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MAPPING AND ASSESSMENT OF GROUND WATER RECHARGE POTENTIAL USING GIS, MULTI-CRITERIA ANALYSIS AND HYDROLOGICAL MODELLING

MAPEAMENTO E AVALIAÇÃO DO POTENCIAL DE RECARGA DE ÁGUA SUBTERRÂNEA USANDO SIG, ANÁLISE MULTICRITÉRIO E MODELAGEM HIDROLÓGICA

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Abstract

This research develops an integrated methodology to evaluate groundwater recharge potential in arid and semi-arid ecosystems by combining remote sensing, geographic information systems (GIS) and multi-criteria analysis. Five geographic regions (Kenya, India, Botswana, Ethiopia and Saudi Arabia) were analyzed through comparative assessment, identifying variability in very high recharge zones ranging between 0.07% and 14%. The methodology applies high-resolution satellite image processing, geospatial modeling and Analytical Hierarchy Process (AHP) to characterize subsurface water systems comprehensively. The results demonstrate methodological precision between 60.53% and 87.9%, with Areas Under the Curve (AUC) ranging from 0.604 to 0.879, indicating robust model performance across different hydrogeological contexts. The precipitation regimes analyzed vary from 73.8 to 1500mm annually, confirming that recharge potential depends on complex interactions between geomorphological, climatic and structural factors. Statistical validation through ROC curve analysis and empirical well data verification supports the reliability of the integrated approach. The study establishes the need for adaptive methodologies that recognize the dynamic nature of groundwater recharge systems, contributing to sustainable water resource management strategies in water-scarce regions.

Keywords: Multi-criteria Analysis. Water Resources Management. Groundwater Recharge. Geographic Information Systems. Remote Sensing.

Resumo

Esta pesquisa desenvolve uma metodologia integrada para avaliar o potencial de recarga de águas subterrâneas em ecossistemas áridos e semiáridos, combinando sensoriamento remoto, sistemas de informação geográfica (SIG) e análise multicritério. Cinco regiões geográficas (Quênia, Índia, Botsuana, Etiópia e Arábia Saudita) foram analisadas por meio de avaliação comparativa, identificando variabilidade em zonas de recarga muito altas, variando entre 0,07% e 14%. A metodologia aplica processamento de imagens de satélite de alta resolução, modelagem geoespacial e o Processo Analítico de Hierarquia (AHP) para caracterizar sistemas de água subterrânea de forma abrangente. Os resultados demonstram precisão metodológica entre 60,53% e 87,9%, com Áreas Sob a Curva (AUC) variando de 0,604 a 0,879, indicando desempenho robusto do modelo em diferentes contextos hidrogeológicos. Os regimes de precipitação analisados variam de 73,8 a 1500 mm anuais, confirmando que o potencial de recarga depende de interações complexas entre fatores geomorfológicos, climáticos e estruturais. A validação estatística por meio da análise da curva ROC e verificação empírica dos dados de poços apoia a confiabilidade da abordagem integrada. O estudo estabelece a necessidade de metodologias adaptativas que reconheçam a natureza dinâmica dos sistemas de recarga de água subterrânea, contribuindo para estratégias sustentáveis de gestão dos recursos hídricos em regiões com escassez de água.

Keywords: *Análise Multicritério. Gestão de Recursos Hídricos. Recarga de Águas Subterrâneas. Sistemas de Informação Geográfica. Sensoriamento Remoto.*

1 INTRODUCTION

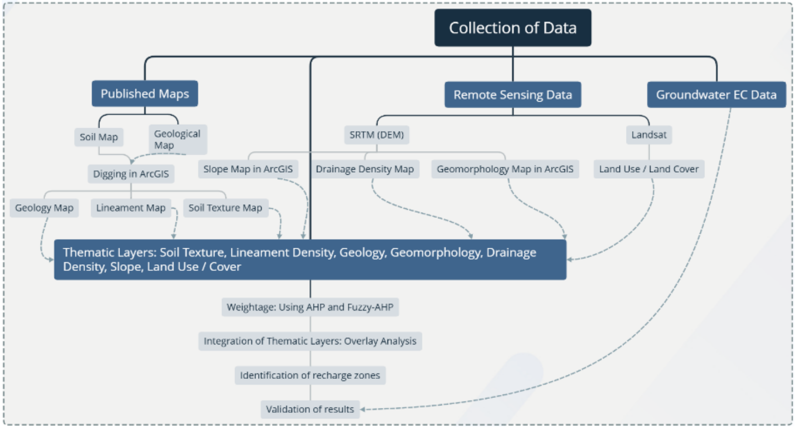
Groundwater resources constitute a fundamental component for ecosystem sustainability in regions characterized by limited and irregular precipitation (Araúzo *et al*. (2020); Boyás *et al*. (2021); the identification of potential recharge zones represents a complex scientific challenge that requires integrated methodological approaches; furthermore, aquifer recharge constitutes an essential hydrogeological process, defined as the volume of water that infiltrates into the saturated zone of the subsurface system (Vargas *et al*., 2023). The principal mechanisms include direct precipitation infiltration, surface runoff recharge, transfer from surface water bodies and lateral interzonal recharge (Maddio *et al*., 2023).

