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Spatial Delineation of Groundwater Potential Zones Using GIS Remote Sensing and the Analytic Hierarchy Process in Beledweyne, Somalia

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Abstract
Beledweyne, Somalia, faces recurring water-supply pressures arising from variable rainfall, flooding, drought, surface-water contamination, and limited treatment infrastructure. This study delineates groundwater potential zones by integrating geographic information systems, remote sensing, and the analytic hierarchy process. Six thematic factors—rainfall, geology, slope, drainage density, lineament density, and soil type—were standardized, weighted through pairwise comparison, and combined in a spatial overlay model. The resulting map classified the study area into very low, low, high, and very high groundwater-potential zones. High-potential areas covered 36.52% of the study area, while very-high-potential areas covered 19.30%; together, these zones accounted for 55.82% of Beledweyne. The most favorable zones were associated with permeable geological conditions, lower drainage density, and greater rainfall contribution. Borehole and dug-well locations obtained from the FAO SWALIM water-source database were overlaid on the potential map as a spatial plausibility check. The findings provide a screening tool for prioritizing hydrogeological investigation, borehole siting, managed recharge, and water-resource planning. The map also identifies lower-potential areas where groundwater development may require greater caution and additional evidence. Because the model relies on weighted thematic layers and does not report a quantitative validation statistic, the mapped classes should guide field investigation rather than replace pumping tests, water-quality assessment, or long-term groundwater monitoring.

Keywords: Groundwater potential, Geographic information systems, Remote sensing, Analytic hierarchy process, Beledweyne

1. Introduction

Beledweyne, the central city of Somalia crossed by the Shabelle River, faces significant hydrological challenges that have increasingly compromised the availability and quality of surface water. These challenges are exacerbated by a range of anthropogenic activities, climatic variations, and the absence of adequate water treatment facilities. Consequently, the reliance on surface water sources for drinking and other domestic uses has become unsustainable, prompting a shift toward exploring alternative water sources (Mukherjee & Singh, 2020). This research seeks to delineate groundwater potential zones (GPZs) in Beledweyne using Geographic Information System (GIS) techniques to provide a sustainable solution to the water

scarcity issue. Groundwater, generally less susceptible to pollution compared to surface water, offers a viable option for addressing the city's potable water needs (Arulbalaji et al., 2019).

Recent studies underscore the efficacy of integrating GIS with remote sensing to systematically evaluate and map groundwater resources, particularly in semi-arid regions like Beledweyne. Such integrations facilitate the effective management of groundwater, which is crucial for sustainable development and ecological balance (Machiwal et al., 2011). In Beledweyne, where environmental factors such as droughts and floods further complicate water resource management, the use of advanced GIS and Analytical Hierarchy Process (AHP) techniques can pinpoint areas with significant groundwater reserves, thus guiding strategic planning and utilization (Rehman et al., 2024).

Moreover, the exploration and proper management of groundwater potential zones could support a range of activities beyond domestic use, including agricultural irrigation, industrial operations, and ecological sustenance, which are vital for the socio-economic development of the region. The anticipated outcome of this research includes the creation of high-resolution maps that delineate areas with varied groundwater availability, thus offering a strategic blueprint for resource allocation and infrastructure development. This study also aims to contribute to the existing literature by providing updated empirical data and refined methodologies tailored to the unique environmental and geological characteristics of Beledweyne.

1.1 Study Objectives

- Delineate groundwater potential zones in Beledweyne by integrating GIS and remote-sensing data for drainage density, rainfall, lineament density, soil type, slope, and geology.
- Apply the analytic hierarchy process to weight and integrate the thematic layers used in groundwater-potential mapping.
- Compare the mapped potential zones with the spatial distribution of documented boreholes and dug wells in Beledweyne.

2. Literature Review

Groundwater-potential mapping commonly uses three groups of models: statistical and multicriteria methods, machine-learning methods, and hybrid or ensemble approaches (Thanh et al., 2022). Statistical approaches include weights of evidence, frequency ratios, evidential belief functions, and multicriteria decision methods such as the analytic hierarchy process. Machine-learning approaches include logistic regression, support-vector machines, random forests, and boosted trees. Table 1 summarizes recent studies, their input parameters, modeling choices, validation methods, findings, and limitations.

Table 1. Summarized Review of Literature

Reference	Location	Year	Parameters	Models	Validation	Key Findings	Gaps and Limitations / Future Direction
Chemirik et al., 2024	Mostaganem Plateau, Northwest Algeria	2024	7 layers including LULC, geology, rainfall, DD, LD, slope and Soil	AHP MOLUSCE	Depth for 12 monitoring wells.	1) The study found that climate change has significantly impacted groundwater potential zones in the Mostaganem plateau, Algeria. 2) Moderate potential zones have decreased, while fair and low potential zones have increased. Projections indicate further declines in groundwater potential due to reduced rainfall and intensified agriculture.	The study highlights the need for a more comprehensive assessment of groundwater resources that includes factors like groundwater quality, evapotranspiration, soil moisture, and resilience mechanisms.
Dahal & Kshetri, 2024	Phewa Watershed in Nepal	2024	6 layers including slope, elevation, DD, rainfall, soil and LULC	Statistical (AHP)	N/A	The study found that the lower part of the landscape has higher groundwater potential than the upper part due to its flatter terrain, which allows for better water infiltration	The research lacks field validation, meaning the results were not confirmed by on-site measurements. This could lead to inaccuracies in the identified groundwater potential zones
Sarkar et al., 2024	Bangladesh	2024	14 layers including curvature, DD, slope, roughness, rainfall, temperature, relative humidity,	ML including ANN, LR, and LMT	ROC-AUC	The study identified high groundwater stress in southern hill tracts. Groundwater potential is elevated near rivers and harbors, but coastal regions show varied results. The ANN model outperformed LR and LMT in	The study recommends expanding the model comparison to include SVM, RF, and DT. Additionally, incorporating novel variables like land use changes and aquifer properties within RCP scenarios can enhance prediction accuracy.

