Tanzania Journal of Science
Volume 51(4), 2025
journal homepage: https://commons.udsm.ac.tz/tjs/

Aquifer distribution in Lukobe ward, Morogoro municipality, Tanzania: Mapped resources for sustainable water access

Kelvin K Kayuni*
Department of Geoscience, University of Dar es Salaam, P.O. Box 35052, Dar es Salaam, Tanzania.

Keywords

Lukobe;
Unconfined;
Aquifer;
Mapping;
Density;

Abstract

In response to the ongoing challenges posed by the scarcity of reliable fresh-water sources in Lukobe Ward, Morogoro Municipality, Tanzania, this study applied an integrated approach that combines geospatial and geophysical datasets to identify previously undocumented aquifers. The datasets utilized include an apparent density map generated from high-resolution GGMPlus satellite gravity data, a geological map (Quarter Degree Sheet 183), a water drainage map, and a slope map created from a digital elevation model (DEM). The analysis successfully identified four unconfined, saprolitic aquifers in the study area, designated as aquifers A, B, C, and D. These aquifers span areas of 12.2 km^2, 1.1 km^2, 1.6 km^2, and 7.5 km^2, respectively. Aquifers A and D attain maximum thicknesses of up to 360 m and 200 m, respectively. Aquifers B and C exhibit an average thickness of 280 m. Aquifers A and D are situated beneath relatively thick soil layers measuring 60 m and 95 m, respectively, whereas aquifers B and C are located beneath a thinner soil cover of 40 m. The discovery of these aquifers provides valuable insights for future groundwater exploration in the Morogoro Municipality, offering precise targets for the development of public water wells.

Introduction and Background

In urban areas, water availability and quality are critical concerns due to continuous population growth that exceeds the available fresh-water resources (Alameddine et al. 2016). Previous studies, such as Raphael et al. (2022) and Uhagile and Salehe (2024), have reported water scarcity at the household level in Lukobe. These studies examined water accessibility in terms of household sources of water supply, availability, consumption, and spending.

Raphael et al. (2022) reported that 80% of households are not connected to the public water supply networks; they rely on sources such as rainwater, streams, shallow boreholes, and shallow wells. Data from Uhagile and Salehe (2024) strongly agree with these findings, showing that 100% of households in Lukobe rely on purchasing water from vendors and harvesting rainwater, 63.1% fetch water from privately owned sources, while 61.1% utilize shallow wells. Despite these coping strategies, 88.2% of households obtain only 40 to 100 L of water per day. This quantity falls below the recommendations set forth by the United Nations (UN) for water access, which suggest that a sufficient amount of water is at least 50 to 100 L per person per day (United Nations 2012, Akoteyon 2016). Thus, it is evident that the amount of water used at the household level in Lukobe does not meet the minimum requirements. The high reliance on private water sources and shallow wells underscores the limitations of formal water supply systems and the need for alternative water sources to meet household needs (Uhagile and Salehe 2024).

Groundwater is one of the preferred alternative sources of water supply in urban areas as it exhibits numerous benefits, such as excellent natural quality, requiring only precautionary measures before being directed into the main distribution systems (Foster 2022). In comparison to surface water, groundwater availability tends to be more stable, as it is less affected by seasonal changes and extreme weather events, such as droughts, thereby serving as a crucial resource when surface reservoirs run dry. Additionally, groundwater undergoes natural filtration as it percolates through soil and rock layers, often requiring minimal treatment for portable use. These characteristics make groundwater an attractive option for urban areas seeking cost-effective and reliable water supply solutions (Vila-Tojo et al. 2022).

Despite the clear advantages of groundwater for urban water supply, Lukobe Ward lacks aquifer mapping data to guide its sustainable development. The absence of subsurface data has limited efforts to identify high-yield zones suitable for public water wells. This study, therefore, aims to delineate aquifers in Lukobe that can serve as reliable alternative water sources for the community.

* Corresponding author: kelvinkayuni13@gmail.com
Received 21 May 2025, Revised 8 Nov 2025, Accepted 10 December 2025, Published December 24 2025
https://doi.org/10.65085/2507-7961.1003

ISSN 0856-1761, e-ISSN 2507-7961

Location of the Study Area

The study area is located in the eastern part of Tanzania, in the Morogoro region, between latitudes 6˚40’0” - 6˚50’0” S and longitudes 37˚30’0” - 37˚40’0” E. It covers an area of 355.5 km^2, extending from west of Morogoro Municipality to the eastern part of Mvomero District (Figure 1).

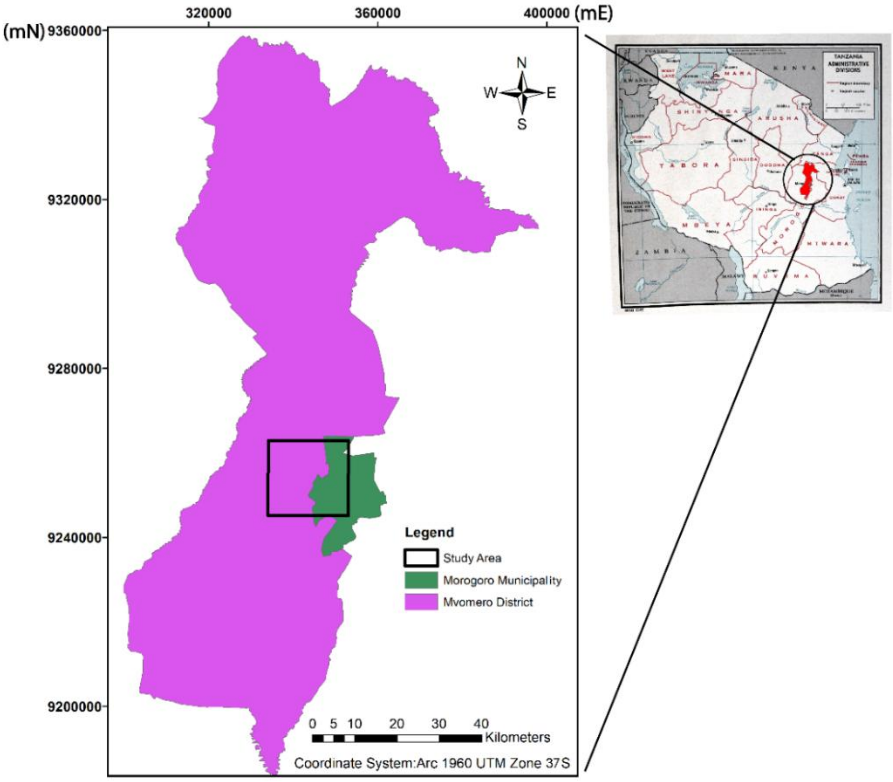

Figure 1: A sketch map of Morogoro Municipality and Mvomero District showing the location of the study area. Source: Contributors (2025).