Contemporary methodological evolution is characterized by the integration of advanced technologies including remote sensing through high-resolution satellite sensors, geographic information systems (GIS), multi-criteria analysis methods and computational hydrological modeling (Vázquez-Guevara *et al*., 2023). These approaches offer significant advantages such as extensive spatial coverage, integrated multifactorial analysis and generation of high-precision hydrogeological cartography (Cejudo *et al*., 2022). This analysis presents a methodological transformation characterized by the integration of multiple information sources, implementation of advanced geospatial techniques, development of complex computational modeling and systematic consideration of climatic and anthropogenic variables (Diriba *et al*., 2024). Additionally, advanced methodologies for evaluating groundwater recharge potential are analyzed through integrated techniques of remote sensing, GIS and multi-criteria analysis, evaluating the precision of different methodological approaches and characterizing the determining factors of groundwater recharge potential.

2 MATERIALS AND METHODS

A methodology that integrates approaches developed by Githinji *et al*., (2022), Lavanya and Muthukumar, (2024), Lentswe and Molwalefhe, (2020), Gulbet *et al*., (2025) and Alshehri *et al*., (2024) is presented, combining advanced geospatial techniques, multi-criteria analysis and georeferenced information processing.

Figure 1. Methodological framework for evaluating potential groundwater recharge zones.



Source: Authors

This figure shows a schematic diagram illustrating the comprehensive methodological approach for recharge zone delineation, including identification and processing of thematic layers, weight assignment through AHP, layer integration through overlay analysis and results validation (Githinji *et al*., 2022).

2.1 Integrated methodological protocol

The systematic protocol includes the following components: (i) Data collection through high-resolution multispectral satellite sensors (Sentinel, Landsat) with spatial resolutions between 10-30m, (ii) Generation of Digital Elevation Models (DEM) with altimetric precision less than 10m, (iii) Extraction of thematic layers including topographic slope, drainage density, normalized difference vegetation index (NDVI), structural lineaments and lithological characterization, (iv) Application of Analytical Hierarchy Process (AHP) for multi-criteria weighting, (v) Integration through weighted overlay analysis in GIS environment and (vi) Statistical validation through ROC curves and area under the curve (AUC) calculation.

2.2 Data collection

The analyzed data acquisition process implements a multi-source system that integrates various high-resolution geospatial information databases; consequently, this protocol combines data from remote sensors, official cartography and meteorological records to establish a comprehensive hydrogeological information base.

2.2.1 Satellite and topographic data

Topographic data are derived from SRTM (Shuttle Radar Topography Mission) sensors with resolutions of 12.5-30m and vertical precision less than 10m. Multispectral images originate from two primary sources: Sentinel-2 (10-20m resolution, 13 spectral bands between 443-2190nm) and Landsat 8 OLI (15-30m resolution, 11 spectral bands between 430-2290nm). These sensors enable high-resolution hydrogeological discrimination through spectral analysis of land cover, vegetation indices and surface moisture characterization.

