an open source JavaScript library, was used to build and render interactive web maps within HTML documents. While customization requires programming knowledge, OpenLayers offers robust capabilities for creating dynamic, browser accessible geospatial applications.

3.2.2. XAMPP Installation

The system environment was initialized by setting up XAMPP, a cross-platform web server package. The appropriate version for the Windows operating system was downloaded from the official Apache Friends website: https://www.apachefriends. org/index.html. Installation commenced by executing the downloaded .exe installer. During the process, the default installation path C:\xampp was selected, and the setup was completed by following the provided on-screen instructions.

3.2.2.1. Apache Configuration

Following installation, the XAMPP Control Panel was launched. From the interface, both the Apache and MySQL services were started by clicking their respective “Start” buttons.



Modules Service	Module	PID(s)	Port(s)	Actions			
	Apache			Start	Admin	Config	Logs
	MySQL	17360	3306	Stop	Admin	Config	Logs
	FileZilla			Start	Admin	Config	Logs
	Mercury			Start	Admin	Config	Logs
	Tomcat			Start	Admin	Config	Logs

```
10:33:22 AM  [main]    Control Panel Ready
10:33:25 AM  [Apache]  Attempting to start Apache app...
10:33:25 AM  [Apache]  Status change detected: running
10:34:51 AM  [Apache]  Attempting to stop Apache (PID: 12940)
10:34:51 AM  [Apache]  Attempting to stop Apache (PID: 14872)
10:34:51 AM  [Apache]  Status change detected: stopped
10:34:52 AM  [mysql]   Attempting to start MySQL app...
10:34:52 AM  [mysql]   Status change detected: running
```

Figure. 4. The Apache Configuration

To ensure successful initialization and identify any potential issues, system logs were examined. Apache logs are located in xampp/apache/logs/, while MySQL logs can typically be found in xampp/mysql/data/ or xampp/mysql/log/.

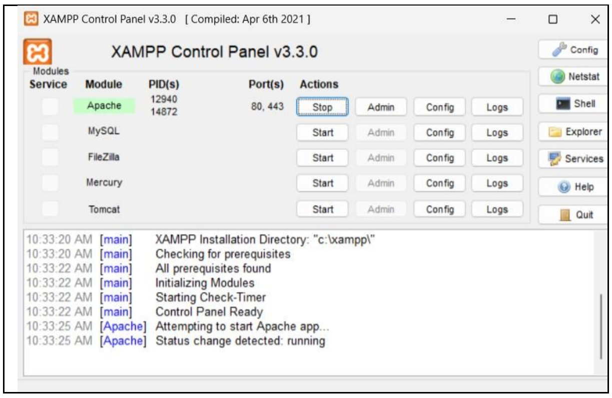
b) Apache Configuration:

Prior to finalizing the Apache configuration, as shown in Figure 4, it was crucial to verify the correct linkage of the PHP module. Since the module filename may vary depending on the installed PHP version, careful attention was paid to referencing the correct module. After confirming and applying the configuration changes, Apache was restarted either via the control panel or using the command line to ensure all modifications were properly implemented.

b) MySQL Configuration:

In the Windows environment, MySQL was configured by accessing the configuration file located at C:\xampp\mysql\bin\my.ini. Memory allocation settings were adjusted according to available system resources, following the recommended guideline of allocating approximately 70-80% of total RAM for dedicated servers. After modifying the configuration, the MySQL service was restarted to apply the changes.

As a critical security measure, the default root password for MySQL was changed immediately after installation using phpMyAdmin. This step is essential for protecting the database from unauthorized access and ensuring a secure development environment.



Modules Service	Module	PID(s)	Port(s)	Actions			
	Apache	12940 14872	80, 443	Stop	Admin	Config	Logs
	MySQL			Start	Admin	Config	Logs
	FileZilla			Start	Admin	Config	Logs
	Mercury			Start	Admin	Config	Logs
	Tomcat			Start	Admin	Config	Logs

```
10:33:20 AM  [main]    XAMPP Installation Directory: "c:\xampp\"
10:33:20 AM  [main]    Checking for prerequisites
10:33:22 AM  [main]    All prerequisites found
10:33:22 AM  [main]    Initializing Modules
10:33:22 AM  [main]    Starting Check-Timer
10:33:22 AM  [main]    Control Panel Ready
10:33:25 AM  [Apache]  Attempting to start Apache app...
10:33:25 AM  [Apache]  Status change detected: running
```

Figure. 5. Configuration of MSQL

The resulting setup, illustrated in Figure 5, establishes a secure and stable foundation for initiating development of the utility network management system. It is important to note that specific configuration details may vary depending on system requirements and conditions such as port conflicts or permission issues. To maintain system stability, it is recommended to regularly review log files for troubleshooting and performance monitoring.

