Application of Augmented Reality for Mapping and Evaluating Encroachments on Bulk Water Pipeline Systems

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ABSTRACT

This study focuses on identifying and evaluating encroachments of bulk water pipelines and servitude areas using Augmented Reality (AR). The study's objectives were to use existing pipeline, servitude, and encroachment data for AR Visualization, quantify the impact of encroachments, and assess the performance of AR positions against baseline reference points established using Trimble R12i GNSS. The pipelines investigated include the L06, J10&J08, S01/S04, and K05, which are located in the City of Ekurhuleni Metropolitan Municipality region with a high number of reported encroachments. Existing data for pipelines affected, servitudes, and encroachment reports was acquired in shapefile format and loaded in ArcGIS for visualisation and processing. 3D pipeline models were created using attribute data for existing pipelines, including description, horizontal and vertical alignment, pipeline diameter, and ground elevations.

Encroachments within a 0-2m radius from the pipeline had higher Encroachment Severity Index (ESI) values due to potential infrastructure damage, maintenance restrictions, and pipeline burst catastrophes. Comparative analysis indicated strong positional correlation between the AR dataset linked to the Leica GG04 receiver and R12i GNSS survey baseline data. The VGIS AR application demonstrated its suitability for mapping and analysing encroachments due to lower RMSE values below 5cm. The information gen
erated from the AR field reports can be used to justify legal actions and as evidence in court.

The AR models can be used to create awareness about the existence of the bulk water pipelines and servitude areas within communities, and highlight the risks associated with encroachments. This study paves the way for AR mapping to be integrated into routine pipeline inspection, mapping and investigation of encroachments.

Keywords: Augmented Reality (AR), Encroachments Detection, Bulk Water Infrastructure, Servitude Areas, GNSS and 3D Modelling

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1. INTRODUCTION

Urban water infrastructure (UWI) serves as a crucial component for accomplishing sustainable development goals (SDGs) by ensuring access to clean water for consumption, sanitation, and wastewater management, hence fostering sustainable urban environments(Ferdowsi *et al.*, 2024).The rise in the intensity and frequency of natural disasters in recent decades has contributed to infrastructure damage (Janke, Tryby and Clark, 2014). Water supply and wastewater infrastructure systems are essential components of a healthy ecosystem, and their resilience to disasters is crucial for efficient disaster response and recovery(Pamidimukkala *et al.*, 2021). While several studies have explored the problems posed by natural catastrophes to water systems, there have been few comprehensive analyses the issues of encroachment on water infrastructure.

Bulk water pipeline servitudes are facing increasing threats from illegal occupation, which jeopardises the security of critical infrastructure but also leads to operational inefficiencies, legal challenges, and potential environmental damage (Rand Water, 2023a). Having access to a reliable, clean portable water supply is a basic human right, according to the Constitution of the Republic of South Africa (Tony, 2021). Increasing numbers of encroachments on the area of supply for bulk water infrastructure have become a threat to the integrity of this vital source (Rand Water, 2022). Encroachments occur as a result of the construction or establishment of unauthorised settlements over the designated pipeline and servitude area.

A state-owned bulk water utility located in the Gauteng province plays a significant role in ensuring a continuous water supply to various regions within the Gauteng, Free State, Mpumalanga, and Northwest provinces. Recognised as one of the largest bulk water utility service providers in Africa, this bulk water service provider supplies clean water to a population of over 11 million and includes stakeholders such as farmers, municipalities, mining companies, and industries. The bulk water utility sources raw water from the Vaal Dam, which is transported through bulk water pipelines to the Zuukerbosch and Vereeniging purification and pumping plants (Rand Water, 2023b).

The Gauteng province is the most densely populated province in South Africa, with a population density estimated to be 876 persons per square kilometre(Statistics South Africa, 2024) . The Gauteng population is estimated to be 15,931,824, occupying a total area of 18,178 square kilometres (Statistics South Africa, 2024) . The Gauteng province is regarded as the country's economic hub. This is where cities such as Johannesburg and Pretoria are located, where a significant portion of the population resides, and various industries operate. The demand for housing and water within these regions is high as a result.

According to reports, the primary bulk water service provider in Gauteng produces 5000 megalitres (Ml/d) of water per day (Rand Water, 2023b). The launch of the Zukerbosch Station 5A in 2023 resulted in an increase in daily water production to 5200 mega litres per day (Rand Water, 2024). It has been reported that 80% of the water produced by the bulk water utility in Gauteng is pumped to Metros. Consumption patterns observed in Gauteng metros from the period 2023-2024 depicted consumption, which was 11.8% higher than the expected target (Rand Water, 2024). Encroachment challenges to bulk water infrastructure significantly affect the provision of water to households, industries, and farms. The water supply system is already constrained; the bulk water service provider experiences challenges in maintaining, repairing, and installing additional pipeline infrastructure to meet the growing water demands within the Gauteng Region (Rand Water, 2024).

1.1. Formal and informal encroachments

Formal encroachment is a term used to refer to unauthorised construction activities over the pipeline and servitude area from established townships, suburbs, businesses, and property developments that failed to comply with the conditions associated with bulk water servitudes (Dželalija and Roić, 2023). As a result, houses, shopping complexes, and malls are constructed over the designated pipeline servitude area, exerting pressure on the pipelines and increasing the risks of structural failure (Ossai and Njoku, 2024). Formal encroachments result from planned property projects, housing, urban expansions or authorised construction activities that later deviate from the initial conditions of establishment. Informal Encroachments often result from land grabs, whereby communities regard the land occupied by the pipelines as vacant and establish shack dwellings over the servitude area(Dželalija and Roić, 2023).

Encroachments on bulk water infrastructure can cause physical damage due to the pressure exerted on the pipeline by the structures constructed within the servitude, supply disruptions, prevent access for maintenance and repairs and urban planning challenges (Ossai and Njoku, 2024). They can lead to leaks, breakages, and increased water contamination risks. Encroachments can result in catastrophe if the pipeline bursts. Coordination among government agencies, communities, and policymakers is crucial for managing these issues. Future pipelines may also face challenges in identifying alternative routes due to encroachments occupying the designated right-of-way servitude.