2.2.2 Geological and geomorphological cartography

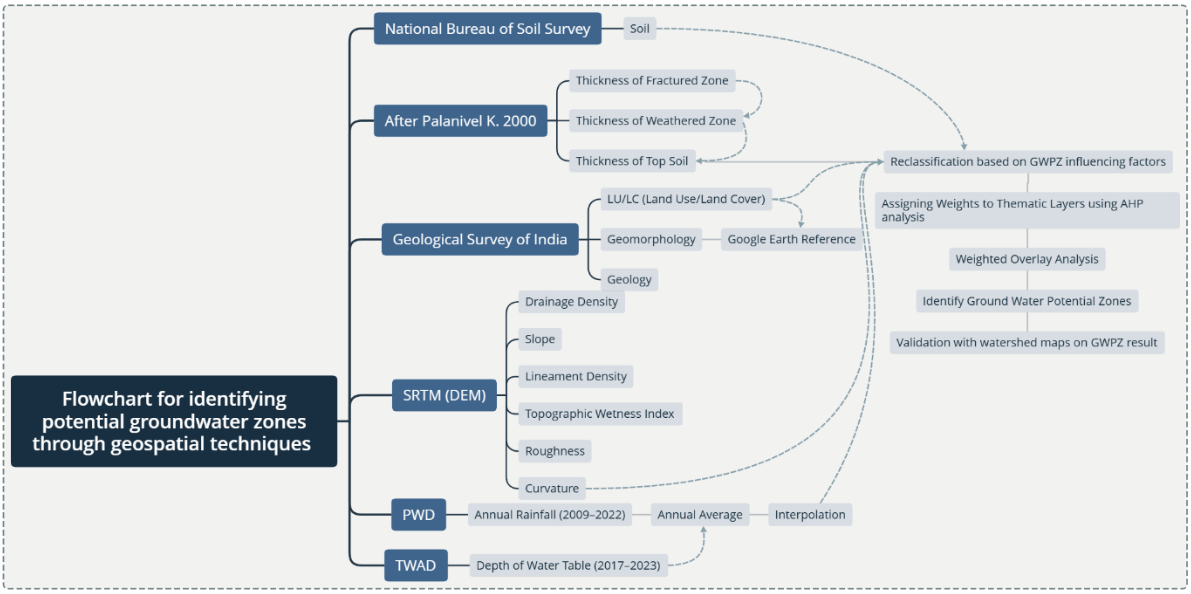
Geological cartography is obtained through official governmental sources that utilize standardized classification systems such as FAO soil taxonomy and USGS lithological classifications. Scales vary from 1:50,000 to 1:250,000, implementing interoperability protocols that ensure geospatial data compatibility. Geomorphological characterization includes structural units, sedimentary, igneous and metamorphic formations, with emphasis on hydrogeological properties such as porosity, permeability and storage capacity.

2.2.3 Climatic and hydrological variables

Climatic variables are processed through advanced geostatistical techniques, integrating spatially distributed meteorological station data with 10-15 year time series. Historical precipitation is interpolated using Inverse Distance Weighting (IDW) and ordinary Kriging methods, considering topographic gradients and orographic effects. Temperature is processed through thermal interpolation that considers altitudinal gradients (-6.5°C/1000m), solar radiation and local geomorphological characteristics.

Figure 2

Methodological flowchart for identifying potential groundwater zones through geospatial techniques.



Flow diagram illustrating the complete analysis process, from data acquisition to final groundwater potential map generation, showing the integration of remote sensing, GIS and multi-criteria analysis techniques (Lavanya and Muthukumar, 2024).

2.3 Geospatial information processing

Geospatial processing implements a multiparametric analysis protocol that captures the inherent complexity of subsurface hydrogeological systems.

2.3.1 Topographic characterization

Topographic characterization utilizes surface analysis algorithms applied to Digital Elevation Models to calculate elevation variations between contiguous pixels. Slope analysis employs gradient operators that determine maximum directional change rates:

$$\text{Slope} = \arctan\left(\sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2}\right) * \left(\frac{180}{\pi}\right) \qquad (1)$$

where:

$\partial z/\partial x$ y $\partial z/\partial y$ represent partial derivatives of elevation Z with respect to X and Y coordinates respectively, expressing results in degrees.

Curvature analysis quantifies morphological variations through second-order derivatives, distinguishing between concave and convex surfaces. The Topographic Position Index (TPI) compares each cell's elevation with its neighborhood average, characterizing specific geomorphological units:

$$\mathrm{TPI} = Z_0 - \bar{Z} \qquad (2)$$

where:

Z_0 is the central pixel elevation and $\bar{Z}$ is the neighborhood average elevation. The Terrain Roughness Index (TRI) quantifies altitudinal variability through standard deviation of elevations in moving windows.