3.2.3. Database Setup

The database setup was carried out using phpMyAdmin, a web-based interface for managing MySQL databases. php-MyAdmin was configured to manage various components of the utility network system, including building footprints, distribution pipelines, main pipelines, road centre lines, study areas, valves, and water distribution stations. Each of these components was structured as a separate table, with defined attributes tailored to support both operational needs and analytical functions.

This structured approach ensures efficient data management and enables seamless integration with the web-based application for real-time access and analysis.

3.2.3.1. phpMyAdmin

phpMyAdmin is a free, open-source web application devel-oped in PHP that facilitates the management of

MySQL and MariaDB database systems. It provides a user-friendly inter-face for performing a wide range of database administration tasks, making it particularly useful for web-based application development.

Key functionalities of phpMyAdmin include:

- Database administration: Create, modify, and delete databases with ease.
- Table management: Manage tables by creating, editing, and removing them, along with defining columns, data types, and relationships.
- SQL query execution: Directly write and execute SQL queries to manipulate data, such as inserting, updating, deleting, and retrieving records.
- User and permission management: Create and manage user accounts, assign privileges, and control access levels.
- Data import/export: Import data from SQL files and export databases or individual tables in multiple formats, including SQL and CSV.
- Server monitoring: Monitor server performance and status to ensure efficient operation.

Before accessing phpMyAdmin, it is essential to start the Apache and MySQL services through the XAMPP Control Panel. Ensuring these services are running allows for success-ful connection and database management via the phpMyAd-min interface.

3.2.4. Create a Database

3.2.4.1. Database initialization in phpMyAdmin

Upon navigating to http://localhost/phpmyadmin, the "New" or "Create database" option was selected from the phpMyAdmin interface. A new database named utility_network_db was created by entering the name and clicking the "Create" button. Within this database, several tables were established to store and manage different components of the utility network system.

3.2.4.2. Creating the footprints table

A dedicated table was created to store data related to building footprints within the utility network. This table includes the following key attributes:

- id – A unique identifier for each building footprint (primary key).
- building – Descriptive data or labels related to individual buildings.
- geometry – Spatial data representing the building shape and location in geometric format.

These attributes enable both spatial visualization and analytical operations on building infrastructure data.

3.2.4.3. Distribution pipelines

This table stores information related to the utility network's distribution pipelines. It includes key attributes such as:

- pipeline_id – Unique identifier for each pipeline.
- material – Type of material used (e.g., PVC, steel).
- diameter – Diameter of the pipeline.
- length – Length of the pipeline segment.
- geometry – Spatial representation of the pipeline
- id – Internal record identifier.

3.2.4.4. Main (Principal) pipelines

Designed for larger-scale infrastructure, the Principal Pipelines table mirrors the structure of the distribution pipelines table but is intended for major water transmission lines. The same core attributes such as material, diameter, length, geometry, and pipeline ID are used to ensure consistency across pipeline datasets.

3.2.4.5. Road Centerlines

This table stores geospatial data representing road centerlines within the utility network area. These features are useful for spatial reference, analysis, and alignment with other infrastructure components.

3.2.4.6. Study areas

The Study Areas table defines the boundaries of research or analysis zones within the utility network. These polygons help focus spatial queries, reporting, and analysis within specific geographic extents.

In summary, despite some limitations, such as performance issues when managing large datasets, phpMyAdmin served as an effective tool for establishing and managing the database. It operates within the XAMPP environment, which requires both Apache and MySQL services to be running, adding a layer of complexity to the setup process. Nevertheless, the database setup for utility_network_db was successfully completed using phpMyAdmin. Multiple tables were created to represent critical components of the utility network, including water distribution stations, pipelines, building footprints, road centerlines, study areas, and valves. Each table was structured with carefully selected attributes to support robust data storage, analysis, and operational use.

PhpMyAdmin proved to be a dependable and user-friendly solution for database management. However, for long-term deployment, it is recommended to implement security best practices and consider performance optimization techniques to ensure scalability and system integrity.