Reference	Location	Year	Parameters	Models	Validation	Key Findings	Gaps and Limitations / Future Direction
			LD, land use and land cover, general soil types, geology, geomorphology, TPI, TWI			predicting groundwater potential, though all models achieved over 80% accuracy	
Choudhary et al., 2022	Godavari sub-basin of India.	2022	15 Layers including slope, aspect, altitude, plan curvature, profile curvature, TWI, NDBI, rainfall, distance to roads, distance to streams, DD, geomorphology, SPI, LULC and soil	Statistical methods such as TOPSIS, WoE and F-FR ML was also applied including XGB and ET	50 observation wells and ROC	The primary research gap in groundwater assessment lies in the need for more accurate and comprehensive data, refined models, and a better understanding of uncertainties.	Future research should focus on improving data quality, refining models, quantifying uncertainties, addressing contamination, updating standards, estimating recharge, and exploring management strategies to ensure reliable groundwater assessments and sustainable practices.
Razavi-Termeh et al., 2024	Isfahan City, Iran	2024	16 layers including	ML such as RF, and human-inspired metaheuristic algorithm Such as	175 observation wells, RMSE, MAE, and ROC	The study encountered limitations due to the lack of current well data, potentially affecting the accuracy of its findings. Additionally, it did not explore subsidence in regions with groundwater potential, hindering	Future studies could explore the correlation between water quality parameters and groundwater potential, incorporate multidisciplinary approaches, investigate the impact of climate change on groundwater, and

Reference	Location	Year	Parameters	Models	Validation	Key Findings	Gaps and Limitations / Future Direction
				TLBO, SPBO, ICA		a comprehensive understanding of land subsidence issues	explore advanced machine learning algorithms for GPM.
Dandapat et al., 2024	Jhargram, West Bengal, India	2024	7 layers including hydrogeology, slope, LD, rainfall, DD, soil type, and LULC	It applied AHP	57 observation wells and ROC.	Groundwater assessments are often hampered by limited data, simplified models, and scale constraints.	future research should focus on improving data, refining models, considering wider scales, integrating water resources, addressing climate change, utilizing emerging technologies, and fostering public engagement
Çelik et al., 2024	Mersin, Turkey	2024	15 Layer including	Statistical (AHP, TOPSIS and VIKOR)	60 Observation wells.	This study identified GPZ using GIS based methods like AHP, TOPSIS and VIKOR.	Absence of detailed data on well discharge and groundwater depth could hinder more precise evaluations. Future directions should focus on incorporating more comprehensive datasets, including well performance metrics, and expanding the methodology to other regions facing similar water management challenges to enhance the robustness of groundwater assessments
Ghanim et al., 2023	Habawnah Basin of Southern Saudi Arabia	2023	7 layers including geology, LULC, LD, soil	Statistical (AHP)	75 Observation wells.	The study successfully employed GIS and AHP techniques to assess and map groundwater potential zones in a large basin in southern	The study faced limitations, including the exclusion of thematic layers like aquifer thickness and recharge rates, and

Reference	Location	Year	Parameters	Models	Validation	Key Findings	Gaps and Limitations / Future Direction
			characteristics, DD, and rainfall			Saudi Arabia, identifying areas with high, low, and moderate potential.	the lack of high-resolution data. Anthropogenic activities affecting groundwater availability were not considered, and the complex geology of the Habawnah Basin made it difficult to identify consistent groundwater patterns. Future research should incorporate more thematic layers and high-resolution datasets, conduct long-term groundwater monitoring, and validate models through field studies.
Arabameri et al., 2019	Shahroud Plain, Iran	2018	15 layers including LULC, distance to fault, slope, fault density, distance to road, elevation, soil depth, lithology, soil type, rainfall, DD, TWI, distance to stream, plan curvature and slope aspect	Statistical and ML models such as (WoE, TOPSIS, RF and BLR)	122 groundwater well and ROC	This study indicates that combining well data of groundwater, physical properties derived from remote sensing, and thematic information can generate accurate maps of the groundwater potential. These maps help in determining the best locations for extraction hence minimizing wastage of funds that would otherwise be used in drilling and deepening wells in unfavorable areas.	Some of the constraints of the study include data quality, and geographical restrictions which limits the generalization of the results. The future research should include the use of more data sources, the development of new models that can better predict the dynamic values required for actual groundwater management, and longer time span investigations that address the temporal variability in groundwater systems.

Reference	Location	Year	Parameters	Models	Validation	Key Findings	Gaps and Limitations / Future Direction
Duguma, 2023	Upper Blue Nile River Basin, Ethiopia	2023	10 layers including Geomorphology LULC, Lithology, soil type, DD, soil texture, slope, LD rainfall and elevation	Statistical (AHP)	13 Observed wells	The study identified that close to 33.58% of the Guder watershed holds good to very good groundwater potential, relying on GIS and remote sensing to evaluate geomorphology and land use variables. This research facilitates sustainable management of groundwater in that region.	Limitations in the study include a reliance on available data that might not include all local variations, along with the failure of extensive field validation. Future research approaches recommend merging more complete field data with studies of additional influencing factors for greater accuracy and improved management strategies.