2.3.2 Surface hydrological analysis

Hydrological analysis employs specialized GIS tools to characterize surface drainage patterns. Drainage density constitutes a key indicator of runoff transport efficiency:

$$\mathrm{Dd} = \frac{L}{A} \qquad (3)$$

where:

L represents total channel length (km)
and A represents watershed area (km^2).

This metric is obtained through automatic network extraction algorithms that identify flow directions and flow accumulation. It should be noted that structural lineaments are identified through principal component analysis in satellite images, applying edge enhancement techniques and automatic detection of linear discontinuities;

furthermore, proximity to water bodies is evaluated by generating Euclidean distance surfaces that calculate minimum distance to surface water elements.

2.3.3 Spectral and ecological characterization

Spectral analysis implements high-precision protocols for vegetation indices. The Normalized Difference Vegetation Index (NDVI) evaluates photosynthetic activity and vegetation density:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}} \qquad (4)$$

where:

NIR is near-infrared reflectance and RED is red band reflectance.
NDVI values range between -1 and +1: values near +1 indicate vigorous vegetation, values near 0 represent bare soil and negative values indicate presence of water or snow.

Processing includes atmospheric correction, radiometric calibration and spectral normalization. Land use and cover classification employs supervised algorithms including maximum likelihood and support vector machines, achieving accuracies exceeding 85%; vegetation characterization integrates spectral classifications, texture analysis and field verification.

2.4 Advanced analysis methods

2.4.1 Analytical hierarchy process (AHP)

AHP decomposes complex problems into hierarchical structures, facilitating systematic analysis of interactions between multiple hydrogeological variables; the methodology follows Saaty's (1980) protocol adapted for hydrogeological characterization.

Pairwise comparison utilizes Saaty's scale (1-9) to quantify relative importance: 1 (equal), 3 (moderate), 5 (strong), 7 (very strong), 9 (extreme) with intermediate values for gradations; also, the process constructs a comparison matrix “A” where each element a_{ij} represents the relative importance of criterion i over j:

$$A = [a_{ij}]$$

$$\text{where: } a_{ij} = \frac{1}{a_{ji}};\ y\ a_{ii} = 1 \qquad (5)$$

The principal eigenvector is calculated by solving the characteristic system, where A is the (n×n) matrix, w is the weighting vector and λmax is the maximum eigenvalue:

$$A * w = \lambda max * w \qquad (6)$$

Consistency is verified by calculating the Consistency Index (CI = (λmax - n)/(n - 1)) and Consistency Ratio (CR = CI/RI), where RI comes from tabulated values. A CR < 0.10 indicates acceptable consistency.

Layer integration employs weighted overlay analysis, calculating the Recharge Potential Index (RPI):

$$RPI = \Sigma(w_i * R_i) \qquad (7)$$

where:

w_i is the weight of criterion i from AHP,
R_i is the reclassified value (1-5 scale)
and the summation encompasses all criteria (i = 1 to n).

2.4.2 Statistical validation techniques

Statistical validation employs ROC (Receiver Operating Characteristic) curves as a fundamental tool, plotting true positive rates versus false positive rates at different classification thresholds.

ROC analysis calculates True Positive Rate *(TPR = TP/(TP + FN))* and False Positive Rate *(FPR = FP/(FP + TN))*, where TP, FP, TN, FN represent true positives, false positives, true negatives and false negatives respectively. The Area Under the Curve (AUC) is determined by integration:

$$\mathrm{AUC} = \int_0^1 \mathrm{TPR}\left(\mathrm{FPR}^{-1}(x)\right)dx \qquad (8)$$

AUC quantifies model precision between 0.5 (random) and 1.0 (perfect). Standard interpretation classifies: 0.9-1.0 (excellent), 0.8-0.9 (good), 0.7-0.8 (moderate), 0.6-0.7 (poor), 0.5-0.6 (failure). Empirical validation contrasts predicted zones with location and performance of actual wells through geospatial overlay.

2.4.3 Sensitivity and uncertainty analysis

Sensitivity analysis is implemented through systematic variation of AHP weightings, evaluating result robustness against changes in assigned weights. Uncertainty is quantified through Monte Carlo analysis, generating multiple model realizations with random parameters within defined ranges; error propagation is evaluated through bootstrap techniques, providing confidence intervals for model predictions.