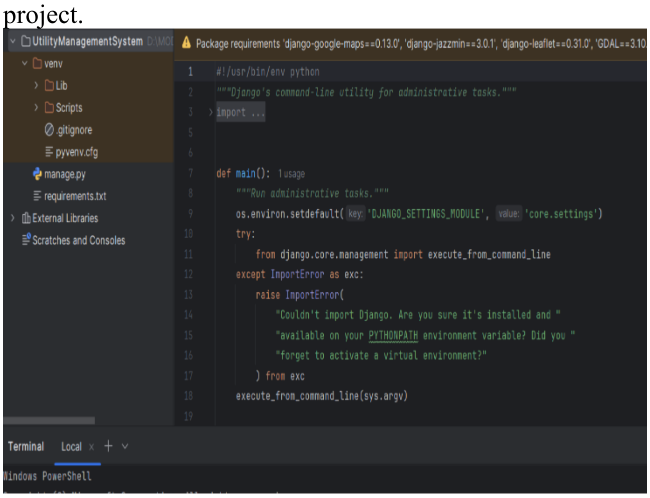
3.2.5. Integration with PyCharm Community Edition

In this section, we provide an in-depth overview of how a utility network database was integrated with Python, utilizing the PyCharm Community Edition and the Django web framework. The project focused on building a robust system for managing and visualizing geospatial data, streamlining database operations, and delivering a user-friendly interface for both administrators and end users.

We detail the setup, development, and implementation stages, highlighting key challenges faced and the solutions applied to create a scalable and effective system.

3.2.5.1 Configuring PyCharm with Essential Libraries

The integration of the utility network database with Python was implemented using the PyCharm Community Edition, an efficient and beginner friendly Integrated Development Environment (IDE) tailored for Python development. The configuration process started with downloading and installing PyCharm from the official JetBrains website. After installation, a new Python project was initialized, followed by the setup of a virtual environment to manage dependencies specific to the project. This isolated environment ensured consistency across development stages and prevented conflicts with system-wide Python packages.



Package requirements 'django-google-maps==0.13.0', 'django-jazzmin==3.0.1', 'django-leaflet==0.31.0', 'GDAL==3.10

```
#!/usr/bin/env python
"""Django's command-line utility for administrative tasks."""
import ...


def main():
    """Run administrative tasks."""
    os.environ.setdefault( key: 'DJANGO_SETTINGS_MODULE',  value: 'core.settings')
    try:
        from django.core.management import execute_from_command_line
    except ImportError as exc:
        raise ImportError(
            "Couldn't import Django. Are you sure it's installed and "
            "available on your PYTHONPATH environment variable? Did you "
            "forget to activate a virtual environment?"
        ) from exc
    execute_from_command_line(sys.argv)

```

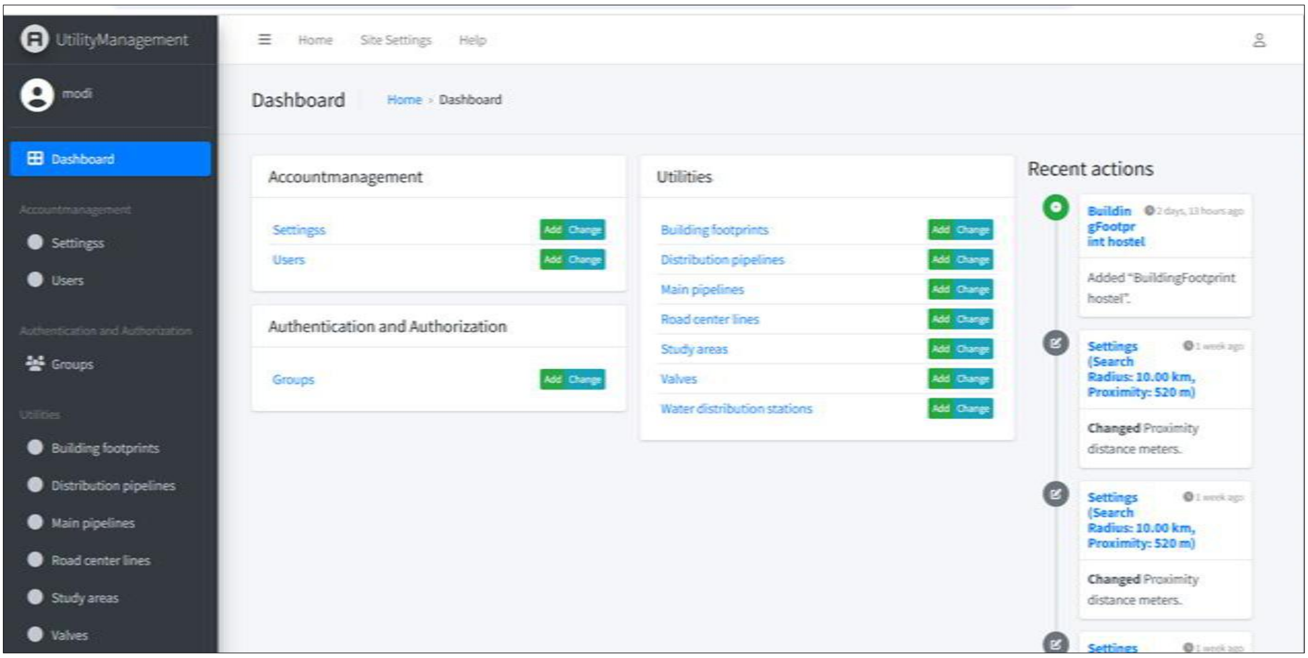
```
Windows PowerShell
```

Figure. 6. The Django Framework

To support database connectivity, geospatial data processing, and web application functionality, a set of essential Python libraries was installed via the PyCharm terminal. Each library was selected based on its relevance to the project's requirements, including data handling, spatial processing, and Django-based application development.