Chemirik et al. (2024) mapped groundwater potential on the Mostaganem Plateau in northwestern Algeria by integrating AHP, remote sensing, GIS, and land-use projections. Their results suggested that moderate- and high-potential zones declined between 2000 and 2014 and may decline further under projected rainfall and agricultural change. The study did not incorporate groundwater quality, evapotranspiration losses, or soil-moisture dynamics, indicating a need for broader hydroclimatic and resilience assessment.

Choudhary et al. (2022) compared bivariate, multicriteria, and machine-learning approaches in India's upper Godavari sub-basin. Enhanced weights-of-evidence, TOPSIS, frequency-ratio, XGBoost, and extra-trees models produced high classification accuracy and were evaluated using predictive-value, sensitivity, specificity, and nonparametric tests. The authors noted that aquifer condition and hydraulic conductivity could further improve model reliability and recommended testing additional optimization algorithms.

Ghanim et al. (2023) used GIS and AHP to map groundwater potential in southern Saudi Arabia using geology, slope, land use, lineament density, soil, drainage density, and rainfall. The map was validated against well data, but the authors identified missing information on aquifer thickness, recharge, groundwater depth, river proximity, and water demand. Arabameri et al. (2019) compared random forest, weights of evidence, binary logistic regression, and TOPSIS in Iran's Shahroud Plain and likewise emphasized the importance of well data, thematic-layer quality, and regional limitations.

Duguma (2023) combined GIS and remote sensing to evaluate groundwater potential in Ethiopia's Guder watershed. Approximately 33.58% of the area was classified as having good to excellent potential, and well-discharge data were used for validation. The study nevertheless depended on available secondary data and recommended more extensive field validation to capture local variation.

2.1 Analytic Hierarchy Process

The analytic hierarchy process (AHP) is a transparent multicriteria decision method that decomposes a complex problem into criteria that can be compared pairwise (Saaty, 1987). Its principal advantage is the ability to combine quantitative data with expert judgment and to produce explicit criterion weights. For groundwater-potential mapping, AHP is useful because hydrological, geological, and environmental layers have different measurement scales and contributions. Table 2 compares methods reported in recent mapping studies. AHP remains appropriate for the present data-scarce setting, although its results depend on the quality of the thematic layers, the defensibility of expert judgments, and the consistency of the pairwise-comparison matrix.

Table 2: Methods Utilized to Identify Groundwater Potential Zones

Reference	Country	Year	Methods								
			AHP	TOPSIS	Fuzzy	WoE	FR	BWoE	VIKOR	ML	Others
Atangana Njock et al., 2022	Gorezen River watershed in Ethiopia	2024	√								
Chemirik et al., 2024	Mostaganem Plateau, Northwest Algeria	2024	√								
Dahal & Kshetri, 2024	Phewa Watershed in Nepal	2024	√								
Sarkar et al., 2024	Bangladesh	2024								√	
Razavi-Termeh et al., 2024	Isfahan City, Iran	2024								√	
Dandapat et al., 2024	Jhargram, West Bengal, India	2024	√								
Çelik et al., 2024	Mersin, Turkey	2024	√	√					√		
Ghanim et al., 2023	Habawnah Basin of Southern Saudi Arabia	2023	√								
Arabameri et al., 2019	Shahroud Plain, Iran	2018		√		√				√	

Reference	Country	Year	Methods								
			AHP	TOPSIS	Fuzzy	WoE	FR	BWoE	VIKOR	ML	Others
Duguma, 2023	Upper Blue Nile River Basin, Ethiopia	2023	√								

3. Methodology

This study integrated GIS, remote sensing, and AHP to delineate groundwater-potential zones in Beledweyne. Rainfall, geology, slope, drainage density, lineament density, and soil type were prepared as thematic raster layers, standardized to a common suitability scale, weighted through AHP, and combined using weighted overlay. Figure 1 summarizes the workflow. The final classes were compared with documented borehole and dug-well locations from the FAO SWALIM water-source database.