Geomorphology of Lukobe

Lukobe is situated southeast of the Wami flats and northwest of the Uluguru Mountains. The central portion of Lukobe is dominated by mountainous terrain, with elevations ranging from 750 to 1,350 m above sea level. In contrast, the eastern and western zones are predominantly low-lying plains, with elevations ranging from 432 to 625 m above sea level (Figure 2).

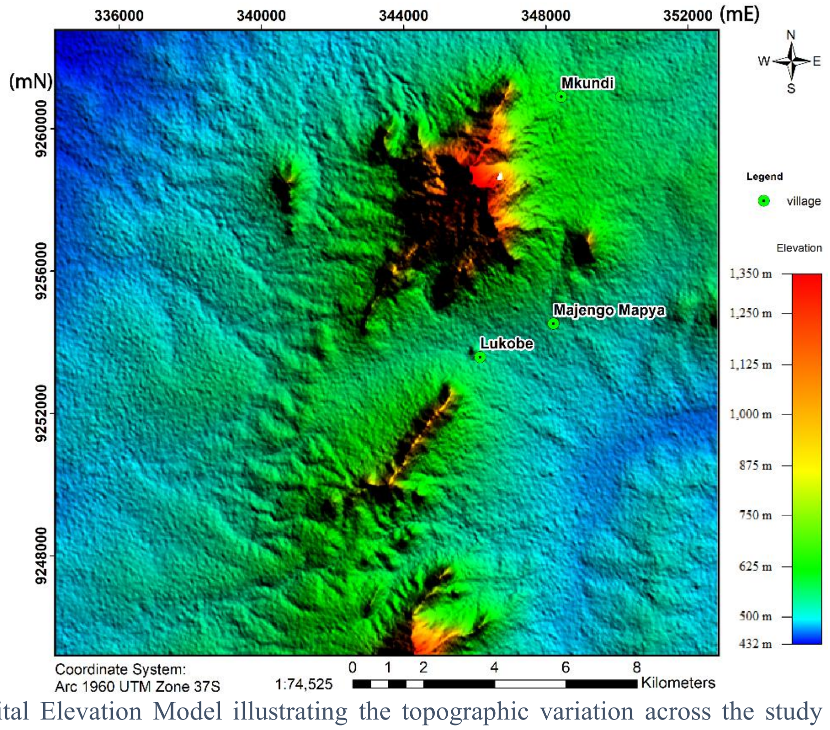

Figure 2: 2D Digital Elevation Model illustrating the topographic variation across the study area. Modified from (USGS 2000)

Geology of Lukobe (QDS 183)

The area covers the east-central part of the Morogoro (QDS 183) block and is mainly characterized by metamorphic rocks (Usagaran basements). These include banded muscovite-biotite migmatites, along with hornblende gneisses and granulites. These lithologies are widely exposed in the central region, stretching from south to north. Surrounding these metamorphic rocks are deposits of sand and sandy hill wash, succeeded laterally by layers of red and reddish-brown soils. The area also features alluvial deposits and mbuga soils (Sampson and Wright 1961, Figure 3). These soil types influence recharge potential, with sandy soils promoting rapid infiltration and loamy soils balancing retention and flow (U.S. Department of Agriculture 2014, Agriculture Institute 2023).

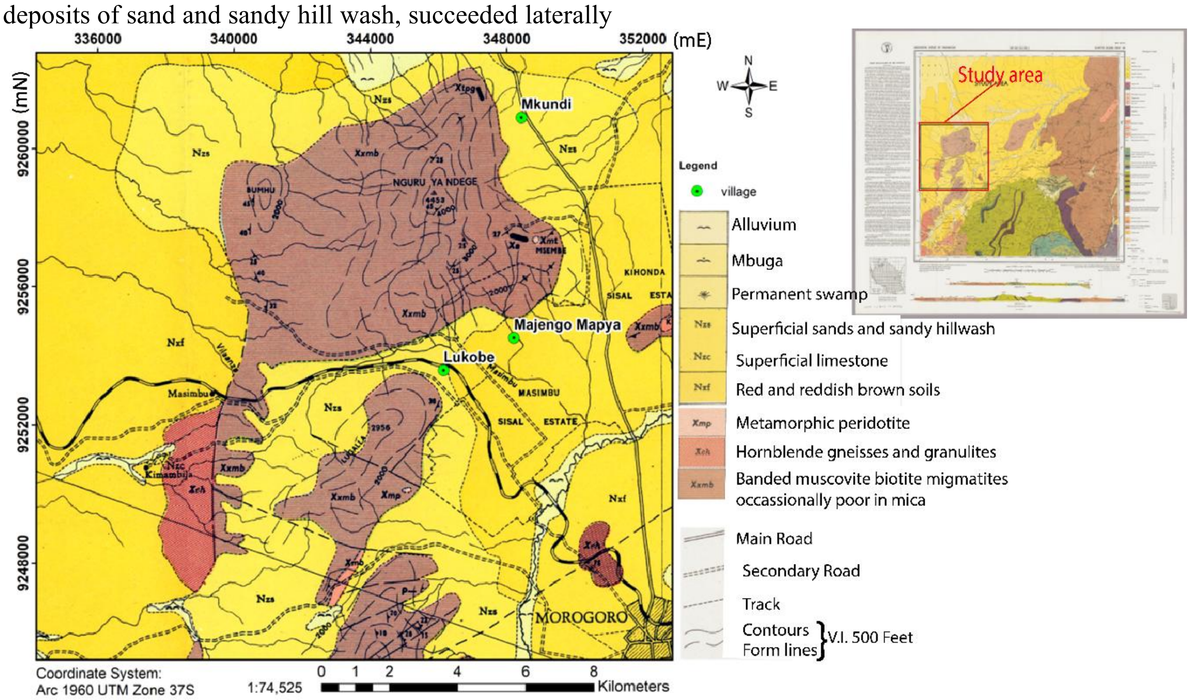

Figure 3: Geological map of the study area, illustrating lithological units and structural features relevant to groundwater potential assessment. Cut from (Sampson and Wright 1961).

