UNIVERSITY OF MISKOLC

MIKOVINY SÁMUEL DOCTORAL SCHOOL OF EARTH SCIENCES

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AN INTEGRATED GEO-HYDRO-INFORMATICS APPROACH FOR GROUNDWATER POTENTIAL ASSESSMENT IN THE HIGHLAND OF ERITREA

PhD Thesis Booklet By:

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1. INTRODUCTION

Groundwater is a critical resource in arid and semi-arid regions, where limited rainfall and surface water make it essential for domestic use, agriculture, and livelihoods. Yet its availability is highly variable and increasingly stressed by population growth and climate change. In Eritrea, groundwater is particularly vital due to erratic rainfall and scarce surface-water resources, with the upper Mereb catchment serving as a key water source for rural communities and agriculture (Alemngus et al., 2017; Measho et al., 2020). However, complex geology, limited systematic exploration, and reliance on conventional methods have led to inefficient groundwater development and frequent borehole failures. As a result, there is a strong need for modern, integrated approaches to groundwater potential assessment to support sustainable water-resource management in the region.

2. AIMS of PhD WORK

This research investigates the groundwater system of the upper Mereb catchment with the primary aim of supporting scientifically grounded decision-making for groundwater development and management in the Eritrean Highlands. The study combines a strong case-study focus on the local groundwater system with the application of an integrated methodological framework. The research therefore seeks both to improve understanding of groundwater conditions in the upper Mereb catchment and to demonstrate the value of advanced analytical methods in a data-scarce regional context.

Specifically, the research addresses the following core questions:

(i) What are the dominant lithological units and structural features that have a contribution in controlling groundwater occurrence in the upper Mereb catchment, as identified through integrated litho-structural mapping approaches?

(ii) Which areas of the catchment have the highest groundwater potential, and how reliably can these zones be delineated using complementary statistical and decision-based models?

(iii) What are the main controlling factors for groundwater quality in the upper Mereb, and to what extent is groundwater suitable for drinking and agricultural use under current hydrogeochemical conditions?

(iv) How can the integrated evaluation of groundwater occurrence, potential, and quality improve decision-making for sustainable groundwater development and resource protection at the catchment scale?

To answer these research questions, the study applies a comprehensive, multi-method framework that integrates: (1) lithological and structural mapping using remote sensing data, gravity information, hillshade-derived lineament analysis, and machine-learning techniques; (2) groundwater potential zonation through the combined application of the Analytical Hierarchy Process (AHP) and Frequency Ratio (FR) models; and (3) groundwater quality assessment based on hydrochemical parameters and multivariate statistical analyses.

The novelty of this research, therefore, lies in addressing key groundwater-related research questions through the first-time application of a fully integrated geospatial, geophysical, and data-driven framework in the upper Mereb catchment. Although the individual methods have been applied in other regions, their combined and coordinated use to explicitly link litho-structural controls, groundwater potential, and groundwater quality represents a new contribution to the data-scarce setting of the study area. By applying this integrated approach to answer clearly defined research questions, the study generates reliable baseline information and an improved conceptual understanding of the groundwater system. These outcomes provide practical decision-support for groundwater development, resource protection, and long-term water security planning in the Eritrean Highlands.

3. STUDY AREA DESCRIPTION

The upper Mereb catchment is located in southern Eritrea (Zoba Debub) within the central Eritrean Highlands (Gehbrehiwot & Kozlov, 2019) and covers an area of approximately 1,480 km². It includes the administrative sub-zones of Galanefhi, Debarwa, Mendefera, Dekemhare, and Mai-Ayni, with elevations ranging from about 1,554 to 2,450 m above mean sea level. The catchment is characterized by highly variable topography, including flat plains, fault-bounded grabens, linear ridges associated with dyke swarms, and deeply incised valleys, and is drained by the seasonally flowing Mereb River and its tributaries. Climatically, the area lies within the moist highland agro-climatic zone and experiences a generally cool climate. Rainfall is strongly seasonal, with the majority occurring during the summer monsoon period (June–September), supplemented by minor spring rainfall. Annual precipitation shows strong spatial and temporal variability, ranging from less than 300 mm to over 900 mm, with increasing irregularity in recent decades, highlighting growing water-resource management challenges.

Geologically, the catchment forms part of the Neoproterozoic Arabian-Nubian Shield and exhibits complex lithological and structural characteristics (Ali et al., 2013; Ghebreab et al., 2009). The area comprises Precambrian metamorphic basement rocks overlain by sedimentary formations and extensive Tertiary basaltic lava flows, with granitoid intrusions distributed throughout. Groundwater occurrence is largely controlled by secondary permeability associated with faults, fractures, and dyke swarms, as the dominant basement and basaltic rocks are otherwise of low primary permeability. Vegetation is generally sparse and reflects semi-arid conditions, with denser cover along river courses, higher elevations, and agricultural areas in valley bottoms.