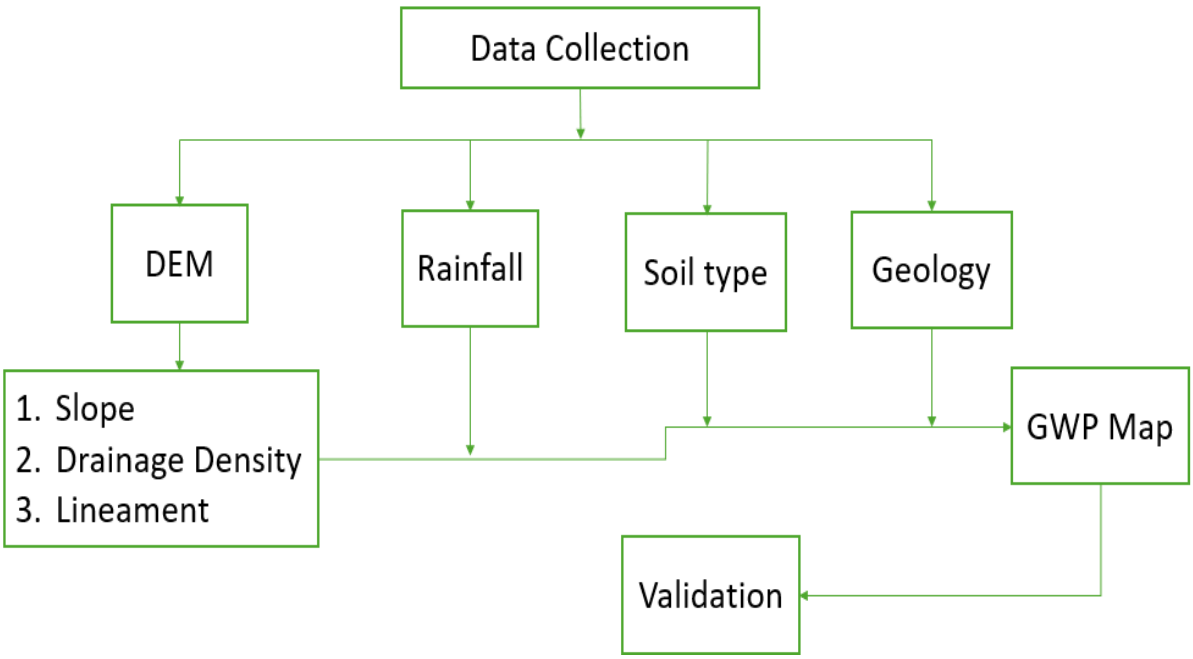


Figure 1: Groundwater Potential Mapping Workflow

3.1 Analytic Hierarchy Process Framework

3.1.1 Pairwise Comparison Matrix

Table 3 presents the pairwise-comparison matrix used to judge the relative importance of rainfall, geology, slope, drainage density, lineament density, and soil type for groundwater potential. Each cell expresses the importance of the row criterion relative to the column criterion using the AHP comparison scale.

Table 3: Pairwise Comparison Matrix

Criteria	Rainfall	Geology	Slope	Drainage	Lineament	Soil
Rainfall	1	2	3	4	5	6
Geology	1/2	1	2	3	4	5
Slope	1/3	1/2	1	2	3	4
Drainage	1/4	1/3	1/2	1	2	3
Lineament	1/5	1/4	1/3	1/2	1	2
Soil	1/6	1/5	1/4	1/3	1/2	1

Each matrix cell represents the relative importance assigned to one criterion compared with another.

3.1.2 Normalized Pairwise Comparison Matrix

Table 4 presents the normalized pairwise-comparison matrix. Each entry was divided by the sum of its column so that the relative contributions could be compared on a common scale. Criterion weights were then derived from the row averages. For the matrix in Table 3, the maximum eigenvalue is λmax = 6.122, giving a consistency index CI = (λmax − n)/(n − 1) = 0.024 and, with a random index RI = 1.24 for n = 6, a consistency ratio CR = CI/RI = 0.020. Because CR < 0.10, the pairwise judgments are acceptably consistent (Saaty, 1987).

Table 4: Normalized Pairwise Comparison Matrix

Criteria	Rainfall	Geology	Slope	Drainage	Lineament	Soil
Rainfall	0.408	0.467	0.424	0.369	0.323	0.286
Geology	0.204	0.233	0.282	0.277	0.258	0.238
Slope	0.136	0.117	0.141	0.185	0.194	0.19
Drainage	0.102	0.078	0.071	0.092	0.129	0.143
Lineament	0.082	0.058	0.047	0.046	0.065	0.095
Soil	0.068	0.047	0.035	0.031	0.032	0.048

Formula: Each normalized cell n_{ij} is calculated as:

$$n_{ij} = \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}}$$

The denominator is the sum of the corresponding column.

3.1.3 Criterion Weights

The weights in Table 5 were calculated by averaging the normalized values across each row. Rainfall received the largest weight (.38), followed by geology (.25), slope (.16), drainage density (.10), lineament density (.07), and soil type (.04). These weights were applied in the GIS weighted-overlay model to produce the groundwater-potential map. The consistency ratio of 0.020 (Section 3.1.2) supports their use in the overlay.

Table 5: Weights

Criteria	Weights
Rainfall	0.38
Geology	0.25
Slope	0.16
Drainage	0.1
Lineament	0.07
Soil	0.04

Formula: The weight W_i for each criterion is calculated as:

$$W_i = \frac{1}{n}\sum_{j=1}^{n} n_{ij}$$

The weight for each criterion equals the average of its normalized row values, where n is the number of criteria.

3.2 Study Area

Beledweyne is situated along the Shabelle River in central Somalia and experiences recurring floods, droughts, surface-water quality concerns, and limited water-treatment capacity. These conditions increase interest in groundwater as a complementary source for domestic, agricultural, and urban water supply. Figure 2 shows the study area.