Target Zones for Aquifer Mapping

Deeper aquifers suitable for groundwater extraction are often located in low-lying areas with sediment cover (Cavallina et al. 2022, Alamirew et al. 2025). The western and eastern zones in Lukobe are characterized by low-lying plains (Figure 2) with sediment deposits (Sampson and Wright 1961, Figure 3). Therefore, this study focuses on aquifer mapping in these zones where deep aquifers are considerably localized.

Material and Methods

To achieve the objectives of this study, three key datasets were employed: a geological map (QDS 183) obtained from https://purl.stanford.edu/bn911hv6633, a Digital Elevation Model of the Shuttle Radar Topography Mission, downloaded from the United States Geological Survey (USGS) website via https://earthexplorer.usgs.gov/, and high-resolution satellite gravity data from the GGMplus model accessed through http://ddfe.curtin.edu.au/models/GGMplus/. A description of the use of each dataset is provided below:

Geological Map (QDS 183)

The geological map was used to assess lithological variations in the study area, with a focus on identifying aquifer recharge zones. These zones are mainly characterized by the presence of sand, sandy hill wash, alluvium, mbuga soils, and red to reddish-brown soils (Figure 3). Such lithological types are known for their high porosity and permeability, influencing groundwater recharge (U.S. Department of Agriculture 2014, Agriculture Institute 2023).

Digital Elevation Model (DEM SRTM)

The DEM SRTM was employed to extract slope and drainage network information across the study area, with particular emphasis on the eastern and western zones characterized by sedimentary cover (Figure 3). One way to obtain the slope and drainage networks is by their extraction from DEM using ArcGIS (Tarboton 2003, Das et al. 2016, Monteiro et al. 2018). The resulting slope map facilitated the identification of low gradient zones, which are conducive to reduced surface runoff and enhanced infiltration, key indicators of groundwater recharge potential. Additionally, the drainage network map was utilized to assess flow direction and delineate outlet points where surface water converges. In low-lying terrain with a sedimentary cover, convergence points often coincide with infiltration-prone areas; these are ideal targets for aquifer mapping (SRBC 2023).

GGMPlus Gravity Data

The GGMPlus satellite gravity data enabled the analysis of subsurface density variations and the geometry of the aquifers. GGMPlus provides gravity field data at 220 m resolution for all land regions of Earth within 60 degrees of latitude (Hirt et al. 2013).

For the study area, a total of 6,800 free-fall gravity acceleration data points were downloaded from the GGMPlus model and used as Observation gravity (gObs) data. The GGMPlus acceleration values closely match field-based Observation gravity data, showing a correlation level above 95% (Suprianto et al. 2021).
The downloaded free-fall gravity acceleration data were processed and corrected using Oasis Montaj Software, following standard gravity correction procedures described by Kearey et al. (2002). These corrections included Latitude Correction, Free Air Correction, Bouguer Correction, and Terrane Correction, resulting in the calculation of the Complete Bouguer Anomaly (CBA) for the study area. The subsequent steps after calculating the CBA are outlined below.

Isolation of the Residual Bouguer Anomaly from the Regional Field and Noise

The Complete Bouguer Anomaly (CBA) is a combination of three gravity signals, such as the regional gravity field, residual components, and measurement noise (Siambone et al. 2022). In gravity surveying, the first step in interpretation is to remove the regional field and noise from CBA to isolate the residual anomalies (Kearey et al. 2002).

In this study, residual anomalies from the CBA were extracted using interactive spectral filtering techniques, specifically the Butterworth Bandpass filter. A central cutoff wavelength of 7000 m was used to separate the residual anomaly from the regional field, while a cutoff of 1800 m was applied to eliminate short-wavelength noise.

Downward Continuation

The residual Bouguer anomaly data were downward continued to a depth where the anomalies began to exhibit significant fluctuations. As noted by Kearey et al. (2002), the emergence of these fluctuations provides a reliable estimate for the limiting depth of the causative anomalous bodies.

Apparent Density Mapping

When an inverse density deconvolution filter is applied to residual gravity anomalies, the resulting gravity components yield apparent density values for the upper crust that correlate well with average densities obtained from rock samples (Granser et al. 1989).
In this study, the apparent density map was utilized to identify low-density residual anomalies, which correspond to the water-bearing zones.

2D Modelling

Two-dimensional gravity modelling was performed using residual Bouguer anomaly data, apparent densities, geological data, and surface elevation data within the GM-SYS software environment. This integrated approach facilitated the determination of the aquifer depth, thickness, and associated density distributions.

Results

Slope of the Lukobe Area

The slope map (Figure 4) indicates that the western and eastern zones of Lukobe exhibit gentle to very gentle slopes (0-5%), characterized by sand, sandy hill wash, and red to reddish-brown soil covers (Figure 3). In contrast, the central zone is characterized by steep slopes ranging from 21% to 264%, with extensive outcrops of migmatitic rocks (Figure 3). Gentle to very gentle slopes are associated with reduced surface runoff (FAO 2006), while the sediment cover enhances infiltration capacity due to its high porosity, thereby promoting groundwater recharge and the development of deep aquifers (Cavallina et al. 2022, Alamirew et al. 2025).