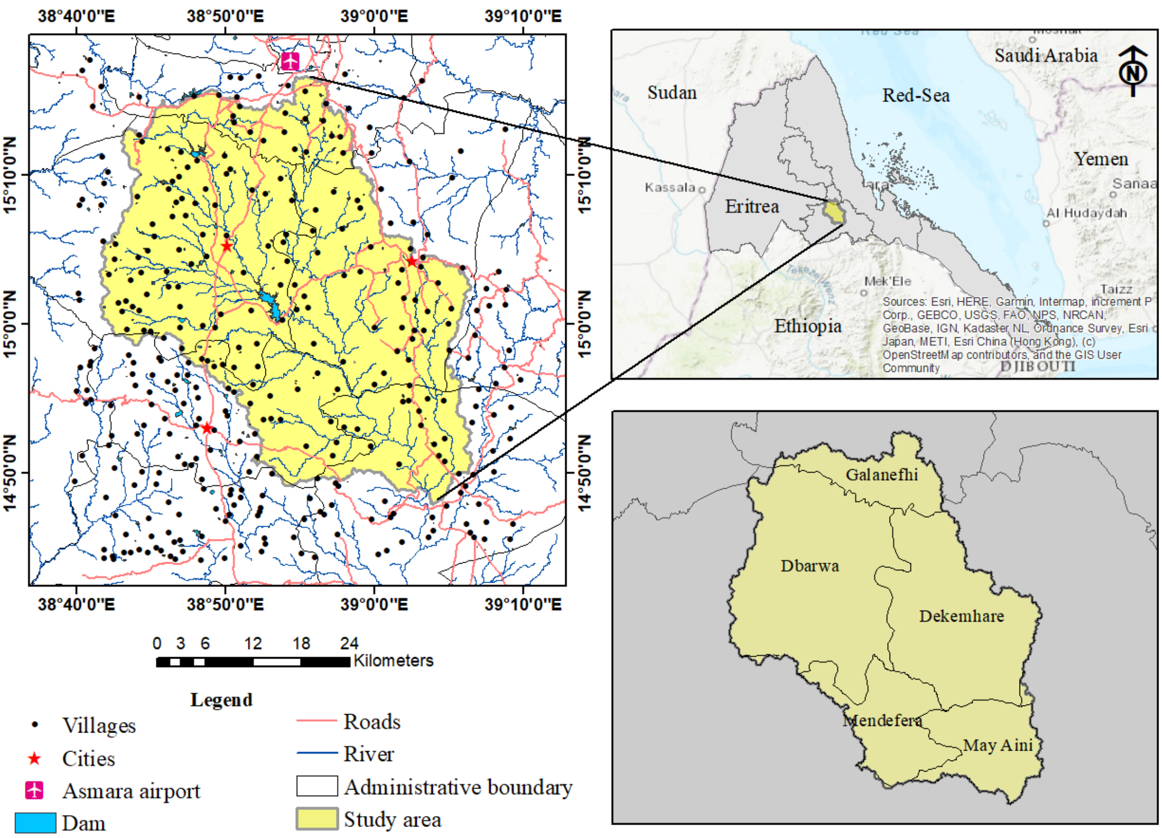

Fig. 1 Geographical location of the study area

4. MATERIALS and METHODS

4.1. Datasets

This study employs three complementary categories of datasets to assess groundwater resources in the upper Mereb catchment. The first includes geological and geospatial data, derived from geological mapping, field observations, multispectral remote sensing imagery, and gravity information, which together support the identification of lithological and structural controls on groundwater occurrence. The second dataset focuses on groundwater potential assessment and incorporates key environmental conditioning factors such as Slope, rainfall, geology, lineament density, soil types, drainage density, land use/land cover, and existing well locations. The third dataset consists of hydrochemical data collected from the Asmara Water Resources Department, distributed across the study area, and used to evaluate groundwater-controlling factors as well as its suitability for domestic and agricultural purposes through statistical, graphical, and hydrochemical analyses. Collectively, these datasets form an integrated framework that underpins both the spatial and qualitative dimensions of groundwater resource assessment in the study area.

4.2.Methods

4.2.1. Litho-structural mapping

Litho-structural characterization in this study was achieved through an integrated geospatial approach combining remote sensing–based geological mapping and machine-learning techniques (Fig. 2). Multispectral satellite imagery was processed using band ratio analysis, false color composites, principal component analysis (PCA), and supervised classification to enhance lithological discrimination (Said et al., 2023; Traore et al., 2025). The delineation and interpretation of lithological units were supported by field-collected geological information, ensuring accurate identification of rock types and improving the reliability of the resulting geological map (K. M. Asghede et al., 2025). The remote sensing–derived lithological information was then converted into pixel-based datasets and used as training and testing inputs for Artificial Neural Networks (ANN) and Support Vector Machines (SVM). The application of machine learning significantly enhanced the developed lithological map by capturing complex, non-linear relationships between spectral characteristics and rock units (El-Omairi et al., 2025). While also reducing the time and resources required for extensive field investigations in a data-limited environment.

Structural features were analyzed through a combination of satellite gravity data and terrain-based lineament analysis. Gravity data, which represent the combined effects of shallow and deep subsurface sources, were processed using regional and residual separation, as well as Total Horizontal Derivative (THD) and First Vertical Derivative (FVD) filters, to delineate faults, fractures, and major structural boundaries (Eldosouky et al., 2020). In addition, hillshade maps generated from digital elevation models were examined under varying illumination azimuths to manually extract surface lineaments, ensuring improved detection of structurally controlled features expressed in the topography. The integration of gravity-derived structures with hillshade-based lineament patterns provided a more comprehensive representation of the structural framework. This combined litho-structural analysis highlights zones of fractured rock and enhanced secondary permeability, which play a critical role in controlling groundwater occurrence and movement, thereby directly supporting groundwater potential assessment and sustainable groundwater resource planning in the upper Mereb catchment.