1.2. Impacts of pipeline encroachment

The state-owned bulk water utility has an extensive bulk water pipeline network covering a total length of 18000 kilometres. This bulk water pipeline network is vital for supplying water to a large portion of the population and economic activities within South Africa (Rand Water, 2023). Notably, bulk underground pipelines pose a unique challenge for utility management. These pipelines are not visible to human sight, as a result inspection and monitoring of the vital infrastructure is difficult. Lack of visibility of the infrastructure leads to delays to detect and address issues such as pipeline encroachments or structural defects, such as leaks. Planning and execution of maintenance works is further exacerbated by the complex spatial relationships of the underground pipelines to other concealed utilities.

Aged pipelines are more vulnerable to defects such as corrosion, leakage and degradation; as a result aging infrastructure increases the risk of catastrophe within the pipeline area (Fu, Yerdaw and Plante, 2022). Incomplete and inaccurate pipeline, servitude and condition records of the underground utilities further complicate the management effort, leading to challenges for the assessment of the pipeline and identification of potential areas of concerns (Li *et al.*, 2023). The potential for accidental damage or third-party interference, such as encroachments from informal settlements, poses a significant risk to the integrity of urban underground pipelines and the surrounding environment.

1.3. Challenges and imperatives in managing urban underground pipelines

The management of subsurface utilities presents several challenges that require a systematic solution. In the context of bulk water, pipeline encroachment which is a result of invasion of the designated right of way by external activities such as construction and land grabs, is a major challenge in managing underground utilities (Newton and Hart, 2020). Inspection and monitoring of concealed underground utilities is a challenging exercise. In densely populated urban areas, the complex geographical links of these pipelines can make planning and running maintenance or repairs challenging. Aging infrastructure and insufficient utility records further complicate urban pipeline management.

Effective and efficient management of underground utility seeks to ensure the safety and reliability of the utility operations. The potential for inadvertent harm or interference from third parties, such as informal settlements, underscores the significance of routine maintenance and inspections. New technologies and techniques can help improve pipeline management and reduce the risk of encroachment and other issues (Huang et al., 2023). Efficient communication and collaboration among pipeline operators, regulators, and other stakeholders are important to guarantee the security and reliability of metropolitan underground pipelines(Wei *et al.*, 2018) .

1.4. AR/VR for pipeline and right-of-way mapping

The use of Augmented Reality (AR) and Virtual Reality (VR) provides several advantages for the pipeline mapping and evaluation of subsurface utilities (Li *et al.*, 2023). The AR technologies allow for the real time visualisation and representation of underground utilities such as pipelines in real time. The real time visualisation assists with enhancement of our understanding of the complex spatial relationships between encroachments and water pipelines (Grover, Sidana and Jain, 2021).

Regarding bulk water services, it is absolutely crucial to solve the problems with encroachment resulting from informal settlements. Early intervention and mitigating techniques made possible by AR/VR technologies can help to enable early identification of engineering and environmental limitations across the pipeline routing and inspection process. Virtual GIS models let environmental scientists, surveyors, and engineers quickly find restrictions and share their ideas with stakeholders. This guarantees alignment among all the engaged stakeholders and speeds decision-making. Including spatial visualisations inside the AR/VR domain helps to find and monitor geohazards along the pipeline rights-of-way, thereby strengthening the general integrity of the pipelines and protecting human life and well-being.

Pipeline mapping with AR/VR technology simplifies and speeds the procedure, saving a lot of time and money. Also, it improves decision-making capacity by giving stakeholders a thorough and immersive visualisation of the pipeline system, therefore allowing informed decisions based on correct and current data (Wei et al., 2018). The seamless communication and collaboration facilitated by AR/VR technologies ensure alignment with project objectives and requirements.

2. OBJECTIVES

2.1. To use existing commissioned pipeline, servitude, and encroachment data for AR Visualisation:

- Investigate the steps involved in using existing commissioned bulk water pipeline, servitude, and encroachment data to visualise the operational pipeline system through augmented reality technology.

2.2. To quantify the Impact of encroachments:

- Examine the effect of the encroachments on the pipeline based on the area occupied and the distance to the pipeline.

2.3. To evaluate site performance using the vGIS augmented reality application for the visualisation of encroachments:

- To evaluate the site-level performance of the vGIS augmented reality (AR) application linked to Leica GG04 smart antenna for the visualisation and assessment of pipeline encroachments by analysing positional deviations relative to a Trimble R12i GNSS-based reference survey.

Research questions:
Given the objectives, the research questions are:

Q1. What are the key steps in utilising existing pipeline, servitude, and encroachment data for visualisation through AR technology?

Q2. How do various encroachments differ in spatial distribution and severity along bulk water pipeline systems?

Q3. How does the site-level performance of the vGIS augmented reality application support the identification and visual assessment of pipeline encroachments when evaluated against a GNSS-based reference survey?

3. THEORETICAL FRAMEWORK

Yan et al. (2019) presented a thorough model for utilities data governance. It is suggested to efficiently control the whole workflow of subterranean utility data collecting to its latter application. Introduced first was a three-dimensional (3D) subterranean utility data model that emphasizes the complex geometric and spatial features of subsurface utilities. Concurrently, a necessary link was created between the cadastral parcels and data, therefore simplifying land management procedures (Sürmeneli, 2023). Based on a new information model, the representation of utility information was thoroughly examined addressing the progressive change of utility data formats and assuring their seamless distribution to end-users(Sürmeneli *et al*., 2022) .

As shown in Figure 1 below, this framework comprises of five various roles that together support several phases of the work process, therefore guaranteeing a comprehensive strategy towards utility data management. Through careful coordination of these responsibilities, the framework not only solves the main issues related to the current underground utility database (Sürmeneli, 2022) but also guarantees the seamless operation of the whole work process, from data collecting to utilization (Sürmeneli, 2022).