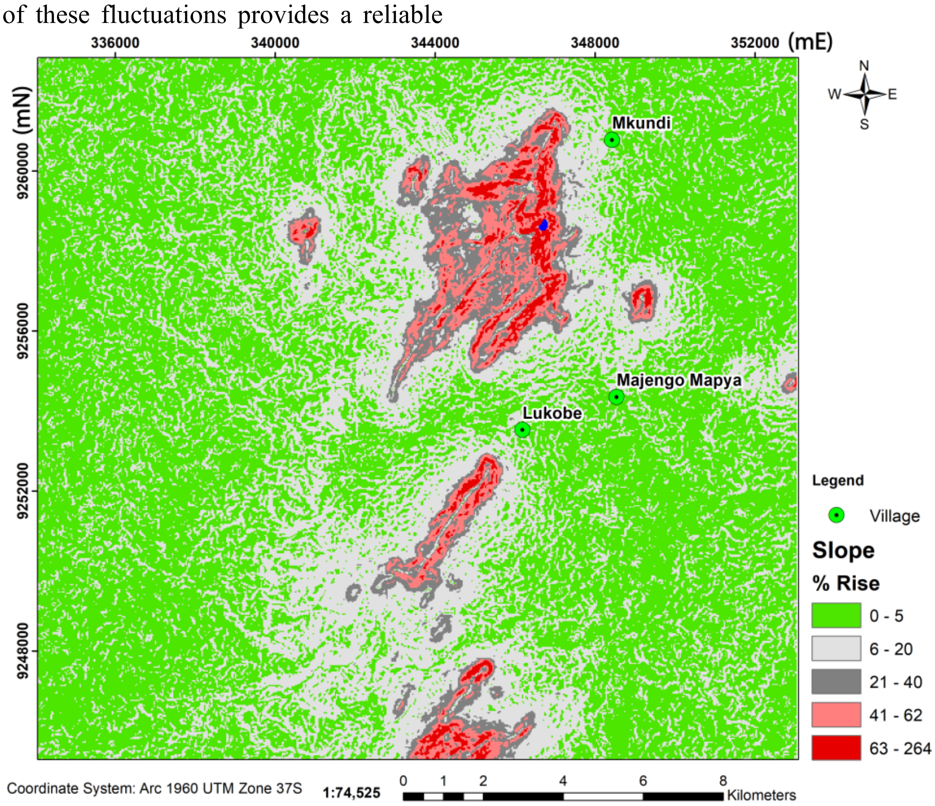

Figure 4: Slope map of the study area showing gentle to very gentle slopes (green zones) in the western and eastern zones.

Water-bearing Zones, from the Density Distribution and Residual Bouguer Anomaly map

The Residual Bouguer Anomaly (RBA) map (Figure 5) highlights the subsurface lithological variations across the study area. Metamorphic units, such as banded muscovite-biotite migmatites, gneisses, and granulites (Figure 3), exhibit positive residual anomalies ranging from 0.10 to 2.68 mGal. These anomalies correspond to higher density values between 2.68 and 2.90 g/cm^3 (Figure 5), indicating the presence of compact, non-weathered basements (Kearey et al. 2002).

In contrast, the negative residual anomalies range from -1.54 to -0.21 mGal, with density values between 2.54 and 2.65 g/cm^3. The most significant negative residual anomalies, shown as deep blue zones on the RBA map (Figure 5), occur in the central part of the study area. These zones align spatially with mountainous terrain as captured in the Digital Elevation Model (DEM, Figure 2) and with steep slope gradients highlighted in the slope map (Figure 4). Such negative anomalies, associated with mountainous terrain and steep slopes, indicate deeply weathered mountain flanks (Kearey et al. 2002). These areas have limited groundwater recharge potential due to rapid surface runoff and minimal infiltration capacity (FAO 2006). Consequently, weathered mountain flanks are categorized as non-potential aquifer zones due to their restricted groundwater recharge capabilities (Cavallina et al. 2022, Alamirew et al. 2025).

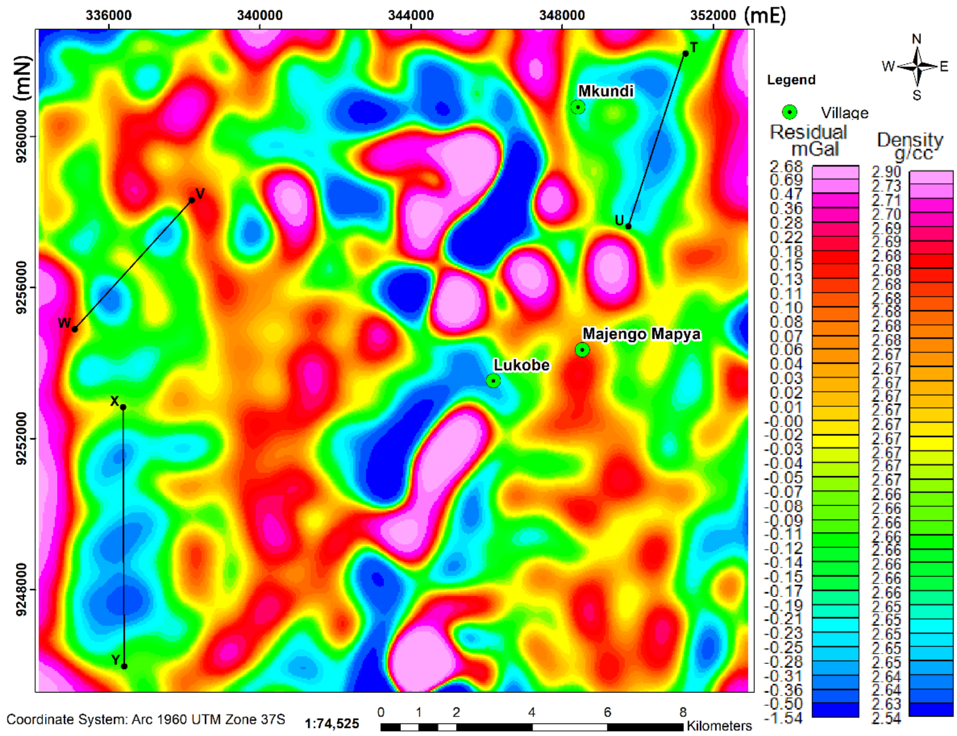

Figure 5.: Residual Bouguer Anomaly map showing the subsurface lithological distributions with their corresponding densities across Lukobe.