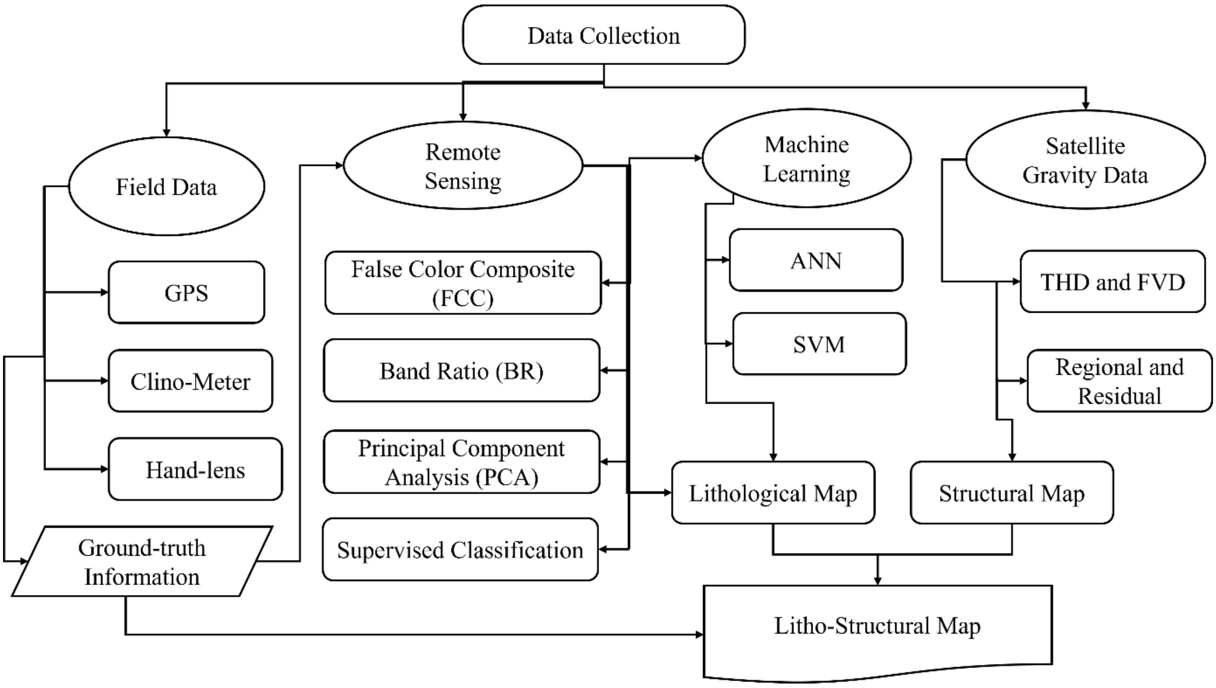

Fig. 2. The flow chart of Litho-Structural Map (THD: Total Horizontal Derivative; FVD: First Vertical Derivative; SVM: Support Vector Machine; ANN: Artificial Neural Network).

4.2.2. Groundwater potential mapping

Groundwater potential mapping in the upper Mereb catchment was conducted using a combined Analytical Hierarchy Process (AHP) and Frequency Ratio (FR) framework (Fig. 3). Both methods utilized the same seven environmental conditioning parameters, geology, slope, soil, land use/land cover, drainage density, lineament density, and rainfall, ensuring methodological consistency and allowing direct comparison between expert-based weighting and statistical evaluation (K. Asghede & Vágó, 2025). In the AHP approach, these parameters were prioritized according to their relative influence on groundwater occurrence in hard-rock and semi-arid environments, based on field knowledge and supporting literature, with consistency checks applied to validate the weighting scheme.