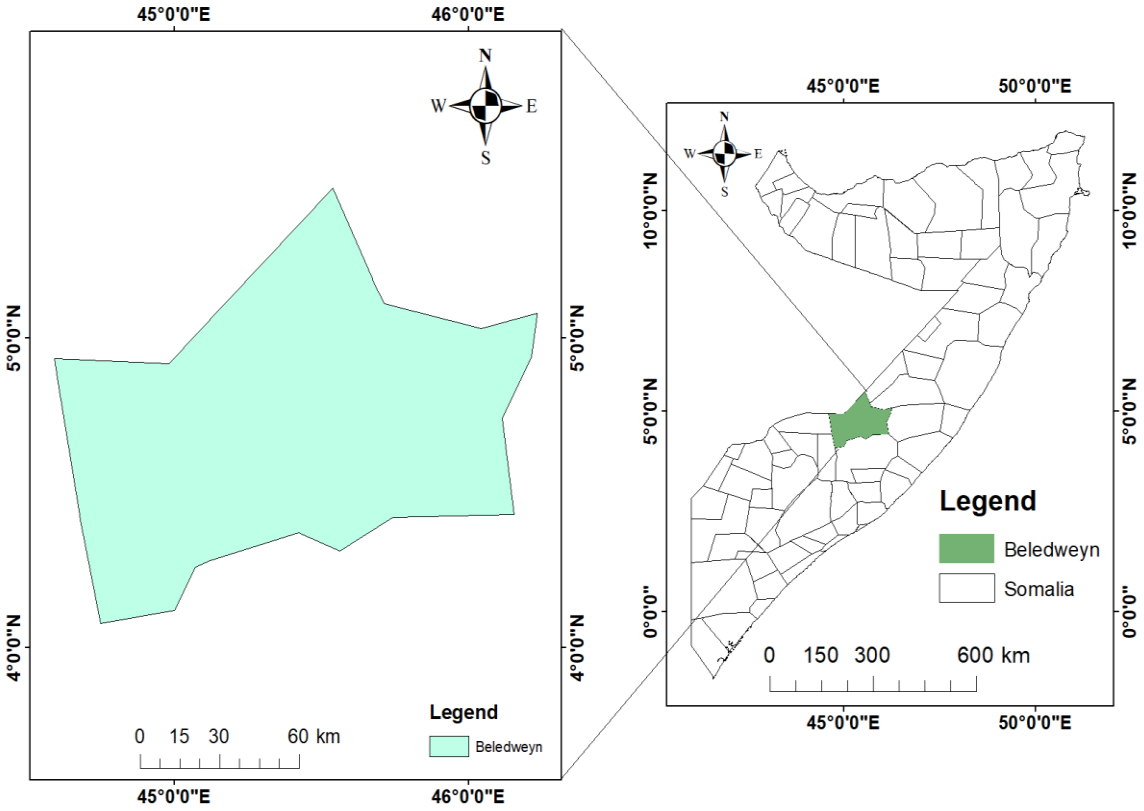


Figure 2: Study Area

4. Results and Discussion

The integrated GIS-AHP analysis combined drainage density, geology, lineament density, soil type, slope, and rainfall to classify groundwater potential across Beledweyne. The following subsections explain how each layer was interpreted and how the weighted layers contributed to the final potential map. These interpretations describe spatial suitability and should not be treated as direct measurements of aquifer yield or water quality.

4.1 Drainage Density

Lower drainage density generally favors infiltration because water remains on the surface longer before becoming runoff (Ganapuram et al., 2009). In the Beledweyne model (Figure 3), low-drainage-density zones therefore received higher groundwater-potential scores. These zones may be suitable for follow-up hydrogeological investigation and managed-recharge planning, but site selection should also consider flood risk, soil permeability, land use, and water quality.

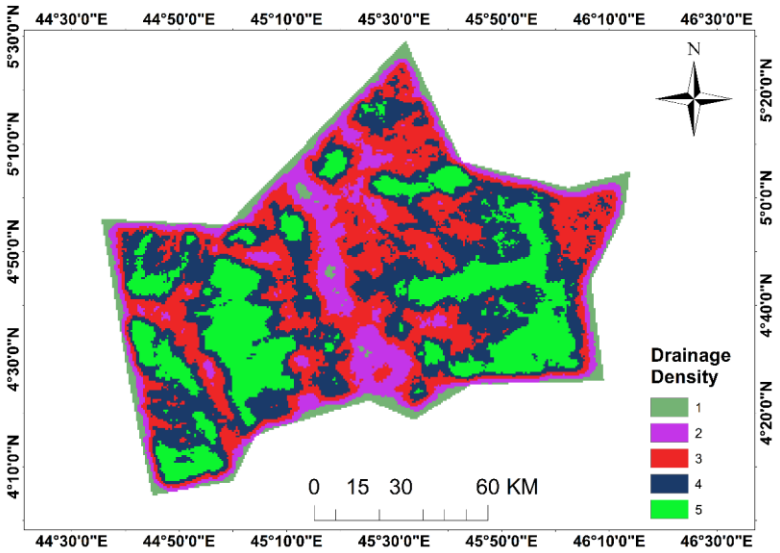


Figure 3: Drainage Density Map

4.2 Geology

Geology influences groundwater storage, transmission, and accessibility (Ghanim et al., 2023). In the geology layer (Figure 4), permeable sedimentary units and fractured formations generally received higher suitability scores, whereas less permeable units received lower scores. The geological layer can guide preliminary borehole targeting, but sustainable abstraction requires field confirmation of aquifer thickness, hydraulic conductivity, recharge, and water quality.