2.5 Region-specific methodologies

2.5.1 Arid and semi-arid ecosystems

Methodologies for arid ecosystems implement specialized protocols considering extreme water limitations. In Kenya, Githinji *et al*. (2022) developed water retention analysis techniques through infiltration modeling in alluvial plains, utilizing modified Green-Ampt equations for arid conditions. In Saudi Arabia, Alshehri *et al*. (2024) implemented fracture and structural lineament analysis through spectral enhancement techniques, identifying preferential infiltration corridors in crystalline formations.

Hydrological modeling for arid zones incorporates specific “runoff coefficients”, elevated evapotranspiration rates and extreme precipitation event analysis; recharge microenvironment characterization is performed through high-resolution analysis (<10m) that identifies topographic depressions, drainage intersections and sedimentary accumulation zones.

2.5.2 Mountain and high-andean systems

Mountain systems require methodological approaches considering extreme altitudinal gradients, vertical climatic variability and structural geological complexity. The methodology integrates topographic shading analysis, orographic effects on precipitation and complex groundwater flow modeling through finite element techniques.

High-Andean watershed analysis implements altimetric correction of climatic variables, considering thermal gradients (-6.5°C/1000m) and pluviometric gradients (+100mm/100m on windward slopes). Geomorphological characterization includes Quaternary glaciation analysis, morainic deposits and drainage systems controlled by tectonic structures.

2.5.3 Tropical and subtropical contexts

Tropical ecosystems present methodological challenges related to high seasonal variability, dense vegetation cover and deep weathering systems. In India, Lavanya and Muthukumar, (2024) developed vegetation canopy penetration techniques through multitemporal analysis, utilizing spectral indices NDVI, EVI and SAVI to characterize coverage dynamics.

Tropical hydrological modeling incorporates monsoon analysis, seasonal precipitation distribution and deforestation effects on recharge patterns. Additionally, weathering profile characterization includes laterization analysis, saprolite development and secondary porosity systems in altered crystalline rocks.

2.6 Methodological recommendations

2.6.1 Protocol standardization

Methodological standardization emerges as a critical component for scientific advancement, requiring definition of uniform criteria for hydrogeological data collection, processing and validation. Standard protocols should include: (i) minimum technical specifications for satellite data (spatial resolution < 30m, temporal resolution < 16 days), (ii) empirical validation methodologies (minimum 10 reference wells per 100 km²), (iii) consistency criteria for AHP analysis (CR < 0.10), (iv) minimum precision thresholds (AUC > 0.7).

2.6.2 Interdisciplinarity and technology transfer

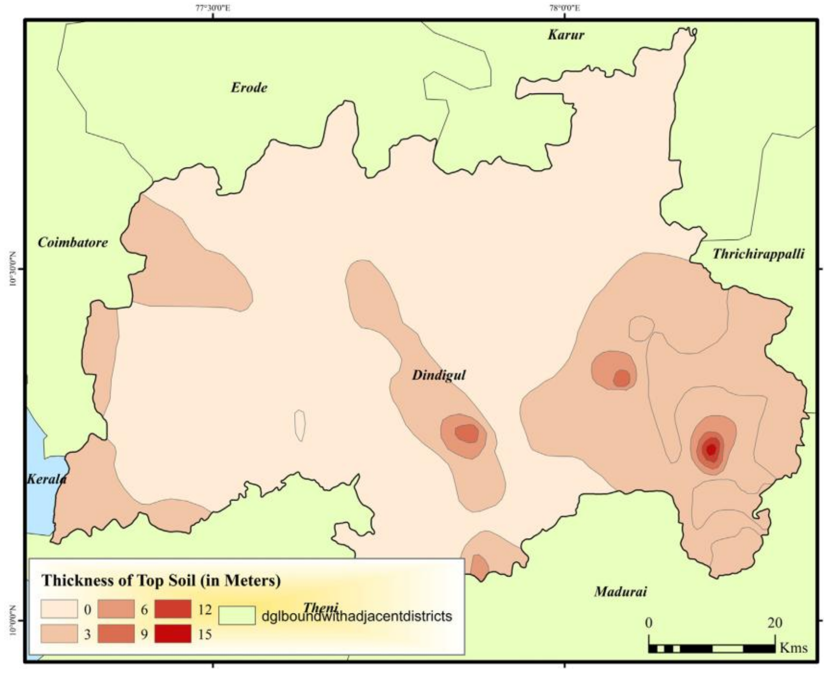
The interdisciplinary approach requires effective integration of geological, hydrological, climatological, ecological and computational knowledge. Technology transfer should promote advanced methodology adoption through development of intuitive visualization interfaces, structured technical training programs and accessible automated analysis platforms. It is worth mentioning that implementation of web-based information systems facilitates democratized access to advanced hydrogeological analysis tools, enabling their application in diverse contexts.