Below is a summary of the key libraries and their respective roles:

- Django: A high-level Python web framework used to build the web application for managing the utility net-work database, as shown in Figure 6. Django's built-in features, such as its Object Relational Mapping (ORM) system and admin interface, significantly streamlined development and data handling.
- psycopg2 and psycopg2 binary: PostgreSQL adapters for Python that enabled interaction with PostgreSQL databases. The binary version simplified installation on Windows systems by including precompiled dependencies.
- mysqlclient: A MySQL database connector for Python, used to connect to and interact with the MySQL-based utility_network_db.



BuildingFootprint hostel — 2 days, 13 hours ago

Added "BuildingFootprint hostel".

Settings (Search Radius: 10.00 km, Proximity: 520 m) — 1 week ago

Changed Proximity distance meters.

Settings (Search Radius: 10.00 km, Proximity: 520 m) — 1 week ago

Changed Proximity distance meters.

Settings — 1 week ago

Figure 7. Development of the Admin Panel

- pygdal and pyproj: Libraries essential for geospatial data processing. These tools were used to handle spatial datasets such as building footprints and pipeline geometries stored in the database.
- django-import-export: A Django library that enabled data import and export operations, facilitating the management of large datasets via the Django admin interface.
- pipwin: A Windows-specific utility for installing un-official Python packages. It was especially useful for managing packages like psycopg2, which often require additional dependencies during installation.

Library installation was conducted via the PyCharm terminal using standard pip install commands. For packages not available through the official Python Package Index (PyPI), pipwin was used as an alternative installer. Furthermore, to enable the execution of scripts within the development environment, the following PowerShell command was executed:

```
Set-ExecutionPolicy RemoteSigned -Scope CurrentUser
```

This configuration allowed all required scripts to execute without restriction, ensuring a smooth development process.

Each library contributed significantly to the overall success of the research project:

- Django served as the core framework for building the web application.
- psycopg2 and mysqlclient facilitated reliable and ef-ficient communication with PostgreSQL and MySQL databases, respectively.
- pygdal and pyproj were essential for handling and processing geospatial data.
- Django-import-export improved data management by enabling streamlined import and export operations through the Django admin interface.

3.2.5.2. Developing the Admin Panel

An administrative panel for managing the utility network database was developed using the Django framework, as shown in Figure 7. To enable full control over the database through the Django admin interface, the data models representing each database table were registered within the admin.py file of the Django application.

This registration process provided administrators with the ability to create, read, update, and delete (CRUD) records directly from a user-friendly web-based interface. By leveraging Django's built-in admin capabilities, the panel significantly enhanced usability and streamlined data management operations for both technical and non-technical users.

3.2.5.3. Developing the User Interface (UI)

As shown in Figure 8. The UI was designed to provide a clean, intuitive, and user-friendly experience for interacting with the utility network system. HTML templates were created and organized within the project's templates directory. These templates were used to render different views, such as one displaying data from the building footprints table and another showing information related to pipeline infrastructure.

To enable navigation, URL routing was configured in the urls.py file, mapping specific routes to their corresponding view functions. This setup allowed users to access various parts of the application efficiently.

Figure 8. Development of User Interface

Additionally, Django forms were implemented to allow users to input and update data, such as modifying pipeline attributes or adding new building footprints. Each form included built-in validation mechanisms to ensure data integrity before any entries were saved to the database. This approach helped maintain consistent, accurate records while providing an accessible interface for both administrative and operational users.

3.3. Testing and Validation of the System for Performance and Accuracy

Figure 9 presents the comprehensive testing and validation process undertaken to evaluate the system's performance and accuracy. This process was essential to ensure that the system met the functional requirements and operational standards necessary for effective utility network monitoring and management.

3.3.1. System Testing

System testing was carried out to assess the functionality of individual application modules, ensuring that each component fulfilled its defined requirements. The evaluation focused on three core modules: the geospatial data visualization interface, the real-time notification system, and the database management tools.