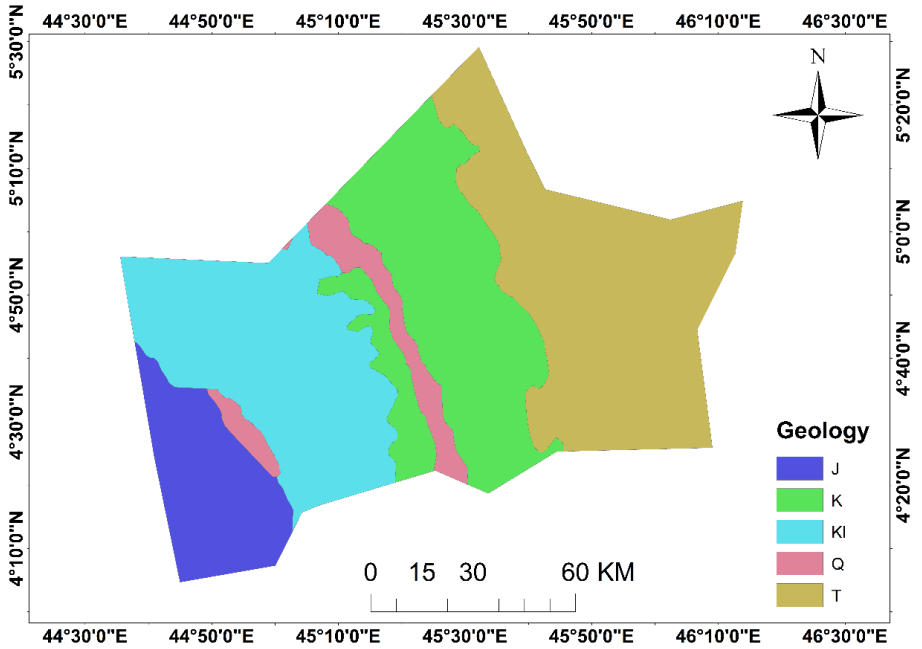


Figure 4: Geology Map

4.3 Lineament Density

Lineaments may represent faults, fractures, or structural discontinuities that enhance secondary porosity and groundwater movement. Areas with greater lineament density (Figure 5) were therefore assigned higher potential in the model (Algaydi et al., 2019). Because lineaments can also create pathways for contaminant transport, field verification should assess both water yield and vulnerability.

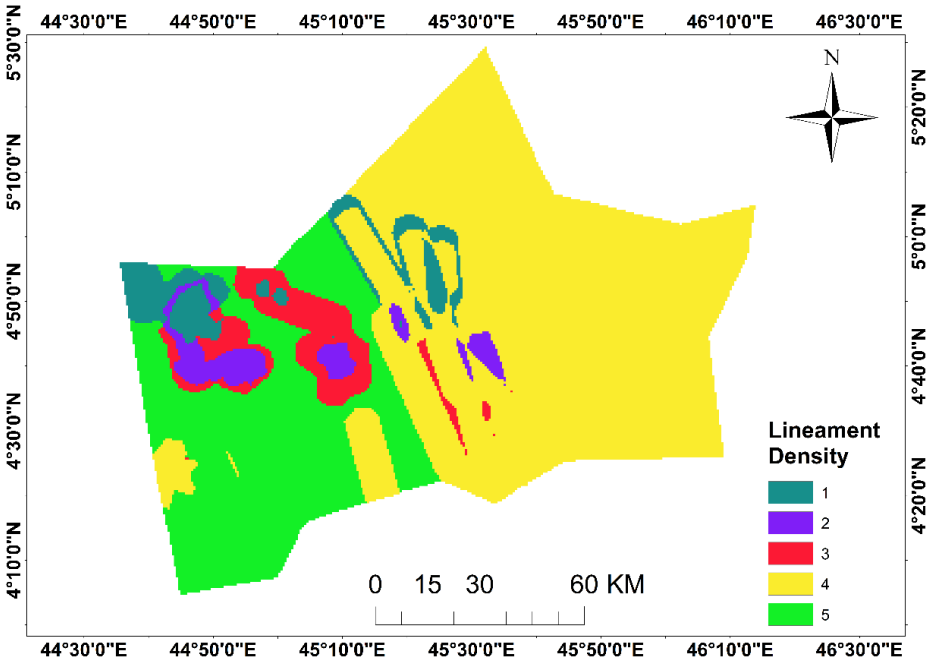


Figure 5: Lineament Map

4.4 Soil Type

Soil texture affects infiltration and groundwater recharge (Ibrahim-Bathis & Ahmed, 2016; Singh et al., 2013). In the soil layer (Figure 6), sandy and loamy soils were treated as more favorable because they typically permit greater infiltration, while clay-rich soils received lower suitability scores. Local soil condition, land cover, compaction, and flood sedimentation should be verified before the map is used to plan recharge interventions.