3 RESULTS

Comparative analysis reveals extraordinary heterogeneity in potential recharge zone distribution. Githinji *et al*. (2022) in Kenya identified 7.6% high recharge area in alluvial plains with 250-300mm annual precipitation. Lavanya and Muthukumar, (2024) in India presented 0.07% very high recharge zone with pluviometric variability of 650-1500mm annually.

Figure 3

Spatial distribution of potential recharge zones in semi-arid watershed.



Map showing final classification of groundwater recharge potential zones, resulting from integration of multiple thematic layers through weighted overlay analysis (Lentswe and Molwalefhe, 2020).

Lentswe and Molwalefhe, (2020) in Botswana developed a model with 8% high recharge zone and 78% moderate recharge. The analysis revealed complex distribution: 22.33% high recharge zone, 35.12% moderate recharge, 19.56% low recharge and 22.92% very low recharge. Gulbet *et al*. (2025) in Ethiopia revealed 14% very high recharge zone, 26% high recharge, 34% moderate recharge, 19% low recharge and 8% very low recharge, with 1097-1269mm annual precipitation. Alshehri *et al*. (2024) in Saudi Arabia showed 4.04% very high recharge zone, 10.95% high recharge, 21.12% moderate recharge, 32.77% low recharge and 31.09% very low recharge, with extremely limited precipitation of 73.8-316mm.

3.1 Analysis of determining factors

Topographic slope manifested as a fundamental hydrodynamic modulator: zones with slopes < 2° showed high infiltration capacity, while slopes > 15° restrictively limited recharge processes. Lineament density emerged as a complex hydrogeological conductor, with preferential orientations varying from NE-SW in Kenya to critical fracturing zones in India.

Lithology demonstrated extraordinary variability: from alluvial and colluvial deposits in Kenya to complex geological mosaics in India, including gneiss, quartzite, basalts and lacustrine sediments. Vegetation cover, evaluated through NDVI, revealed its crucial role in modifying infiltration processes, increasing water retention capacity through generation of root macropores.

3.2 Methodological validation

AHP validation showed precisions ranging between 60.53% (India) and 87.9% (Kenya). Area Under the Curve (AUC) evidenced significant variations: 0.879 in Kenya (excellent precision), 0.60 in India (moderate precision) and 0.604 in Ethiopia (average precision). AHP weightings varied according to context: Ethiopia presented precipitation (30.7%), slope (21.8%) and lithology (15.4%), while Saudi Arabia showed lineament density (12.9%), slope (21.3%) and drainage density (7.4%).

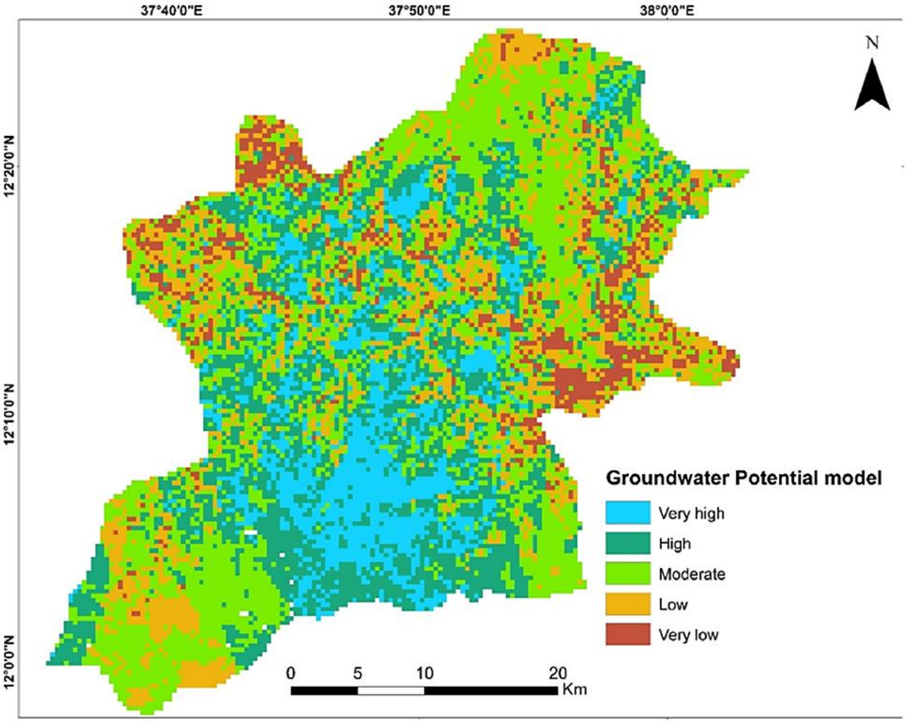
Empirical validation through existing wells demonstrated correspondence between predicted high potential zones and high-yield wells. Lavanya and Muthukumar, (2024) implemented validation with 11 wells, achieving 81.8% global precision, evidencing the capacity of integrated models to characterize complex hydrogeological systems.