Each module underwent independent testing to verify its reliability and accuracy:

- Geospatial Interface: Successfully rendered spatial datasets and accurately displayed pipeline locations on the map, confirming the system's capability to represent infrastructure within its correct geographic context.
- Real-Time Notification System: Operated as expected by generating alerts when predefined spatial conditions were satisfied, demonstrating the module's responsive-ness and effectiveness in proximity-based monitoring.
- Database Management Tools: Accessible through the Django admin interface and custom user forms, these tools enabled smooth data creation, updating, and deletion, validating the proper execution of CRUD operations.

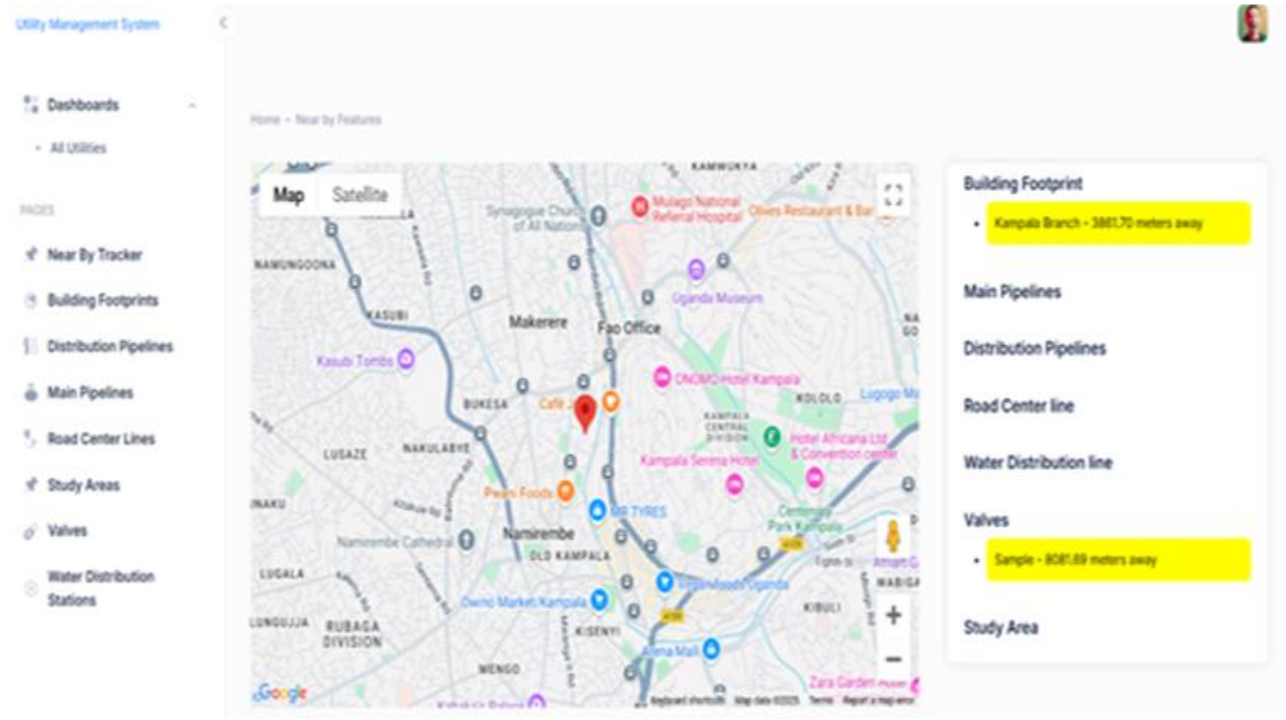
All tested modules met or exceeded performance expectations, indicating the system's operational readiness for deployment.

3.3.2. Validation of Functional Requirements

Validation activities were conducted to verify that the system fulfilled its essential functional requirements, with a particular focus on proximity-based features and geospatial accuracy. This process ensured that the system operated consistently across diverse user environments while accurately representing real-world utility network locations.

To evaluate location accuracy, ground-truth GPS measurements of utility components were collected and compared to the system's geospatial outputs. This comparison confirmed the precision of the spatial data rendered within the application.

Additionally, a custom validation form was created to methodically assess the system's functionalities. The validation involved deploying the application across various mobile devices and web browsers to confirm cross-platform compatibility and stable performance.



Building Footprint

- Kampala Branch - 3881.70 meters away

Main Pipelines

Distribution Pipelines

Road Center line

Water Distribution line

Valves

- Sample - 8081.89 meters away

Study Area

Figure 9. System Testing and Validation

The results demonstrated that proximity alerts were triggered as intended and that the mapping interface accurately displayed utility features with high spatial fidelity.