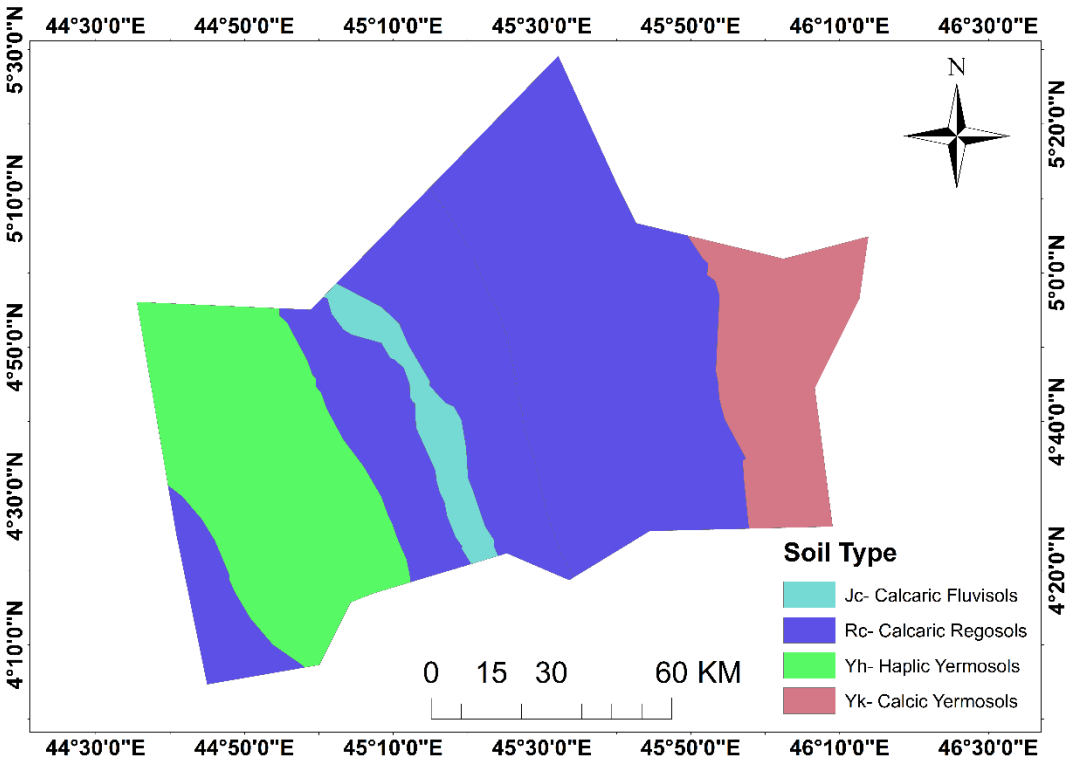


Figure 6: Soil Map

4.5 Slope

Slope affects runoff velocity, erosion, retention time, and infiltration. Gentle slopes (Figure 7) generally favor infiltration and were assigned higher groundwater-potential scores, while steeper slopes were assigned lower scores because they promote rapid runoff (Singh et al., 2013). The slope layer should be interpreted with drainage, soil, and land-use information when identifying recharge or conservation sites.

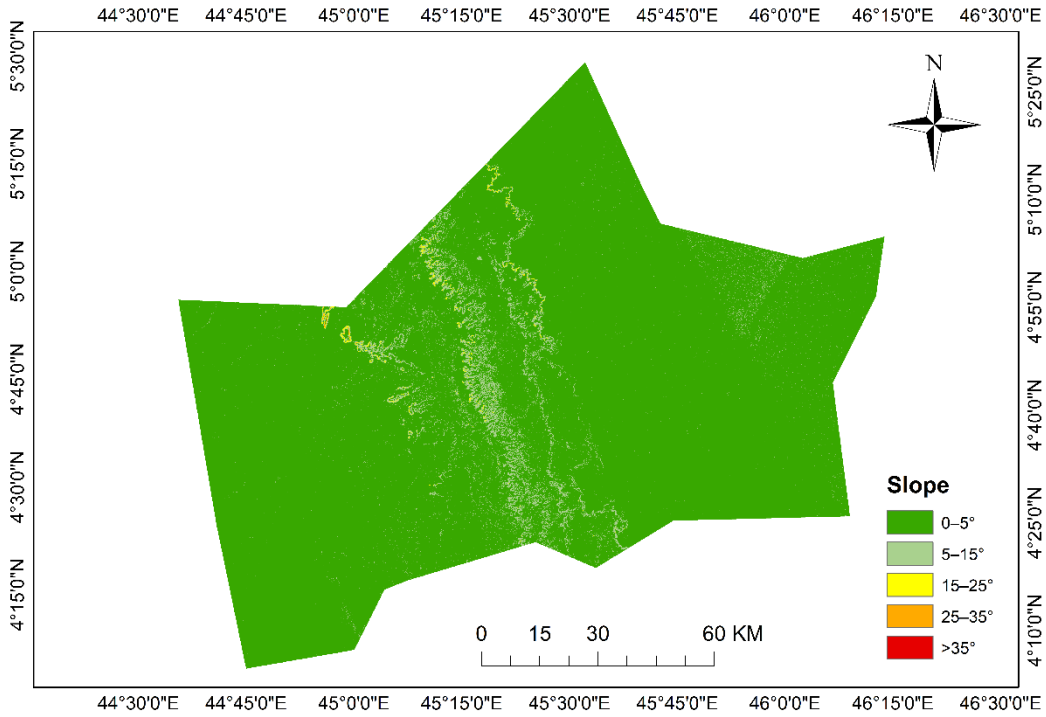


Figure 7: Slope Map7

4.6 Rainfall

Rainfall is the principal input to natural recharge and received the largest AHP weight in this study (Al-Areeq et al., 2022). Spatial rainfall variation (Figure 8) was used to identify areas with comparatively favorable recharge conditions. Because recharge also depends on evapotranspiration, runoff, soil moisture, land cover, and aquifer properties, rainfall should not be interpreted as recharge without supporting hydrological analysis.