The framework furnishes a concrete structure for the systematic management of the work process, thereby facilitating the seamless integration of newly collected 3D data, pre-existing 2D/2.5D data, and cadastral information, all of which play an indispensable role in land administration of underground utilities (Balicanta *et al.*, 2023).

Through its design and implementation, the framework ensures efficient data collection, use, and management (Sürmeneli, 2022), thus facilitating the basic structure and simplicity of the overall working process. All considered together, the framework effectively solves the present issues ailing the subsurface utility database, so providing the road for increased efficiency and cooperation among the several parties engaged in the scene of utility data management (Yan et al., 2019).

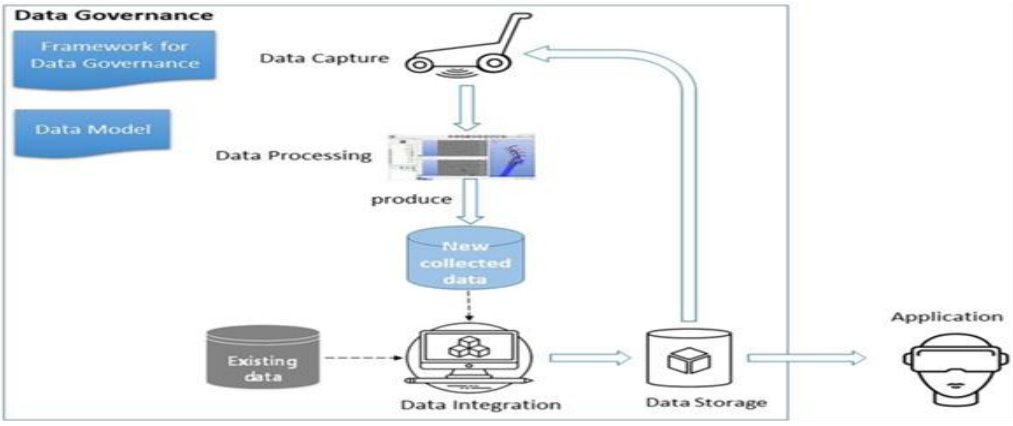

Figure 1: **Utility Governance Framework (Yan *et al.*, 2019)**

4. PROPOSED MODEL OR CONCEPTUAL METHOD

Figure 2 illustrates the conceptual framework that positions the comparative AR-based assessment within a cohesive, GIS-focused data approach for pipeline maintenance and encroachment management. The framework highlights augmented reality (AR) as a visualisation and validation instrument at the field level that enhances, rather than substitutes for, traditional GIS and survey methodologies.

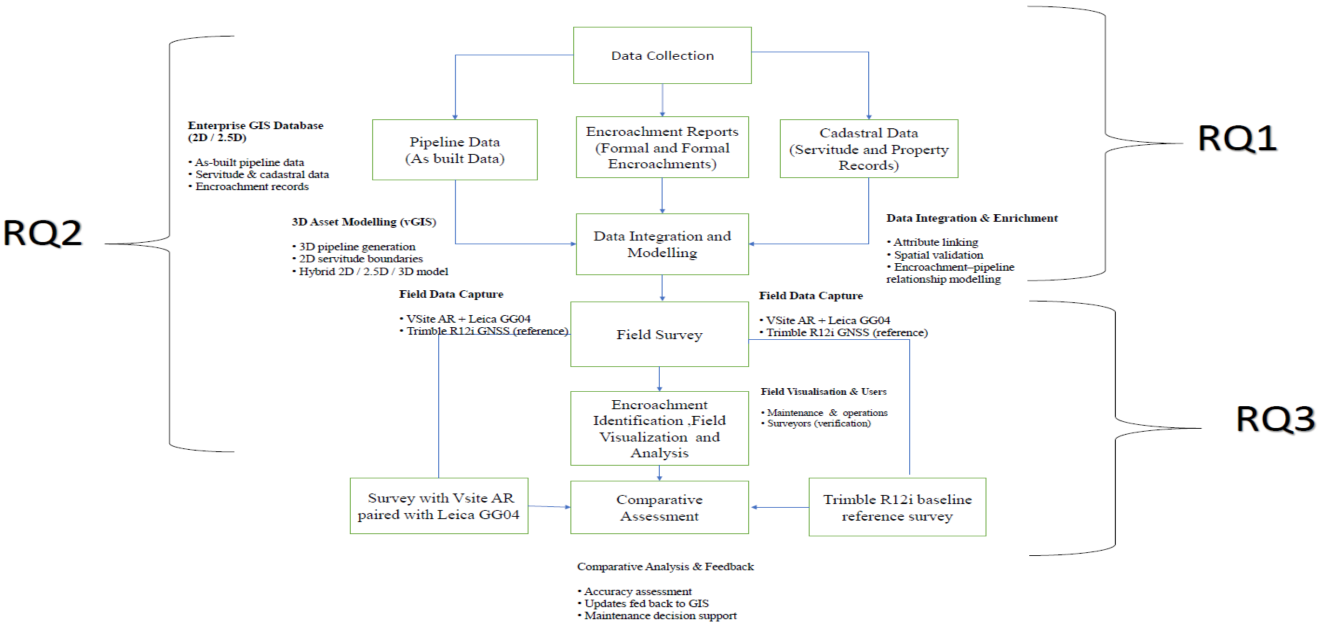

Figure 2 Conceptual Model Adopted for Research

The platform is based on a corporate GIS database that includes authoritative two-dimensional (2D) and two-and-a-half-dimensional (2.5D) spatial datasets, including as-built pipeline records, servitude and cadastral data, and encroachment information. Servitude boundaries remain as two-dimensional entities per their legal definition stipulated within the registered servitude diagrams, whilst pipeline features are augmented with vertical attributes like depth and diameter, facilitating a two-and-a-half-dimensional representation appropriate for spatial analysis and field implementation.