Four additional negative anomalies are observed in low-lying plains: three in the western part and one in the northeastern part. These zones are designated as sections X-Y, V-W, and T-U (Figure 5), and they exhibit residual values ranging from -0.28 to -0.21 mGal (light blue anomalies), with a uniform density of 2.65 g/cm^3.

The geological map (Figure 3) indicates that the western negative anomalies are located beneath red to reddish-brown soils, while the northeastern negative anomaly is found beneath sand and sandy hill wash deposits. These negative anomalies, which are covered by sediment in a low-lying plain, often indicate the presence of weathered and fractured bedrock (Kearey et al. 2002). These weathered and fractured basements, situated beneath a sediment cover in such plains, have the potential to serve as groundwater aquifers (Cavallina et al. 2022; Alamirew et al. 2025). Accordingly, these aquifers in Lukobe are classified as follows: Aquifer A: Section X-Y, Aquifer B and C: Section V-W, and Aquifer D: Section T-U (Figure 5).

The geometric dimensions and subsurface configurations of these aquifers are illustrated in the accompanying two-dimensional (2D) aquifer models.

2D Aquifer Gravity Models

The 2D Aquifer gravity models were created using the GM-SYS program within Oasis Montaj, incorporating various datasets, such as Residual Bouguer anomaly data, apparent density data, downward continued residual gravity, geological information from the geological map, and the Digital Elevation Model of Lukobe. These inputs were utilized to generate subsurface profiles along three transects: X-Y, V-W, and T-U (see Figure 5). The results of the modeling are shown and discussed below.

Aquifer A: Section X-Y, 2D Gravity Model

The 2D gravity model along section X-Y (Figure 6) shows that aquifer A is an unconfined, saprolitic aquifer with a density of 2.65 g/cm^3. It has developed in the fractured and deep weathered zone of Hornblende gneisses and granulite basement rocks. The unweathered basement underlying the aquifer indicates a higher density of 2.90 g/cm^3.

Overlying aquifer A is a 60 m thick layer of red to reddish-brown soil, characterized by a density of 2.4 g/cm^3. Aquifer A has an average thickness of 360 m and extends laterally about 6.8 km.

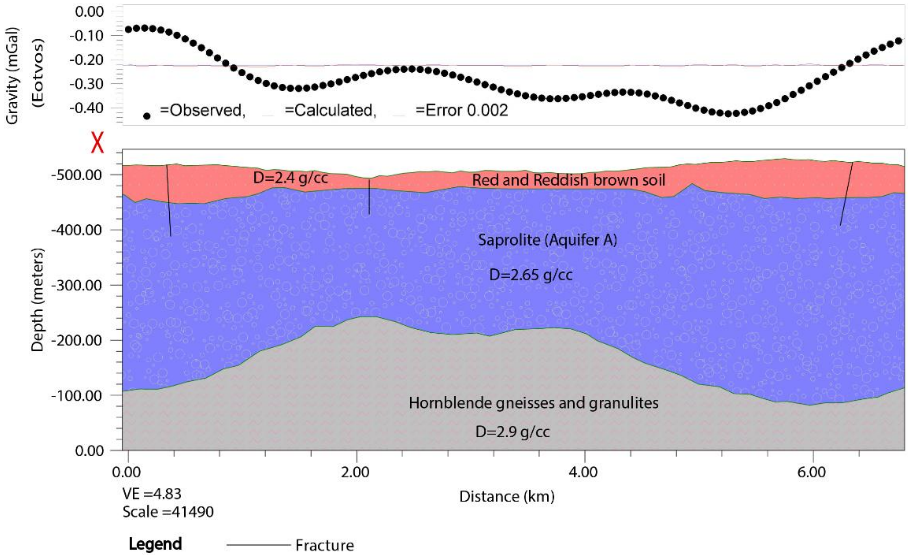

Figure 6: 2D gravity model of Aquifer A along Section X-Y (see Figure 5) illustrating the depth from the surface to the top of the aquifer, along with its thickness and lateral extent. Note that negative depth values (in meters) indicate elevations above sea level.

Aquifer B and C: Section V-W, 2D Gravity Model

2D gravity modeling along section V-W (Figure 7) indicates that Aquifers B and C are unconfined, fractured saprolitic aquifers, each with a density of 2.65 g/cm^3. These aquifers are situated beneath a 40 m thick layer of red to reddish-brown soil and have an average thickness of 280 m. Aquifer B extends 1.2 km laterally, while Aquifer C extends 1.65 km.

Separating the two aquifers is a compact sedimentary unit, 600 m wide, with a density of 2.67 g/cm^3 (Figure 7). Although its exact lithology remains uncertain, it is tentatively interpreted as limestone based on its density and the presence of a limestone outcrop (Nzc, Figure 3) about 1.9 km southeast of the sedimentary unit's trend. This unit runs in a northwest-southeast direction, covering a total length of 2.1 km (see Figure 5, section V-W).