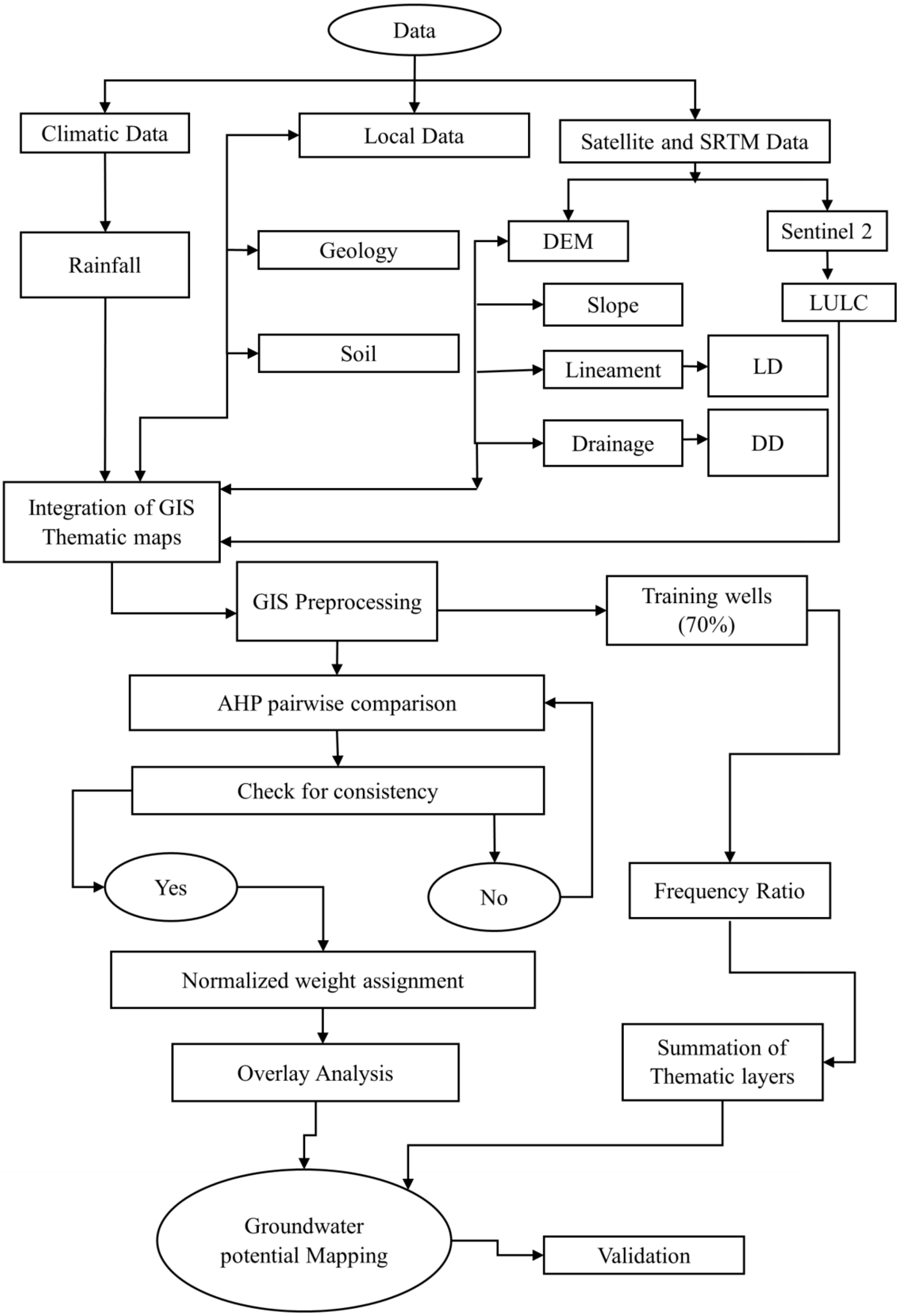

Fig. 3 Groundwater potential mapping framework using AHP and FR.

Note: DD-Drainage Density, LD-Lineament Density, LULC-Land-use/Landcover, DEM-Digital Elevation Model

The FR model complemented the analysis by statistically evaluating the relationship between groundwater occurrence and each class of the selected conditioning parameters (Pawar et al., 2024; Razandi et al., 2015). Groundwater well locations obtained from the Asmara Water Resources Department (WRD) were used as the dependent variable and randomly divided into training and validation datasets. The training wells were spatially overlaid on the thematic layers to quantify their distribution across different parameter classes, and FR values were calculated by relating the proportion of wells in each class to its spatial extent. Values greater than one (FR > 1) indicate favorable conditions for groundwater occurrence, while values less than one (FR < 1) indicate unfavorable conditions. When integrated with AHP-derived expert weighting, the FR results enhance the reliability of groundwater potential zonation and support informed groundwater exploration and sustainable resource planning at the catchment scale.

4.2.3. Hydrochemical data analysis

To comprehensively assess the groundwater quality of the upper Mereb catchment, a combination of hydrochemical, graphical and statistical approaches was employed (Fig. 4). These methods were designed to interpret the chemical composition of groundwater, identify the dominant geochemical processes, and evaluate its suitability for domestic and agricultural purposes. Groundwater samples were collected and analyzed by the Asmara water resources department from representative wells for major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}), anions (HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-) and other parameters following standard procedures. The analytical results were processed using a suite of hydrochemical evaluation tools, including multivariate statistical analysis, Water Quality Index (WQI), and Irrigation Indices. To further evaluate the suitability of groundwater for irrigation, indices such as the Sodium Adsorption Ratio (SAR) and USSL were investigated. The combination of these hydrochemical methods provides a robust framework for diagnosing groundwater quality variations and supporting sustainable groundwater management in the arid and semi-arid upper Mereb catchment (K. M. Asghede et al., 2026).