4. RESULTS AND DISCUSSION

In this section, we present selected results from a series of experiments and analyses carried out to evaluate the performance of our proposed web-based dashboard for under-ground utility monitoring and management. The assessment began with the identification of water network components through field surveys and GPS mapping. This phase included pipeline inventory, evaluation of storage infrastructure, GIS-based spatial analysis using QGIS, and hydraulic modelling with EPANET. Following this, we focused on the development and integration of the web application, with particular attention to its real-time notification capabilities. Finally, system testing and validation were conducted, as described in the sections that follow:

4.1. Identification of Water Network Components

The identification process involved several key activities, as outlined below

4.1.1. Field Survey and GPS Mapping

The field survey was conducted using a handheld GPS device (Garmin GPSMAP 64sx), which achieved an average positional accuracy of 3.37 meters. The survey successfully mapped approximately 15,000 meters of the water distribution network.

a) Depth Measurements

The survey revealed that the average burial depth of the pipelines was approximately 1.2 meters, while shallow-depth zones were observed at depths of ≤ 0.6 meters. Although slightly below the average burial depth of 1.2 - 1.3 meters recommended by Wang and Yin (2022), this was not considered significantly in-adequate. Therefore, the main concern shifts from installation depth to the need for effective monitoring and management practices to ensure the long-term safety, functionality, and durability of the infrastructure.

b) Material Composition and Condition

Figure 10 presents the observed range of material defects identified through field investigations and experimental analysis. The results show that approximately 60% of the PVC components exhibited minimal defects (less than or equal to 5%), indicating they were in good condition. In contrast, 25% of the HDPE components showed no signs of corrosion, reflecting excellent material integrity.

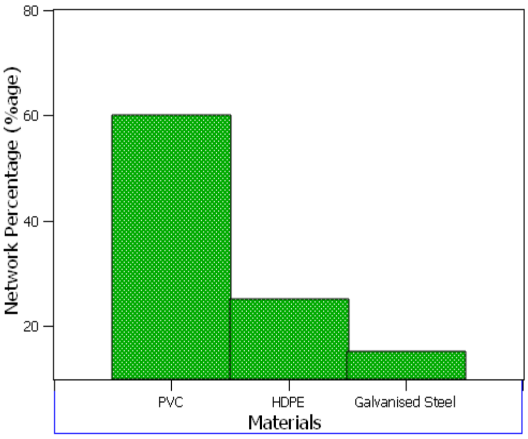


Figure. 10. Condition Assessment on Materials of the Water Network

However, the galvanized steel components demonstrated significant deterioration, with around 15% in poor condition, corresponding to an estimated 80% corrosion level.

Table 1 summarizes the material com-position and associated condition assessments of the water network components, as reflected in the findings illustrated in Figure 10.

Table 1. Material composition and condition of the water network

Material	% of Net-work	Condition Assessment
PVC	60%	Good (≤ 5% observed defects)
HDPE	25%	Excellent (no signs of corrosion)
Galvanized Steel	15%	Poor (approximately 80% corro- sion)

4.1.2. Pipeline Inventory

In this section, Table 2 presents a summary of the material composition and corresponding condition assessments of the water network components. The data is based on findings from the field survey, which documented various elements of the water distribution network. These assessments reflect different levels of defects observed during field investigations and experimental analyses.

Moreover, three critical control valves were identified, each playing a key role in regulating flow at important junctions within the water distribution network

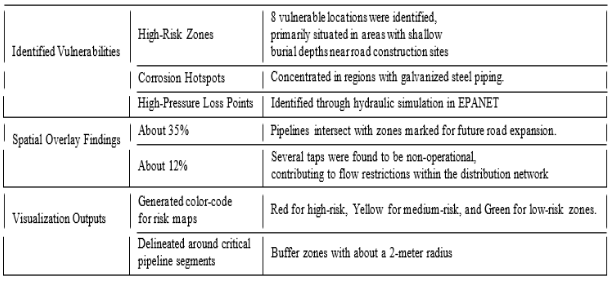
Table 2. Material composition and condition of the water network pipeline inventory

Network Line	Diameter	Length
Main Transmission Lines	3-inch	8,000 meters
Distribution Lines	1-inch	5,000 meters
Service Connections	¼-inch diameter	2,000 meters

4.1.3. GIS Spatial Analysis (QGIS)

The digitized water distribution network was analysed using QGIS version 3.28 to evaluate both structural and operational vulnerabilities. The analysis focused on three key aspects: identified vulnerabilities, spatial overlay findings, and visualization outputs.