A data integration and modelling phase connects pipelines, servitudes, and encroachments into a unified spatial model. This integrated dataset generates three-dimensional (3D) pipeline assets within a vGIS environment. A hybrid modelling technique is utilised, wherein pipelines are depicted in 3D for enhanced spatial comprehension, while servitude extents are maintained in 2D/2.5D. This methodology integrates modelling effort, data quantity, and operational functionality within a GIS-based framework.

The framework clearly differentiates between user roles. Surveyors employ survey-grade GNSS technology for control measurements, positioning verification, and accuracy evaluation. Maintenance and operations professionals utilise AR-enabled tablets to access data, facilitating on-site visualisation of underground pipelines in connection to surface features and servitude borders, thus aiding in encroachment identification and maintenance decision-making.

Field data collection is conducted via two concurrent systems. Augmented reality-based measurements are obtained through the VSite application in conjunction with a Leica GG04 smart antenna functioning in RTK mode, while a Trimble R12i GNSS receiver delivers survey-grade reference measurements. This dual-system methodology facilitates a direct comparison evaluation of positioning accuracy in operational field settings.

The platform includes a feedback loop that reintegrates validated field measurements and observations into the enterprise GIS database. This ensures that validated spatial data facilitates continuous asset monitoring, pipeline upkeep, and land administration activities. The suggested framework illustrates a feasible and scalable integration of GIS, surveying, and AR technologies in accordance with current professional standards in surveying and geographic information management.

5. RESEARCH APPROACH

5.1 Introduction

A quantitative research method has been adopted for this study to provide measurable insights into the effects of encroachments on existing pipelines and servitudes. A purposive sampling method was used for this study to select a section of encroached pipelines in regions with the highest number of reported encroachments. This method is a non-probability sampling technique that involves the deliberate selection of specific data sources that are most relevant to the research objectives (Rai and Thapa, 2021) .

5.2 DATA COLLECTION:

5.2.1 Pipeline and servitude data:

Geospatial datasets in shapefile format for pipelines and servitude area of the affected pipelines were acquired from the bulk water utility supplier's Geospatial Department. The shapefiles came with important attribute information for the pipelines, such as the diameter of the pipeline, the year installed, the material of the pipeline, bend points of the pipe, length of the pipeline, and the coordinates. This information was vital for the creation of a 3D pipeline model. The study focused on existing, operational water pipelines, rather than pipeline servitudes in the planning or design phase.

5.2.2 Encroachment reports

Encroachment reports were obtained from the bulk water utility's Land Services department. This information included types of encroachments, location, approximate length of the encroachment, date reported, and name of the pipeline affected.

5.2.3 Data integration

Data integration was executed using Geographic Information System (GIS) technologies to merge these datasets, creating a cohesive geospatial representation of the pipeline network and its surroundings. This integration facilitates the development of spatial models that represent the relationships among pipelines, encroachments, and land use rights within the properties affected by encroachments.

5.2.4 Pipeline and servitude modelling

2.5D pipelines and 2D servitude areas were modelled to 3D using the Visual Geographic Information System (vGIS) software application. The pipeline and servitude data were loaded on the application. Important attribute information, such as the pipeline diameter, length and position, was used to create an accurate pipeline and servitude model for Augmented Reality visualisation. The model was verified through Vsite application to ensure that the model is projected on the correct location per the database information.

5.2.5 Field surveys

The objective for conducting a field survey was to assess the positional reliability of an AR-based visualisation tool against established survey-grade equipment under real-world field conditions. Two primary data acquisition systems were employed. The first was the VSite AR application deployed on an iPad and integrated with a Leica GG04 smart antenna. This system enabled real-time, on-site visualisation of underground pipeline infrastructure through augmented reality, allowing field personnel to identify potential encroachments relative to the mapped pipeline alignment and boundaries of servitude areas. The system operated using Real-Time Kinematic (RTK) GNSS corrections, providing centimetre-level positioning accuracy under optimal conditions.

The second system comprised a Trimble R12i GNSS receiver paired with a TSC5 controller. This survey-grade instrument, equipped with inertial measurement unit (IMU) technology and tilt compensation, was used to collect highly accurate ground control points and spatial measurements. Operating in RTK mode, the Trimble system provided centimetre-level positional accuracy and served as the reference standard for validating the spatial accuracy of the AR-based measurements.

For each test site, a total of 25 measurement points were collected. This included 15 points measured along the servitude boundary and 10 points measured along the centreline of the pipeline. All points were independently captured using both the VSite AR (Leica GG04) system and the Trimble R12i.

Instrument Accuracy Specifications

According to Leica Geosystems AG. (2025), the accuracy specifications – VSite AR with Leica GG04 Smart Antenna are as follows:

Component: iPad with VSite AR + Leica GG04
Positioning Method: RTK GNSS with AR visualisation
Horizontal Accuracy: ± 1–2 cm
Vertical Accuracy: ± 2–3 cm
Trimble Inc. (2025) stipulates the accuracy of the Trimble R12i with the TSC5 Controller as:

Component: Trimble R12i + TSC5
Positioning Method: RTK GNSS with IMU tilt compensation
Horizontal Accuracy: ± 1 cm + 1 ppm
Vertical Accuracy: ± 2 cm + 1 ppm

5.2.6 Method of measuring points in the VSite/VGIS application

Point measurements in the VSite/VGIS application were conducted using an integrated augmented reality (AR) and GNSS-based workflow designed for real-time spatial data capture and visualisation of underground infrastructure. The system was deployed on an iPad and paired with a Leica GG04 smart antenna operating in Real-Time Kinematic (RTK) mode to ensure centimetre-level positioning accuracy.

To measure a point, the user aligned the AR interface with the physical location of interest on the ground surface along the pipeline servitude areas. The application displayed the georeferenced pipeline model in the field of view, enabling visual confirmation of spatial relationships between surface features and underground assets. Once the target location was visually and physically aligned, the user captured the point using the application's measurement function, which recorded the GNSS-derived XY coordinates in real time and saved the measurements on Vsite database.