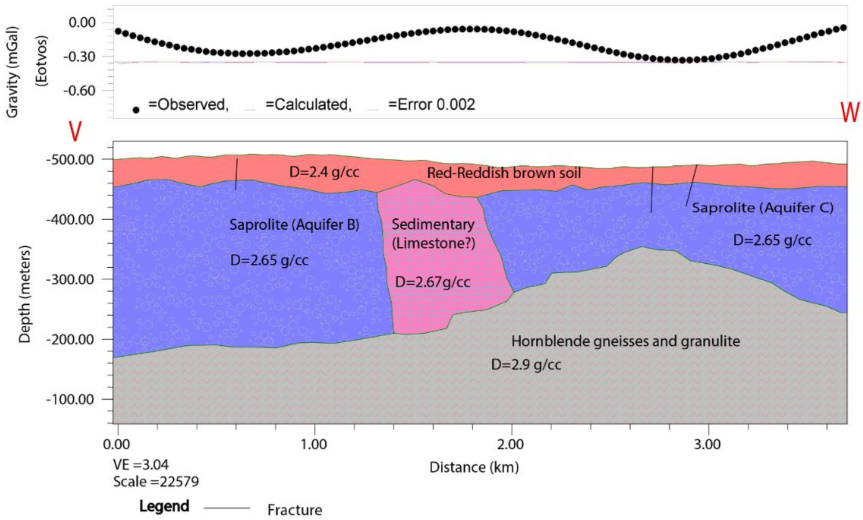

Figure 7: 2D gravity model of Aquifers B and C, as shown in Section V-W (refer to Figure 5), illustrating the depth from the surface to the top of the aquifers, along with their thickness and lateral extents. Note that negative depth values (in meters) indicate elevations above sea level.

Aquifer D: Section T-U, 2D Gravity Model

The 2D gravity model along section T-U (Figure 8) indicates that aquifer D is an unconfined, saprolitic aquifer with a density of 2.65 g/cm^3. This aquifer has developed within the fractured and deep weathered zone of the banded muscovite-biotite migmatite basement.

Above the aquifer is a layer of sand and sandy hill wash with a lower density of 1.9 g/cm^3. The thickness of this overlying layer varies, ranging from 50 m in the northern part (T) to 140 m in the southern part (U) of the aquifer. Aquifer D has an average thickness of 200 m and extends laterally in a northeast-southwest direction for approximately 4.7 km.

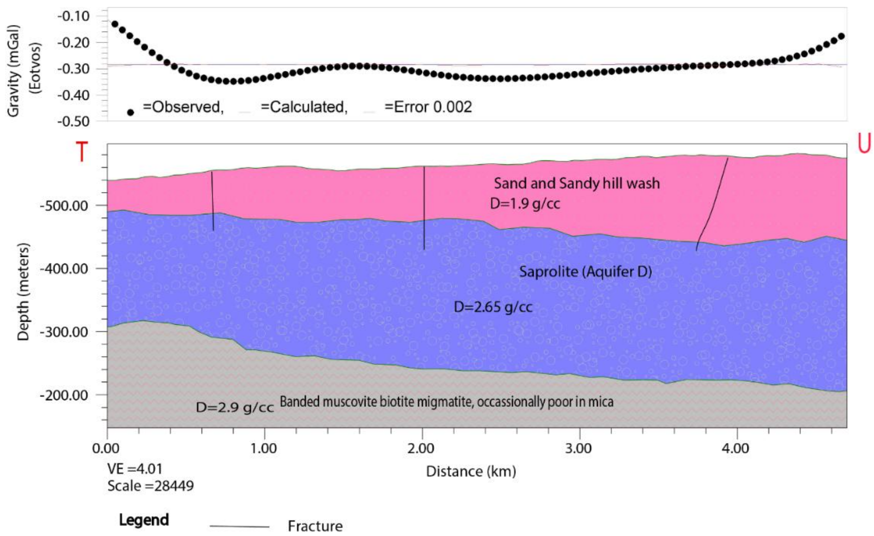

Figure 8: 2D gravity model of Aquifer D along Section T-U (refer to Figure 5) illustrating the depth from the surface to the top of the aquifer, the thickness, and the lateral extent. Note that negative depth values (in meters) indicate elevations above sea level.

Recharge Zones and Aquifer Distribution in Lukobe

The distribution map of aquifers (Figure 9) indicates the locations of the identified four aquifers in Lukobe, labelled A, B, C, and D. Aquifer A is located 9.2 km southwest of Lukobe village center, while Aquifers B and C are about 9.8 km to the west. Aquifer D is situated 5.5 km northeast of the Lukobe village center.

The surface areas of the aquifers are as follows: Aquifer A spans 12.2 km^2, Aquifer B covers 1.1 km^2, Aquifer C extends to 1.6 km^2, and Aquifer D encompasses 7.5 km^2. Each aquifer is recharged by distinct watershed catchments, with estimated sizes of 36 km^2 for Aquifer A, 13 km^2 for Aquifer B, 9 km^2 for Aquifer C, and 24 km^2 for Aquifer D.

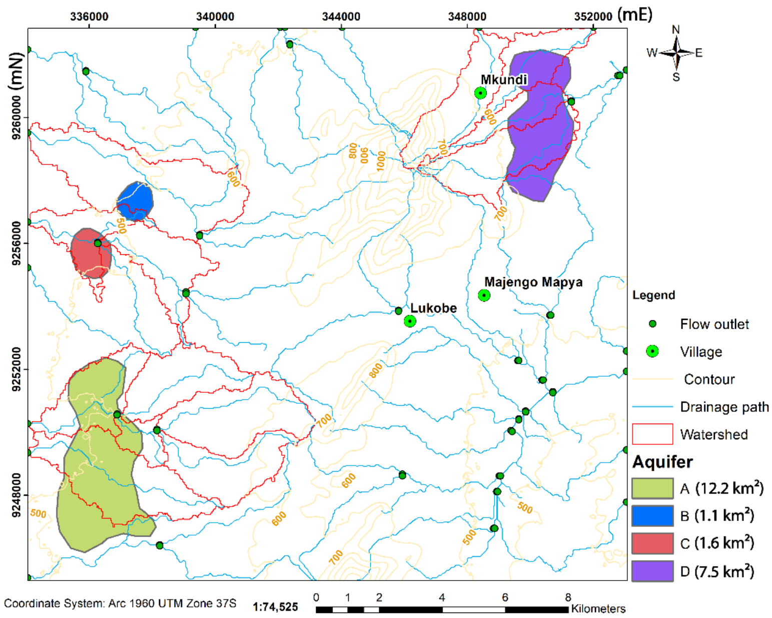

Figure 9: A map showing the distribution of aquifers A, B, C, and D, with their respective recharge zones in the study area.