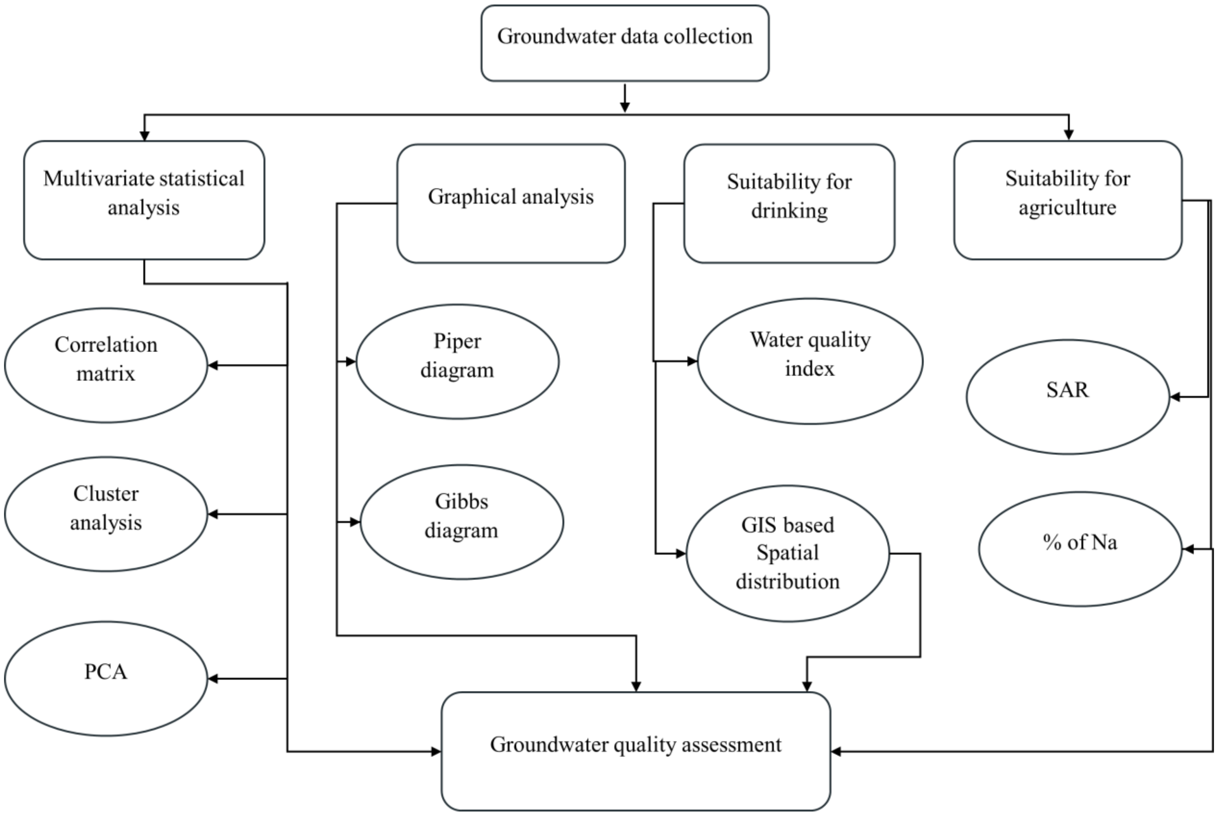

Fig. 4 Comprehensive framework of groundwater quality assessment in the upper Mereb area

5. NEW SCIENTIFIC RESULTS

In my PhD research, I developed a comprehensive hydrogeological framework for assessing groundwater potential and quality in the upper Mereb catchment, based on the integrated interpretation of remote sensing, geological, geophysical, and hydrochemical datasets. As the first systematic investigation of its kind in the study area, this work not only introduces a novel and unified methodological platform but also fills a critical knowledge gap essential for supporting evidence-based decision-making. The major scientific results derived from this research are presented in the following sections.

Thesis 1. Development of litho-structural mapping of upper Mereb area.

I developed litho-structural map of upper Mereb area using integrated remote sensing and geophysical approaches for the purpose of groundwater assessments.

Landsat-9 OLI imagery, satellite gravity data, and DEM-based terrain analysis were combined to establish the framework of the study. Through the application of Principal Component Analysis (PCA), supervised classification, band ratios, and False Color Composite (FCC) techniques, the resulting litho-structural map reveals clear spatial contrasts in lithology across the basin. Basaltic flows dominate the western part of the catchment, whereas metavolcanic, sedimentary, and metasedimentary units are more prevalent in the eastern sectors. Extensive lateritic cover was also identified in both the northern and southern parts of the area, indicating zones of intense weathering that significantly influence surface and subsurface hydrological processes. Structural analysis highlights well-developed lineament systems with dominant NE–SW and NW–SE trends, which are consistent with regional tectonic controls related to Red Sea extension and the interaction between the Arabian and African plates. These structures play a key role in controlling secondary porosity and groundwater movement within the hard-rock terrain. Validation using in-situ geological observations and collected rock samples shows good agreement with the interpreted lithological and structural patterns, increasing confidence in the resulting map. In the Eritrean context, this litho-structural framework provides spatially consistent and cost-effective geological information that supports improved groundwater development planning and also offers potential benefits for broader resource and mineral exploration efforts.

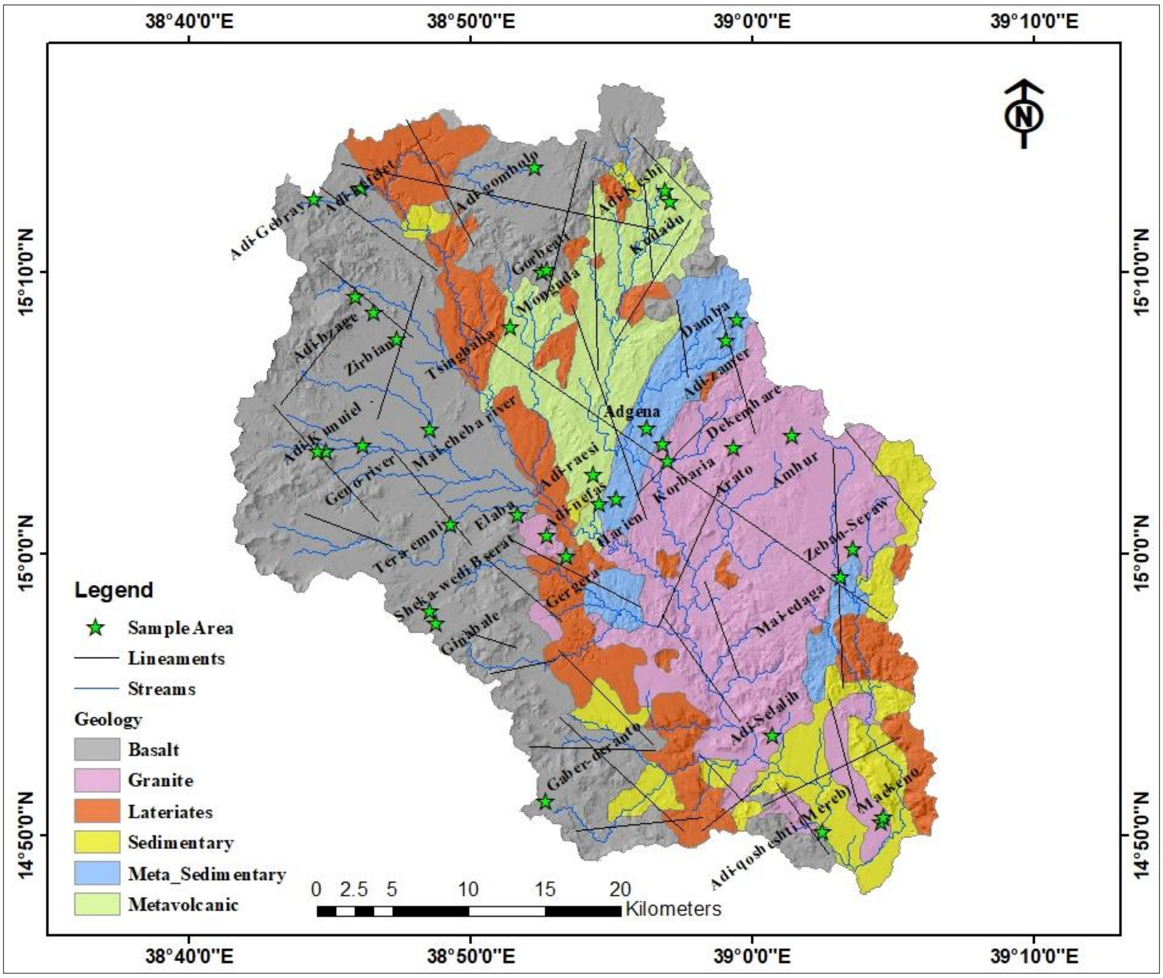

Fig. 5. Litho-structural map of upper Mereb catchment.