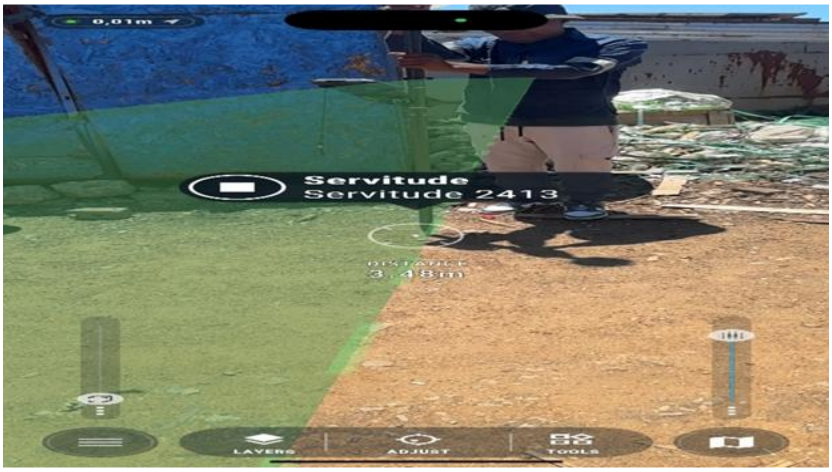

Figure 3: Baseline reference point measurement using Trimble R12i and Vsite application /GG04-based measurements

The recorded point data included horizontal and vertical coordinates referenced to the project's coordinate system and datum. Quality indicators such as GNSS fix status, satellite geometry, and correction type (RTK) were logged to ensure data reliability. Where necessary, repeated measurements were taken at the same location to assess positional consistency and minimise random errors.

These AR-derived point measurements were subsequently exported and compared with survey-grade GNSS measurements collected using a Trimble R12i receiver to evaluate positional accuracy and support the validation of the AR-based measurement approach.

Mitigation of the parallax effect on site

A straightforward yet efficient visual method was employed to alleviate parallax effects and enhance the user's spatial comprehension. The three-dimensional pipeline model is preserved at its accurate georeferenced location beneath ground level, in accordance with real-world coordinates.

Existing permanent pipeline beacons were utilised as major visual references to facilitate accurate interpretation in the field, where accessible. In locations lacking such beacons, temporary surface markers were established using spray paint, derived from validated as-built data or Ground Penetrating Radar (GPR) findings. The picture below shows the user holding the GPR to detect the actual pipeline position for model alignment and reduction of the parallax effect.

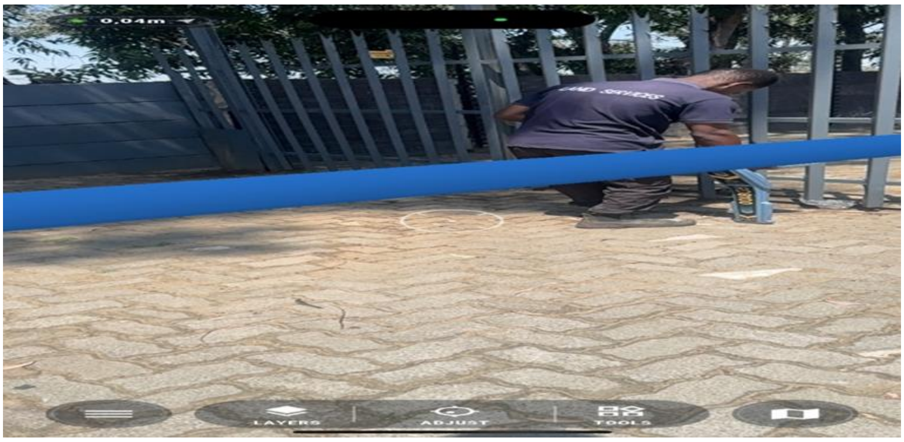

Figure 4: Use of GPR for pipeline detection and alignment

A visible sign was positioned on the ground surface right above the pipeline's actual subterranean location. This superficial reference offers a stable spatial indicator, allowing users to associate the subterranean asset with its vertical projection on the surface, thus mitigating misinterpretation resulting from viewing-angle-dependent parallax effects.

To maintain consistency and minimise excessive perspective distortion, the AR application's field of vision was restricted to a 50 m radius around the user's location, ensuring that only proximate objects were visualised during on-site evaluation.

6. RESULTS

6.1 Introduction

This section presents the analysis of encroachments over the L06, J10&J08, S04/K01 and K05 pipelines using Augmented Reality (AR) visualisation and geospatial assessment techniques. Encroachment risk is estimated using the Encroachment Severity Index (ESI), which considers the density of encroachments along the length of the pipeline investigated and the distance of the structures to the pipeline. Comparative analysis between AR system and traditional survey techniques is conducted and presented by standard deviation, root mean square, and mean positional errors between the positional coordinates obtained from the two platforms. The findings are discussed in terms of encroachment severity, risk levels, and potential implications for infrastructure integrity and safety.

6.1. Study Area 1: L06 Pipeline

The L06 pipeline is in Tamboville Township within the Ekurhuleni Metropolitan Municipality. The L06 pipeline is a 610mm diameter bulk water steel pipeline transporting water from Leeuwpoort - Brakpan Reservoir covering a total length of 2.3km. Figure 3 depicts the section of the pipeline investigated for encroachments in this section spans over a distance of 204.49m.

Figure 5: L06 pipeline site located in Tamboville Township, City of Ekurhuleni

6.1.1. Field visualisation results

Several shack dwellings were identified as encroaching on the pipeline and servitude. A total of 58 informal settlements stretching over a length of 204,49m were identified during the field assessment. Encroachments were mapped, and their proximity to the pipeline was calculated. Informal settlements were observed to be growing along the pipeline corridor, increasing encroachment risks. The informal structures observed along the pipeline and servitude were used for residential purposes.