Discussion

Types of Aquifers in Lukobe

The findings indicate that there are four aquifers in the Lukobe area (see Figure 9). The smallest aquifer has a surface area of 1.1 km^2, while the largest covers 12.2 km^2. The depth to these aquifers ranges from 40 to 140 m beneath a layer of sandy soil. They are developed within weathered and fractured metamorphic (Usagara) basements (see Figures 6-8). These aquifers, overlain by relatively thick permeable layers and developed within the fractured and weathered metamorphic basements, are classified as unconfined saprolitic aquifers (Wright and Burgess 1992, Salako and Adepelumi 2018).

Aquifer Thickness and Deep-Well Suitability in Lukobe

The thickness of the identified aquifers in Lukobe ranges from 200 to 360 m (Figure 6-8). These thicknesses align with the estimated water-wells drilling depths within the Usagaran complex, where water boreholes typically reach depths between 40 and 250 m (Kashaigili 2010). The substantial thicknesses of these aquifers in Lukobe support the construction of very deep wells for domestic water supply, which are commonly drilled at a depth exceeding 80 m. According to Baumann et al. (2005), boreholes in Tanzania are typically categorized as shallow (0-30 m), medium (31-50 m), deep (51-80 m), and very deep (>80 m).

Lukobe Watershed Size and Aquifer Recharge Potential

In an unconfined, saprolitic aquifer like those in Lukobe, recharge mainly occurs through direct rainwater infiltration, preferential flows, and fracture networks (Kashaigili 2010). The groundwater flow often concentrates along a few dominant pathways that regulate the aquifer's hydrological response (Woessner and Eileen 2010, Figure 9). The watersheds in Lukobe are relatively large, ranging from 9 to 36 km^2 (Figure 9), and their size significantly influences the amount of flow, with larger catchments (24-36 km^2) producing more surface runoff and infiltration. Larger catchments facilitate broader surface runoff collection, which enhances infiltration potential and contributes to aquifer recharge (Addisie 2022). Accordingly, aquifers A and D, located within catchments of 24 and 36 km^2, respectively, receive greater recharge volume over time, supporting more reliable long-term groundwater availability than aquifers B and C, which lie within smaller catchments of 13 and 9 km^2, respectively.

Natural Filtration Potential of Lukobe Aquifers

The large size of the watersheds and the unconfined nature of the Lukobe aquifers increase their vulnerability to contamination, particularly from agricultural runoff and municipal wastes. Unconfined aquifers are often susceptible to contamination due to the high permeability of the overburden, which allows surface water from extensive catchment areas to infiltrate directly (FAO 2006). However, when the overburden is thick (>30 m), it provides substantial natural filtration as groundwater percolates through the soil layer. This natural filtration capacity reduces the need for extensive water treatment, often requiring only minimal treatment for potable use (Baumann et al. 2005, Foster 2022, Vila-Tojo et al. 2022). In the case of the Lukobe aquifers, the overburden thickness exceeds 30 m, ranging from 40 to 140 m, providing significant natural filtration, indicating a promising supply of safe water with minimal contamination risks.

Significance of the Lukobe Aquifers in Community Water Supply

The considerable depth, thickness, and lateral extent of the Lukobe aquifers suggest a significant capacity for groundwater storage. These features support the development of very deep wells that can be constructed at depths exceeding 80 meters, making them suitable for meeting domestic water supply needs (Baumann et al. 2005). Integrating these aquifers into municipal water supply systems can improve water availability at the household level in Lukobe, reducing reliance on shallow wells, streams, and water vendors.

Conclusion

This study successfully identified four unconfined saprolitic aquifers, designated A, B, C, and D, located near Lukobe Ward, an area currently facing persistent water scarcity. Based on the findings, the study draws the following conclusions:

- Aquifer A is located 9.2 km southwest of Lukobe Ward. It covers an area of 12.2 km^2 and is situated 60 m beneath a reddish-brown soil layer. Aquifer A has an average thickness of 360 m.
- Aquifers B and C are situated 9.8 km west of Lukobe Ward. Aquifer B has a surface area of 1.1 km^2, while Aquifer C spans an area of 1.6 km^2. Both aquifers are covered by a 40 m thick layer of red to reddish-brown soil and have an average thickness of 280 m.
- Aquifer D is located 5.5 km northeast of Lukobe Ward and encompasses a surface area of 7.5 km^2. It is situated beneath a layer of sand and sandy hill wash, with a thickness varying from 50 m in the northern part to 140 m in the southern part of the aquifer. On average, the aquifer has a thickness of 200 m.

By linking technical insights to local water challenges, this study provides practical guidance for municipal water authorities and supports long-term strategies to enhance public water security in Morogoro Municipality. The approach demonstrated here can be replicated in similar regions throughout Tanzania, contributing to national efforts for sustainable groundwater management.

Recommendations

The identified aquifers in Lukobe exhibit promising geophysical and geological characteristics that indicate potential for sustainable water extraction. To assess the viability of these aquifers further, it is advised that comprehensive resistivity surveys and exploratory drilling be undertaken to evaluate their yield potential. Moreover, active community engagement is crucial for protecting recharge zones through effective land use planning, awareness campaigns, and conservation initiatives in the region.

Acknowledgment

The author expresses gratitude for the United States Geological Survey's DEM SRTM data, GGMPlus gravity models, and the geological map provided by the Tanzania Geological Society, which were essential for the completion of this work.

Declaration of Conflict of Interest

The author declares no conflict of interest.

References

Addisie MB 2022 Groundwater recharge estimation using water table fluctuation and empirical methods. *H2Open J.* 5(3): 457-468.

Agriculture Institute 2023 *Factors Affecting Soil Infiltration Rates.* Agriculture.Institute.

Akoteyon I 2016 Pattern of household access to water supply in Sub-urban settlement in parts of Lagos state, Nigeria. *Malaysian J. Soc. Space.* 12: 93-106.