Thesis 2. Enhancement of lithological mapping of upper Mereb area using Machine Learning.

Lithological mapping of the upper Mereb area can be significantly enhanced using Artificial Neural Networks (ANN) and Support Vector Machines (SVM), providing a cost-effective and time-efficient alternative to traditional geological mapping methods.

The training locations were derived from a field-validated lithological map produced from multispectral remote sensing data. Model parameters, including learning rate, number of iterations, and kernel selection, were carefully adjusted to achieve optimal performance in this geologically complex area. The ANN and SVM models achieved nearly similar overall accuracies, indicating consistent and reliable prediction performance. Basalt, metasedimentary, and sedimentary units were classified with high accuracy, while some confusion remained among laterites, metavolcanics, and granitic rocks due to spectral similarities. Despite these challenges, both machine learning approaches effectively delineated the major lithological units across the study area. These results demonstrate that integrating machine learning with remote sensing data can significantly improve lithological mapping, particularly in regions where field data are limited or access is difficult. The enhanced lithological map can serve as a valuable decision-support tool for groundwater exploration, geological investigations, and resource management in Eritrea, and can be adapted to similar geological settings facing comparable data and accessibility constraints.

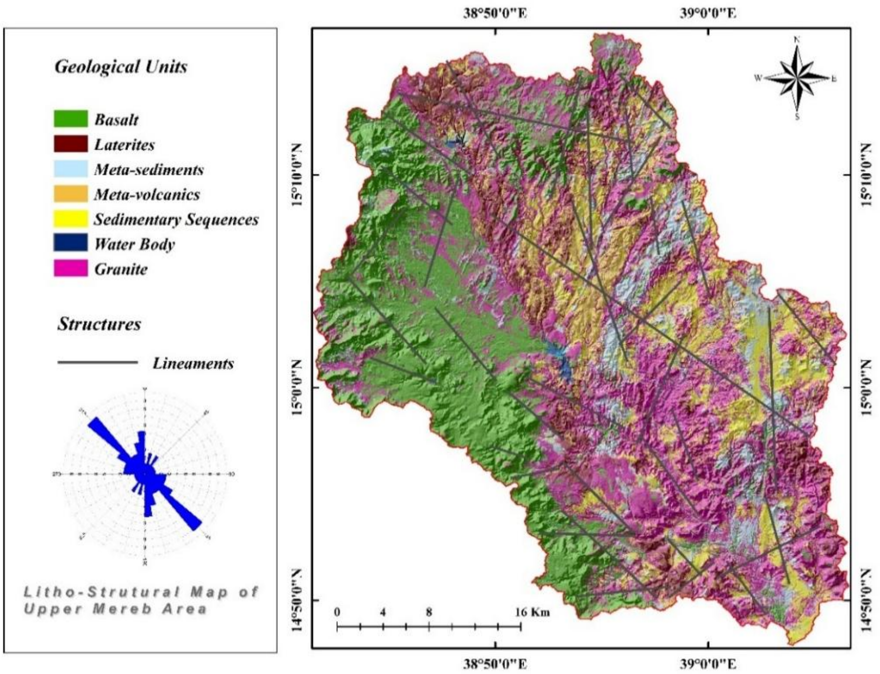

Fig. 6 Machine learning based lithological mapping.

Thesis 3. Delineation of groundwater potential zones in upper Mereb area using expert and data driven approach.

The Analytical Hierarchy Process (AHP) and the Frequency Ratio (FR)-based groundwater potential mapping revealed that the study area is largely dominated by moderate and low groundwater potential zones, with smaller but significant high and very high potential zones concentrated in the northwestern and northeastern regions.

The two approaches, AHP and FR, classified groundwater potential into five zones ranging from very high to very low, producing broadly consistent spatial patterns across the area. Under the AHP model, moderate-potential zones dominate the catchment (50.04%), mainly occurring in the central and northeastern areas where terrain and soil conditions favor moderate infiltration. Low-potential zones account for 35.61% and are concentrated in the southern and southeastern mountainous regions with steep slopes and shallow soils. High and very high potential zones cover 10.51% and 3.32%, respectively, and are primarily located in the northwestern part of the catchment, where gentle slopes and favorable lithology enhance recharge, while very low potential zones (0.52%) correspond mainly to steep granitic terrains. Similarly, the FR model identifies moderate (30.98%) and low (30.23%) potential zones as the dominant classes, largely distributed across the central and eastern areas. Higher potential zones (high: 15.31%; very high: 6.22%) are clustered in the northwestern and northeastern regions characterized by fractured rocks and relatively flat terrain, whereas very low potential zones (17.26%) are mainly associated with the steep southern highlands where infiltration is limited. The application of these GIS-based groundwater-potential modelling approaches represents the first methodological introduction of its kind in the study area, demonstrating the value of an integrated framework for delineating groundwater-potential zones. This framework provides a practical and scalable tool that can be applied to other regions of the country, serving as a foundational reference for future groundwater exploration and resource-management initiatives.