Table 3. Digitized water distribution network



Identified Vulnerabilities	High-Risk Zones	8 vulnerable locations were identified, primarily situated in areas with shallow burial depths near road construction sites
	Corrosion Hotspots	Concentrated in regions with galvanized steel piping.
	High-Pressure Loss Points	Identified through hydraulic simulation in EPANET
Spatial Overlay Findings	About 35%	Pipelines intersect with zones marked for future road expansion.
	About 12%	Several taps were found to be non-operational, contributing to flow restrictions within the distribution network
Visualization Outputs	Generated color-code for risk maps	Red for high-risk, Yellow for medium-risk, and Green for low-risk zones.
	Delineated around critical pipeline segments	Buffer zones with about a 2-meter radius

A summary of these findings is presented in Table 3.

4.1.4. Hydraulic Modelling (EPANET)

In Table 4, the results of the hydraulic simulation of the water distribution network, conducted using EPANET, are presented. This simulation provided valuable insights into the network's performance under varying demand conditions. The analysis revealed that approximately 25% of the net- work experienced significant pressure losses, indicating areas with potential inefficiencies or structural issues. Low-pressure zones, defined by pressure readings below 20 psi, were primarily associated with older sections of the distribution lines, suggesting aging infrastructure as a contributing factor.

Table 4. Hydraulic Performance Analysis

Experimental Aspects	Observed Results
Pressure Loss Areas	Approximately 20%
Low-Pressure Zones	Pressure below 20 psi
Flow Rate Reduction	Up to 40% decrease during peak demand

Furthermore, the simulation indicated a substantial reduction in flow rates, with decreases of up to 40% observed during peak demand periods. This highlights the system's limited capacity to maintain adequate service levels under high load conditions, pointing to potential constraints in both pipe sizing and network layout. These findings underscore the need for targeted interventions, such as infrastructure upgrades and improved demand management strategies, to enhance the network's overall reliability and performance.

4.2. Development and Integrating the Web Application with Real-time Notification Capabilities

The web application developed using the Django framework to facilitate efficient management and visualization of the underground utility network. Designed with a modular architecture, the system supports database interactions, geospatial data rendering, and user role management through a clean, browser-based interface.

As illustrated in Figure 11, which displays both the admin panel and the user interface, a central feature of the application is its real-time notification capability. This functionality was implemented using Django Channels and WebSockets, enabling immediate alerts without requiring page reloads. Notifications are triggered by predefined conditions such as pressure drops, flow irregularities, or future sensor input integrations, allowing administrators and field personnel to respond swiftly to emerging issues. This real-time communication framework greatly enhances operational monitoring, supports rapid decision-making, and strengthens the overall reliability and responsiveness of the utility network.

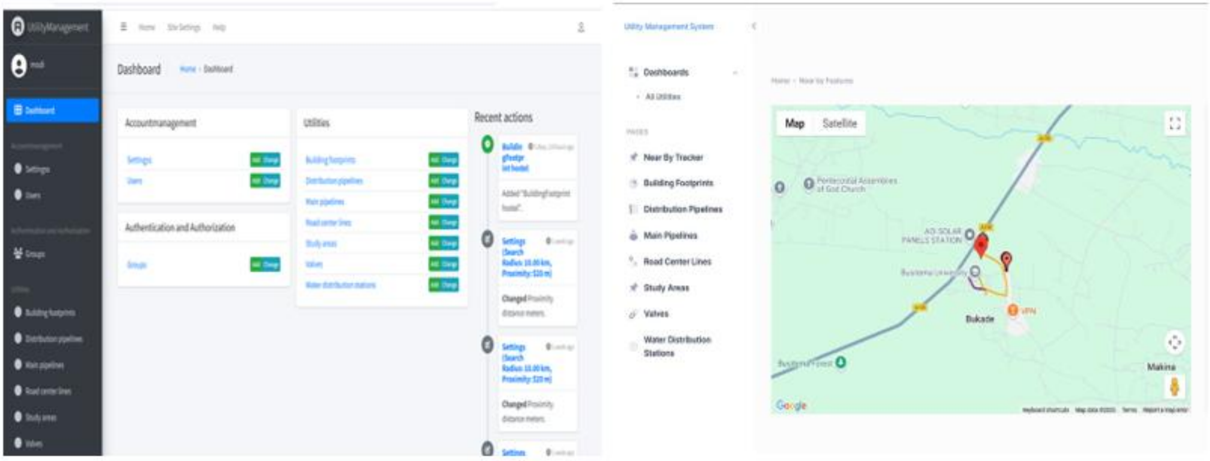
4.3. Testing and Validation of the System

To evaluate the performance and reliability of the developed web-based utility monitoring and management system, a suitable testing and validation process was carried out.

The evaluation focused on key performance metrics including GPS accuracy, notification latency, proximity detection accuracy, and cross-device consistency, as summarized in Table 5.