Within the appendix, Figures A1 and A2 depict an overlaid AR model over the ground. The AR overlay below provides a real-time representation of the pipeline across the informal settlements established within the pipeline area. The overlaid blue line represents the 3D model of the underground bulk water pipeline responsible for transporting water from Leeuwpoort - Brakpan Reservoir. The figures A1 and A2 portray a section of the L06 pipeline invaded by illegal encroachments. From the images, visible informal structures made of metal are established over the servitude or pipeline's right of way. The narrow space visible between the servitude area and the encroaching structures within appendix figures A1 and A2 indicates increasing settlement pressure that can potentially lead to increased encroachment risks within the area over time.

6.2. Study Area 2: J10& J08 pipeline

The J10 & J08 pipelines are located near Germiston Township within Ekurhuleni Metropolitan Municipality. The J08 pipeline is a 610mm diameter, while the J10 is 800mm bulk water steel pipeline transporting water from Shamrock Road – Leeuwpoort, covering a total length of 10.1km. The section of the pipeline investigated for encroachments in this section spans over a distance of 160m.

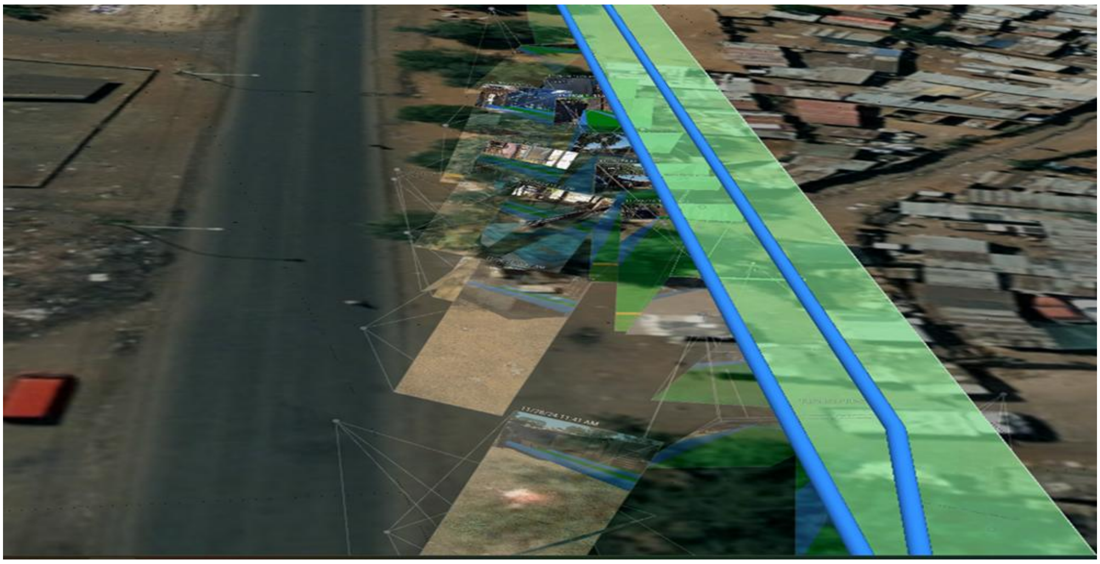

Figure 6: Section of the J10&J08 pipelines located in Germiston Township

6.2.1. Encroachment observations for the J10 And J08 pipelines

Multiple shack dwellings were identified as encroaching on the pipeline servitude. A total of 21 informal settlements stretching over a length of 160m were identified during the field assessment. Encroachments were mapped, and their proximity to the pipeline was calculated. Informal settlements were observed to be growing along the pipeline corridor, increasing encroachment risks. The informal structures observed along the pipeline and servitude were mainly used for informal businesses.

Field Visualisation Results:

The J10 and the J08 Encroachment is dominated by informal business structures established over the pipeline and servitude area. The structures depicted in appendix figure A3 and A4 depict an encroachment scenario where shop-like structures have been established with several trading activities happening within the designated pipeline area. In both figures, the structures run across and along the pipeline and servitude area. The encroachment pattern observed within this area suggests that social and economic pressure are driving people to set up informal structures for economic activities without legal permits.

6.3. Study Area 3: K05 Pipeline Area

6.3.1. Introduction of the study area

The K05 pipeline encroachment area is located within the Watville Township, under the City of Ekurhuleni Metropolitan Municipality. The K05 pipeline is a 610mm diameter bulk water steel pipeline transporting water from Leeuwpoort to Kleinfontein covering a total length of 3.4km. The section of the pipeline investigated for encroachments in this section spans over a distance of 200m.

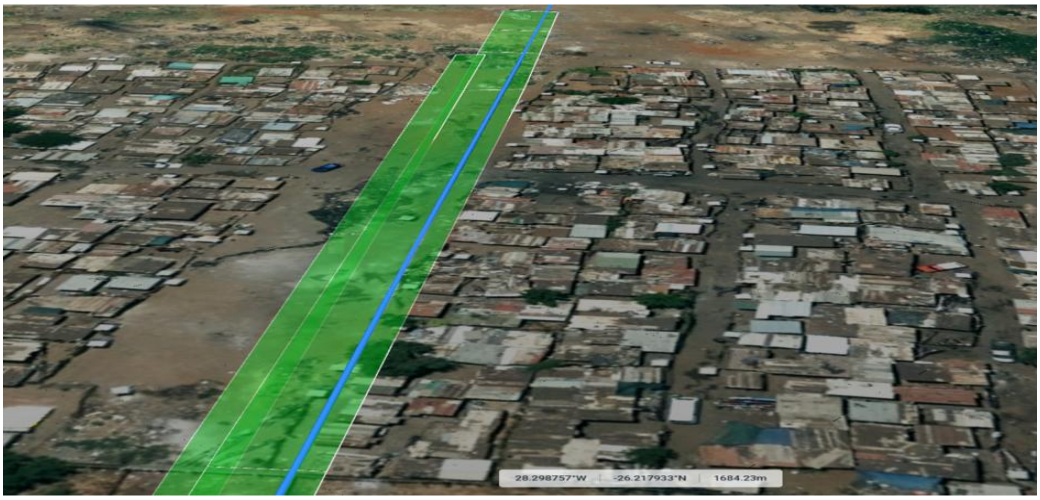

Figure 7: Section of the K05 pipeline located in Watville Township

6.3.2. Field visualisation images

The appendix figures A5 and A6 provide a visualisation of the 3D model for the K05 pipeline and the servitude area. The area is dominated by informal settlements for residential purposes. The western side of the servitude is clear of any encroachments; however, several encroachments were picked up from the eastern side of the servitude area, as depicted in Figures A3 and A4. Some of the structures identified during the field visualisation serve both residential and commercial purposes.