Thesis 4. Comparative Evaluation of AHP and Frequency Ratio (FR) models.

I performed a comparative analysis of the AHP and FR output maps to assess their level of consistency, and the results show a strong spatial agreement between the two models, with both consistently identifying similar high- and low-potential zones.

A spatial comparison analysis of the Analytic Hierarchy Process (AHP) and Frequency Ratio (FR) groundwater-potential models was carried out by overlaying their reclassified outputs to evaluate the degree of agreement between the two approaches. The comparison shows that most of the area falls within the non-high-potential category (75.06%), while 14.5% of the area is identified as high potential by only one of the models, and 10.4% represents zones where both models simultaneously predict high groundwater potential. These results reveal a strong correspondence between AHP and FR in delineating both high- and low-potential zones, with both methods consistently mapping low-potential conditions across the southern, higher-relief terrain. Model validation further supports these findings, as the FR method achieves a slightly higher predictive accuracy (AUC = 0.748) compared to AHP (AUC = 0.704), reflecting the advantage of data-driven techniques that incorporate statistically derived relationships between conditioning factors and observed groundwater occurrences. Overall, the combined use of ROC-based validation and spatial overlay comparison demonstrates that both AHP and FR perform reliably and consistently in delineating groundwater-potential zones, offering a sound basis for informed groundwater planning and resource-management decisions.

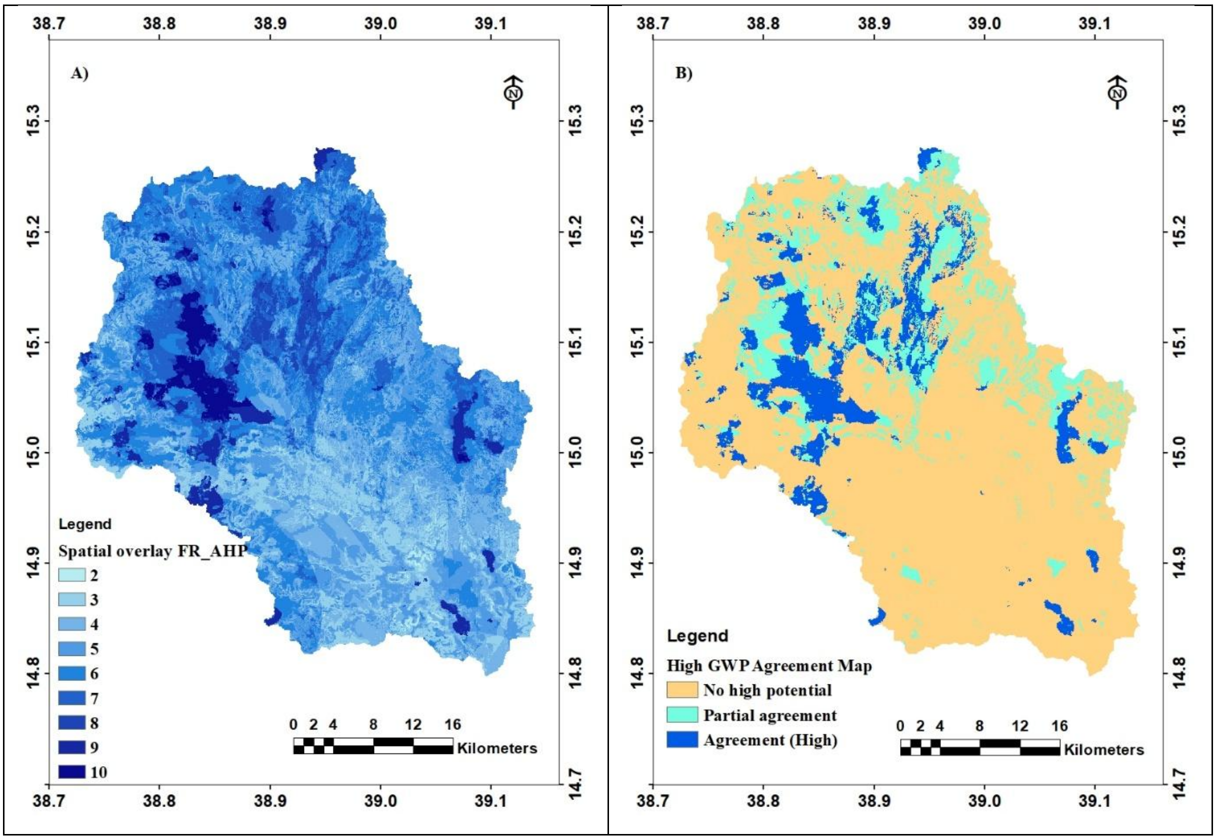

Fig. 7 Comparison of spatial agreement between FR and AHP models.

Thesis 5. Detection of main factors influencing the groundwater quality in the upper Mereb catchment.

I identified the natural and anthropogenic factors that influenced groundwater quality through principal component analysis and hydrochemical methods, where the main result shows that groundwater chemistry is primarily controlled by rock-water interaction processes, with additional influence from agricultural activities and redox conditions.

The Principal Component Analysis (PCA) shows that groundwater quality in the study area is controlled by a combination of natural geological processes and human activities. PC1, which explains the largest share of the variance, reflects the strong influence of rock water interaction process. This was confirmed by Gibbs diagram where most of the samples are projected in the rock dominance zone. The inter-ionic reactions identified that the rock water interactions occurred through carbonate and silicate dissolution, and cation exchange processes. PC2 highlights the joint effect of redox conditions and agricultural inputs, indicating that variations in groundwater chemistry are influenced by both oxidation–reduction processes within the aquifer and nutrients introduced through farming practices, such as nitrate from fertilizers. PC3 to PC5 capture smaller but important processes such as localized salinity changes. When combined, these results show that groundwater evolution is primarily shaped by geogenic controls, with additional contributions from agriculture and redox reactions. The findings provide a clear scientific basis for understanding groundwater quality in the region and offer practical guidance for Eritrea in managing its limited water resources.