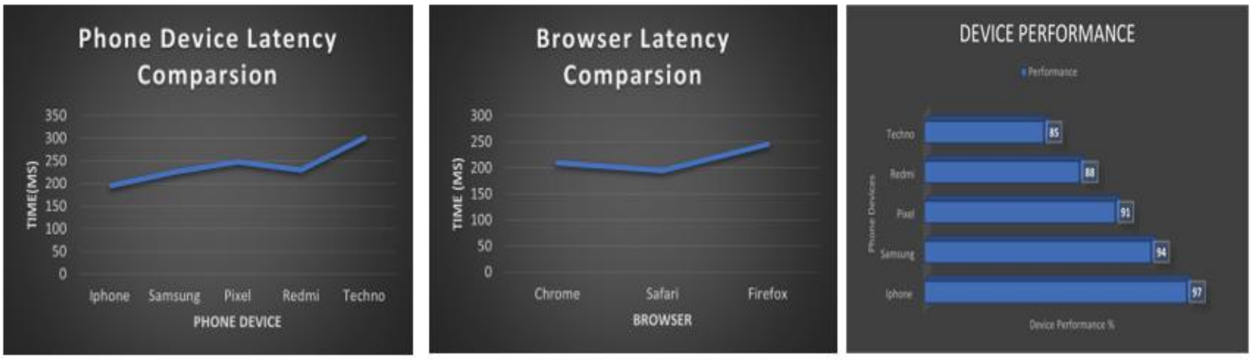
Table 5. Key metrics overview

Metric	Results obtained
GPS Accuracy	80.00%
Notification Delay	200 ms
Proximity Accuracy	5 m
Cross-Phone Device Consistency	75.00%



(a) User Admin Panel (b) User Interface

Figure 11. Development and integration of Web Application with Real-time notification for the User Admin Panel and User Interface



(a) Latency Comparison (b) Latency Comparison (c) Device Performance

Figure 12. Latency comparison analysis and device performance

The results indicate that the system achieved a GPS accuracy rate of 80%, demonstrating reliable spatial referencing during field data acquisition. Real-time notifications, a critical feature of the application, were delivered with an average delay of just 200 milliseconds, highlighting the system's responsiveness and efficiency in alerting users to potential network issues. Proximity-based functionalities were validated with an accuracy of 5 meters, ensuring dependable performance in detecting spatially-triggered events. Furthermore, the system showed a cross device consistency rate of 75%, confirming its functional reliability across various mobile phones and browsers.

To further validate system performance, latency and device responsiveness were analyzed through experimental trials, as depicted in Figure 12. Figure 12(a) and Figure 12(b) compare notification latency across different mobile devices and browser environments, respectively. The results show that while slight variations exist, the system maintained acceptable latency across all platforms. Figure 12(c) illustrates overall device performance, affirming the system's compatibility with a range of hardware configurations and its ability to maintain stability under typical user interactions.

These testing outcomes confirm that the system performs consistently across different usage conditions, delivering reliable real-time alerts, accurate geospatial operations, and stable cross-platform functionality. This validation underscores the system's readiness for practical deployment in utility network monitoring and management applications.

5. CONCLUSION AND FUTURE WORKS

5.1. Future Works

To further enhance the functionality and reliability of the web-based utility monitoring system, future developments will focus on the integration of sensor technologies and artificial intelligence (AI) (Ssemakula et al. 2022; Ssemakula et al., 2023) to enable a more intelligent, autonomous, and predictive infrastructure management platform.

The incorporation of real-time sensors, including pressure sensors, flow meters, leak detectors, and water quality sensors will allow for continuous data collection across the utility net- work. These sensors will serve as vital inputs for monitoring the physical state of the network, enabling the system to detect anomalies such as leakages, blockages, pressure drops, and flow irregularities with greater accuracy and speed.

Building on this sensor data, the implementation of AI algorithms will enable the system to evolve from reactive monitoring to proactive and predictive management. Machine learning models will be trained on historical and real-time data to identify patterns, predict failures, and recommend maintenance actions before issues escalate. This will significantly reduce downtime, operational costs, and resource wastage.

Additionally, AI-powered analytics can support decision-making by prioritizing alerts based on severity, identifying high risk zones, and optimizing water distribution during peak demand periods. These capabilities will transform the current system into a smart infrastructure management tool capable of learning and adapting over time.

The integration of sensors and AI will not only enhance the accuracy and responsiveness of the monitoring system but also contribute to long-term sustainability, resilience, and data- driven planning in utility network monitoring and management.

5.2. Conclusion

Despite the challenges faced during development, the real- time notification system for the water network has been successfully designed, implemented, and tested to fulfil its original objectives. The system accurately estimates proximity and detects networks within a specified radius.

When an entity enters the defined buffer zone around the underground water network, it delivers real-time, color-coded alerts to ensure precise identification of the underground pipelines.

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