3.3 Spatial pattern analysis

Spatial distribution revealed critical patterns in recharge zone configuration. Very high recharge zones concentrated preferentially in: (i) alluvial plains with minimal slopes, (ii) structural lineament intersections, (iii) areas with dense vegetation cover (NDVI > 0.6), (iv) proximity to surface water bodies, (v) permeable geological formations. Percentage variability reflects the intrinsic complexity of hydrogeological systems where geomorphological, climatic and structural factors interact non-linearly.

Figure 4

Groundwater potential map in Libo Kemkem watershed, Ethiopia.



Illustrates spatial distribution of recharge potential zones classified in five categories, from very high to very low potential, resulting from integration of multiple factors through geospatial techniques and multi-criteria analysis (Gulbet *et al*., 2025).

4 DISCUSSION

Comparative analysis demonstrates methodological convergence in recharge potential characterization, although it reveals inherent singularity to each geographical context. Heterogeneity in recharge zone distribution reflects the complexity of hydrogeological systems where multiple factors interact non-linearly. Precipitation acts as a critical modulating factor, with ranges varying from 250-300mm annually in Kenya to 1097-1269mm in Ethiopia. Studies evidence that interactions between precipitation and local geological characteristics determine recharge mechanisms; water scarcity generates critical retention processes (Githinji *et al*., 2022), while temporal precipitation distribution affects recharge effectiveness (Lavanya and Muthukumar, 2024).

Structural lineaments and lithology emerge as complex hydrogeological conductors. The resilience of water systems under arid conditions, with 78% moderate recharge (Lentswe and Molwalefhe, 2020), contrasts with interaction between alkaline basalts and lacustrine sediments that generates specific infiltration microenvironments (Gulbet *et al*., 2025). AHP validation demonstrates notable consistency with precisions between 60.53% and 87.9%. AUC variations (0.604-0.879) confirm the complexity of characterizing systems where non-linear interactions challenge traditional approaches.

The need for integrated methods that recognize the impossibility of universal generalization is emphasized; moreover, findings indicate the necessity to develop high-resolution predictive models that capture the dynamic nature of recharge systems. Each ecosystem presents unique hydrogeological architecture, determined by complex geomorphological, climatic and structural interactions requiring adaptive methodological approaches.

5 CONCLUSIONS

The research demonstrates the effectiveness of integrated methodologies for evaluating groundwater recharge potential. The combination of remote sensing, GIS and multi-criteria analysis surpasses traditional approach limitations through systematic AHP use, geospatial technology integration and multiparametric analysis.

Precision evaluation revealed significant results, with AHP validations between 60.53% and 87.9% and AUC values from 0.604 to 0.879, confirming the capacity of integrated methods to characterize complex hydrogeological systems. Critical factor characterization identified differential importance of precipitation, topographic slope, lineament density and lithology, with regional variations ranging from 73.8 to 1500mm annually.

Results indicate the need to incorporate machine learning techniques and develop adaptive methodologies that recognize inherent hydrogeological system complexity. It is simultaneously confirmed that each ecosystem presents unique hydrogeological architecture, determined by complex geomorphological, climatic and structural interactions. A flexible methodological framework was established that enables comprehensive characterization of groundwater recharge zones, constituting a significant advance in understanding water dynamics and contributing to sustainable groundwater resource management strategy development.

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Authors' Contribution

Both authors contributed equally to the development of this article.

Data availability

All datasets relevant to this study's findings are fully available within the article.

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