6.4. Study Area 4: S04/S01 pipeline

The section of the S04/S01 pipeline affected by encroachments is located within Watville Township, situated within the City of Ekurhuleni Metropolitan Municipality. The SO4/S01 pipeline is a 2100mm diameter bulk water steel pipeline transporting water from Mapleton pumping station to Kleinfontein covering a total length of 31km. The section of the pipeline investigated for encroachments in this section spans over a distance of 282.93m.

Figure 8: Section of the S04 pipeline located in Watville Township

6.4.1. Encroachment observations for the S01/S04 pipelines:

Multiple shack dwellings were identified as encroaching on the pipeline servitude. A total of 80 informal settlements stretching over a length of 282.93m were identified during the field assessment. Encroachments were mapped, and their proximity to the pipeline was calculated. Informal settlements were observed to be expanding along the pipeline route, increasing encroachment risks. The informal structures observed along the pipeline and servitude are used for mixed purposes, including residential, informal businesses and mining activities.

6.4.2. Filed visualisation results

The S04/S01 pipeline encroachment represents a case of high-density encroachment with settlements occupying a 30m wide servitude area. The servitude area within this section, represented by figure A7 partially clear, but also the servitude area is predominantly occupied by encroachments on either side of the pipeline or servitude area. The area is densely packed, with little to no space within the servitude area.

6.5. Encroachment severity index

The encroachment severity index (ESI) is a method used to quantify the effect of encroachments based on the size and the proximity to the pipeline. The ESI is used to provide insights to identify high encroachment risk, where the encroachment could result in damage to infrastructure and fatalities in case of pipeline burst. The figure below depicts how encroachment area was determined for calculation of ESI.

Figure 9: Encroachment area quantification

6.5.1. Summary of encroachment severity results

Formula for calculating ESI:

$$\text{ES}=\sum(Encroached\ Area\ x\ Proximity\ Factor)/Total\ Pipeline\ Lenghth\ Investigated$$

The justifications used to validate the ESI range and Encroachment Severity on the Table 1 Levels were based on the following:

ESI value <0.5

Suppose the encroachment area is further than 5m from the pipeline. In that case, the distance to the pipeline will reduce the severity/risk of the encroachment since maintenance is still possible within the available space.

ESI value 0.5-1

The encroachment scenario in this case is closer to the pipeline, but at no point will the encroachments be directly above the pipeline. The encroachment is still within the servitude area, restricting access to the pipeline for critical maintenance repairs.

ESI Value >1

The ESI value indicates that there are multiple structures directly on top of the pipeline.

Table 1: Encroachment Severity Index range and severity levels

ESI Range	Encroachment Severity Level
<0.5	Low Risk
0.5- 1	Moderate Risk

> 1	High Risk

The Table below provides a range of scales used for determining the proximity factor based on the proximity of the structures to the pipeline. Close proximity structures within a range of 0-2 m from the pipeline are considered to be high risk that can lead to a catastrophic event if the pipeline bursts, and this will restrict maintenance operations from being conducted within the area. Bulk water's utility deeds of servitude stipulate a requirement of at least 2m space from either side of the servitude zone where permanent structures are prohibited. Moderate encroachment refers to encroachment scenarios where the pipeline is within a distance of 2-5m. This is not considered a high-risk scenario since there is a reasonable distance between the pipeline and the structures, although it still presents a significant encroachment risk that has a direct impact on the integrity of the bulk water pipeline system.

Table 2 : Encroachment -pipeline proximity factor

Distance from Pipeline (m)	Proximity Factor (PF)	Risk Level
0-2 m	1.0	High
2-5 m	0.5	Moderate
> 5 m	0.25	Low Risk

Encroachment Area =Area of illegal structures (square metres)
Proximity Factor =Weight assigned based on distance from the pipeline (closer encroachments are more severe).

6.5.2. Summary of Encroachment Severity Results

Table 3 below provides a summary of the encroachment severity index values calculated from the four sites investigated for encroachments. The higher the encroachment index value, the higher the severity of the encroachments over the pipeline and the servitude area. The higher ESI value is an indication that the encroaching structures have occupied more surface area and are located within a very close proximity to the pipeline.

Table 3: ESI values for the encroached pipelines

Pipeline Description	ESI	Pipeline Length Investigated(m)
1.L06	5,66	204,49
2.J10&J08	7,67	160,00
3. K05	0.70	200,00
4. S04/S01	4.40	282.93

6.5.3. Mean Positional Errors (MPE) calculation:

The mean positional errors represent the average errors obtained from the measurements conducted using the Trimble R12i GNSS survey and the model projection using the Vsite AR application with Leica GG04 platform's measurements, which compare very closely along the y and x axis with the mean positional errors less than 2cm. The MPE values obtained from this investigation confirmed that the positional deviations between the two systems were minimal. This finding supports the feasibility of using Augmented Reality for servitude and pipeline in line with research objective 2.1 and also confirms its precision for the identification and mapping of encroachments in line with research objective 2.2.

$MPEy = \frac{\sum_{i=1}^{n} \triangle Y}{n}$ =0,0156m

$MPEx = \frac{\sum_{i=1}^{n} \triangle X}{n}$ = -0,0125m

Where:

n - the total number of measurements per site

△Y-errors in the Y -axis measurement

△X-errors in the X -axis measurement

6.5.4. Root Mean Square Error (RMSE):

The Root Mean Square error calculation was used to establish the positional alignment of the two measurement systems compared. The horizontal positions (y,x) are below 3cm. This indicates that the errors are consistent on both the y and x axes. The horizontal errors indicate an acceptable level of accuracy for mapping applications. This means that the AR application projections closely align with the actual ground truth established through the baseline positions, making it suitable for evaluating servitude encroachments. Research objective 2.3 aims to compare the GG04 AR-based survey with an independent R12i GNSS baseline reference survey; the RMSE values obtained from this study show that the horizontal positions are within acceptable mapping accuracy within 3cm.