Alameddine I, Jawhari G, and El-Fadel M 2016 Social Perception of Public Water Supply Network and Groundwater Quality in an Urban Setting Facing Saltwater Intrusion and Water Shortages. *Environ. Manage.* 59: 571-583.

Alamirew D, Ayanew T, Azagegn T, and Damtew K 2025 Enhancing Groundwater Potential Mapping Through Integrated Validation and Aquifer Characterization in Diverse Geological Settings: A Case Study of Central Ethiopian Highlands and Adjacent RIFT. *Int. J. Environ Res.* 19(36). https://doi.org/10.1007/s41742-024-00678-3

Baumann E, Ball P, and Beyene A 2005 *Rationalization of Drilling Operations in Tanzania. Review of the Borehole Drilling Sector in Tanzania. Dar es Salaam: RWSN*. https://www.rural-water-supply.net/en/resources/182

Cavallina C, Bergamasco A, Cosma M, Da Lio C, Donnici S, Tang CT, and Zaggia L 2022 Morpho-Sedimentary Constraints in the Groundwater Dynamics of Low-lying coastal Area: The Southern Margin of the Venice Lagoon, Italy. *Water.* 14(17): 1-24.

Susquehanna River Basin Commission 2023 *Identifying Optimal Groundwater Recharge Locations and Critical Aquifer Recharge Areas Within the Susquehanna River Basin. SRBC*. Retrieved from https://www.srbc.gov/our-work/programs/planning-operations/identifying-optimal-groundwater-recharge-locations.html

Contributors 2025 *OpenStreetMap*. Retrieved from https://www.openstreetmap.org/#map=6/-6.40/34.89

Das S, Patel P, and Sengupta S 2016 Evaluation of different digital elevation models for analyzing drainage morphometric parameters in a mountainous terrane: a case study of the Supin-Upper Tons Basin, Indian Himalayas. *SpringerPlus*. *5*(1): 15441

FAO 2006 *Guideline for Soil Description.* Rome, Italy.

Foster S 2022 The key role for groundwater in urban water-supply security. *J. Water Clim. Change.* 13(10): 3566-3577. doi:10.2166/wcc.2022.174

Granser H, Meurers B, and SteInhauser P 1989 Apparent Density Mapping and 3D Gravity Inversion in the Eastern Alps. *Geophys. Prospect.* 37: 279-292.

Hirt C, Claessens T, Fecher M, Kuhn R, Pail M, and Rexer 2013 New ultrahigh-resolution picture of Earth's gravity field. *Geophys. Res. Lett. 40*. doi:10.1002/grl.50838

Kashaigili JJ 2010 *Assessment of groundwater availability and its current and potential use and impacts in Tanzania. IWMI*. Retrieved from https://gw-africa.iwmi.org/wp-content/uploads/sites/23/2018/10/Country_Report-Tanzania.pdf

Kearey P, Brooks M, and Hill I 2002 An Introduction to Geophysical Exploration, 3rd ed, Osney Mead, Blackwell Science Ltd.

Monteiro E, Fonte CC, and Lima J 2018 Analysing the Potential of OpenStreetMap Data to Improve the Accuracy of SRTM 30 DEM on Derived Basin Delineation, Slope, and Drainage Networks. *Hydrology.* 5(3): 1-27.

Raphael A, Ngaga Y, and Makarius L 2022 Watershed degradation and water provision in Morogoro Municipality, Tanzania. *Ecohydrol. Hydrobiol.*. 1-8. Retrieved from https://doi.org/10.1016/j.ecohyd.2022.12.004

Salako AO, and Adepelumi AA 2018 Aquifer, Classification and Characterization. In: Javaida and Khan *Aquifers-Matrix and Fluids* (p. Chapter 1), IntechOpen.

Sampson D and Wright A 1961 *Geological map of Morogoro (Quarter Degree Sheet 183) First Edition*. Retrieved from https://searchworks.stanford.edu/view/3243538

Siambone SH, Susilo A, and Maryanto S 2022 Integration of Topex Satellite Gravity and Digital Elevation Model Shuttle Radar Topography Mission (DEM SRTM) Imagery for Subsurface Structure Identification at Tiris Geothermal Area. *Positron* 12(2): 98-111

Suprianto A, Supriyadi PN, and Cahyono BE 2021 Correlation Between GGMPlus, Topex and BGI Gravity Data in Volcanic Areas of Java Island. *J. Phys: Conf. Ser*. 1825(1):1-6.

Tarboton D 2003 *Terrane Analysis Using Digital Elevation Models in Hydrology*. *ESRI Users Conference*. pp. 1-13. San Diego, California. ESRI.

USGS 2000 *EarthExplorer*. U.S. Geological Survey:https://earthexplorer.usgs.gov

U.S. Department of Agriculture NR 2014 *Soil infiltration. U.S. Department of Agriculture, Natural Resources Conservation Service (USDA NRCS)*.

Uhagile B, and Salehe F 2024 Tap Water Scarcity and Alternative Water Sources Used at the Household Level in Morogoro Municipality, Tanzania. *Tanzania J. Agric. Sci.* 23(2): 288-300.

United Nations 2012 *GLAAS 2012 Report: UN-Water Global Analysis and Assessment of Sanitation and Drinking-Water: the Challenge of Extending and Sustaining Services. World Health Organization*.

Vila-Tojo S, Sebucedo JM, Andrade E, Gomez-Roman C, Alzate M, and Seoane G 2022 From scarcity problem diagnosis to recycled water acceptance: A perceptive-axiological model (PAM) of low and high contact uses. *Water Res.* 217:118380 Retrieved from https://doi.org/10.1016/j.watres.2022.118380

Woessner WW and Eileen P 2010 Hydrogeologic Properties of Earth Materials and Principles of Groundwater Flow. Ontario-Canada, The Groundwater Project.

Wright E and Burgess W 1992 The hydrogeology of crystalline basement aquifers in Africa. *Geol. Soc. Special Publ.* 66: 1-27 https://doi.org/10.1144/GSL.SP.1992.066.01.01