Thesis 6. Evaluation of groundwater quality for domestic and agricultural purposes in the upper Mereb catchments.

I assessed groundwater quality in the upper Mereb area for domestic and agricultural purposes using groundwater quality indices and irrigation indices, where the main result shows that groundwater is largely suitable for drinking and irrigation, with minor localized quality issues and salinity as the main limitation for agricultural use.

The Water Quality Index (WQI) shows that groundwater in the upper Mereb catchment is generally suitable for domestic use, with most samples classified as good (74.19%) and a significant portion falling into the excellent category (24.52%). These excellent-quality zones correspond to low mineralization and limited human impact. Only two locations fall into the poor-quality class, where high EC, TDS, Fe, NH_3, and NO_3 values indicate localized contamination. For agricultural use, irrigation indices show that all samples fall within the low sodium-hazard (S1) category, supported by SAR and Na% values that classify most waters as excellent to permissible. However, the USSL diagram places many samples in the medium to high salinity (C2–C3) classes, indicating that salinity not sodium poses the main limitation for irrigation, especially for salt-sensitive crops. Overall, the combined domestic and irrigation assessments show that groundwater in the upper Mereb region is largely safe for drinking and reasonably suitable for irrigation, but targeted monitoring and salinity-management strategies are needed to protect vulnerable zones. The results provide essential guidance for water managers in Eritrea and offer a useful reference for researchers working in similar semi-arid, data-limited environments.

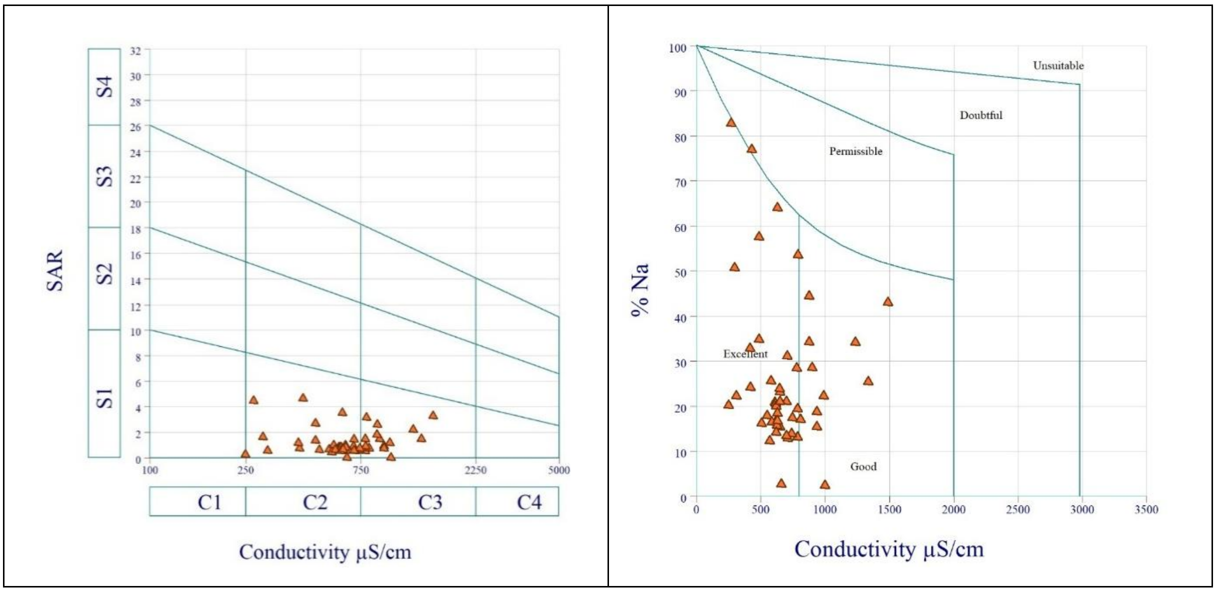

Fig. 8. Irrigation suitability assessment (USSL diagram and Wilcox diagrams).

6. CONCLUSION

This study demonstrates the effectiveness of integrating geospatial and data-driven approaches to better understand groundwater systems in complex, data-limited environments. The analysis of the upper Mereb catchment shows that no single method is sufficient on its own; instead, the strength of the results lies in combining complementary techniques. The consistency between structurally derived lineaments, lithological patterns, and groundwater potential zones highlights the value of integrating independent datasets to improve confidence and interpretability. The combined use of remote sensing, gravity analysis, and machine learning enabled a more spatially continuous understanding of subsurface conditions, while hydrochemical analysis provided essential insight into groundwater quality and usability.

Together, these approaches demonstrate the importance of linking surface and subsurface indicators to capture the full complexity of groundwater systems.

Within Eritrea, this research represents the first application of an integrated hydro-geo-informatics framework for simultaneous groundwater potential and quality assessment, offering a practical decision-support tool for similar data-scarce regions. However, the study also highlights the influence of data quality and availability on model outcomes, particularly where groundwater occurrence is inferred indirectly and hydrochemical data are limited. As such, the results should be considered supportive rather than definitive. Nevertheless, the framework provides a strong basis for future work, where improved datasets, such as detailed well records and expanded water quality sampling, can enhance model accuracy. Overall, this study underscores that groundwater assessment is an iterative process, and that integrated approaches are essential for progressively improving understanding and supporting sustainable water resource management.

7. PUBLICATION AND CONFERENCES

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