$RMSE\ x = \sqrt{\frac{\sum_{i=1}^{n} (\Delta Xi)^2}{n}}$ =0.0268

$RMSE\ y = \sqrt{\frac{\sum_{i=1}^{n} (\Delta Yi)^2}{n}}$ =0.0296

Where:

n - the total number of measurements per site

△Yi-Sum of errors in the Y -axis measurement

△Xi-Sum errors in the X -axis measurement

6.5.5. Standard Deviation:

The standard deviation calculations below indicate that the y direction fluctuates more compared to the x. Research objective 2.1 refers to the use of the existing pipeline, servitude, and encroachment data for visualisation; the low standard deviation indicates that AR platform use was stable. This also supports research objective 2.2 since it measures precisely how far the encroachments are from the pipeline and the servitude area. With respect to objective 2.3, the standard deviation values indicate that the AR application is consistent and can be used to complement existing survey data.

$$\sigma y = \sqrt{\frac{\sum_i^n (\Delta Yi - \Delta Ya)^2}{n-1}} = 0{,}0328$$

$$\sigma x = \sqrt{\frac{\sum_i^n (\Delta Xi - \Delta Xa)^2}{n-1}} = 0{,}0277$$

Where:
n - the total number of measurements per site
△Yi-Sum of errors in the Y -axis measurement
△Xi-Sum errors in the X -axis measurement
△Yia-Mean errors in the Y -axis measurement
△Xia-Mean errors in the X -axis measurement

7. IMPLICATIONS AND RECOMMENDATIONS

7.1 Encroachment Risk Assessment and AR Mapping Reliability:

An encroachment trend, which is predominantly high risk in terms of the ESI values, has been observed. Based on the ESI values used to analyse encroachment risks in this study, it can be concluded that small-sized encroachments can pose higher risks if the structures are located at a very close proximity to the pipeline. Encroachments covering large surface areas but far from the pipeline infrastructure have lower risks despite their size. Encroachment risk mitigation and control efforts should prioritise encroachments on encroachment sites where the ESI values are greater than 1.

The RMSE values obtained from comparing the R12i baseline system and GG04 positions are below 5 cm for measurements taken within a radius of 5m from the AR device, making AR suitable for mapping and evaluating encroachments. GNSS-based AR is reliable for servitude inspections. The relatively lower standard deviation falling within sub 10cm across the two axes indicates that the AR model closely aligns with the actual positions on the ground.

7.2 The implications of the study for the Water Industry:

This study has investigated an innovative approach that can streamline Pipeline Protection and Risk management practices. Decision makers can access encroachment reports in real time remotely while the user or operator is on site, collecting encroachment data. The information generated from the field reports can be used to justify legal actions and as evidence in court. The AR models can be used to create awareness about the existence of the bulk water pipelines and servitude areas within communities and highlight the risks associated with encroachments.

7.3 Implications of the study for academia:

The study has demonstrated how AR can effectively complement existing technologies such as GNSS and GIS in geomatics and infrastructure monitoring. This study paves the way for AR mapping to be integrated into university curriculum as an effective tool that can be used to enhance underground utility mapping, smart cities, infrastructure planning and investigating encroachments. This study paves a way for future research that can include the integration of Remote Sensing, Artificial intelligence and Drones for the investigation of encroachments.

7.4 Future research

This research was limited to regions within the City of Ekurhuleni; future research works can focus on other areas affected by encroachments within the province, such as the City of Johannesburg, Tshwane and Emfuleni. Satellite imagery and AI analytics can be used to provide detailed analysis of the encroachment scenarios and provide real-time encroachment alerts. Future research work can be carried out to assess the usability of AR tools across various stakeholders, varying distances, and environments. Further studies can focus on the AR evidence's validity and regulatory acceptance in cases involving land disputes, pipeline, and servitude encroachments.

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Appendices:

Appendix A: Filed Visualisation Images

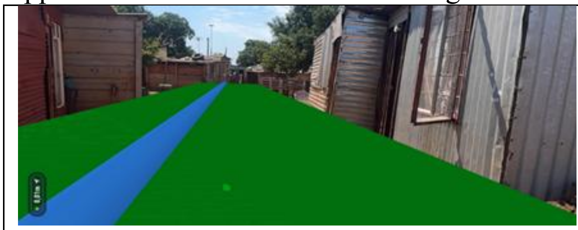

Figure A 1: L06 Pipeline and servitude overlay

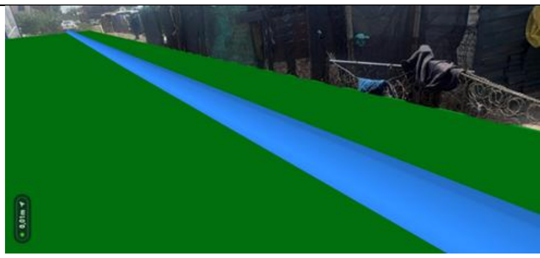

Figure A 2 : KO5 pipeline and servitude AR overlay

Figure A 3 :L06 Pipeline and servitude overlay

Figure A 4 : KO5 pipeline and servitude AR overlay

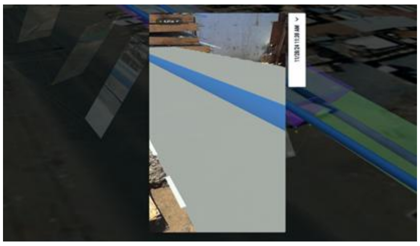

Figure A5:L8 &J10 pipeline and servitude AR overlay

Figure A 6:S04/S01 Pipeline and servitude overlay

Figure A 7 : L8 &J10 pipeline and servitude AR overlay