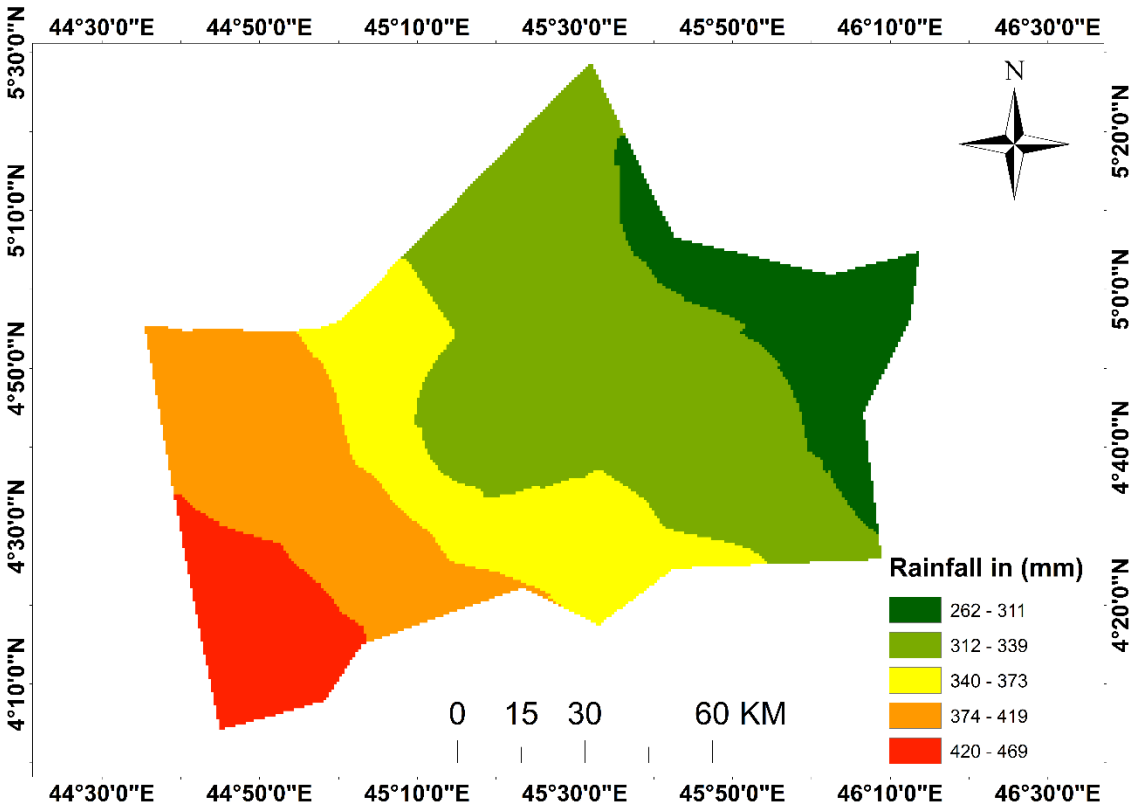


Figure 8: Rainfall Map

4.7 Groundwater Potential Zones

The weighted-overlay model classified the study area into very low, low, high, and very high groundwater-potential zones (Figure 9). Table 6 shows that 36.52% of the area was classified as high potential and 19.30% as very high potential, while 42.84% was classified as low potential and 1.34% as very low potential. Figure 10 compares the mapped classes with the documented borehole and dug-well locations listed in Table 7. This overlay provides a spatial plausibility check but is not a quantitative validation of predictive accuracy.

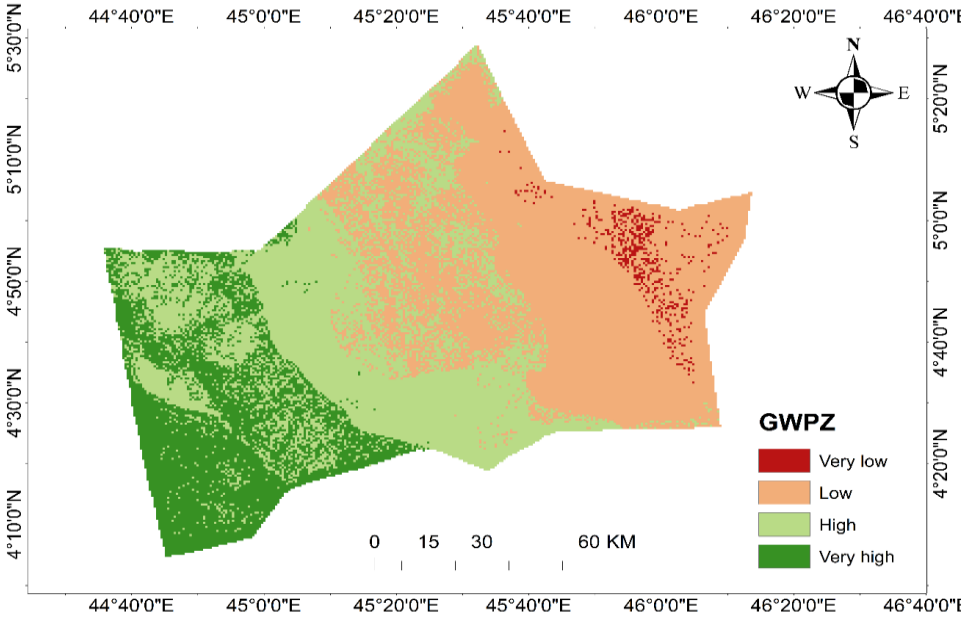


Figure 9: Groundwater Potential Map

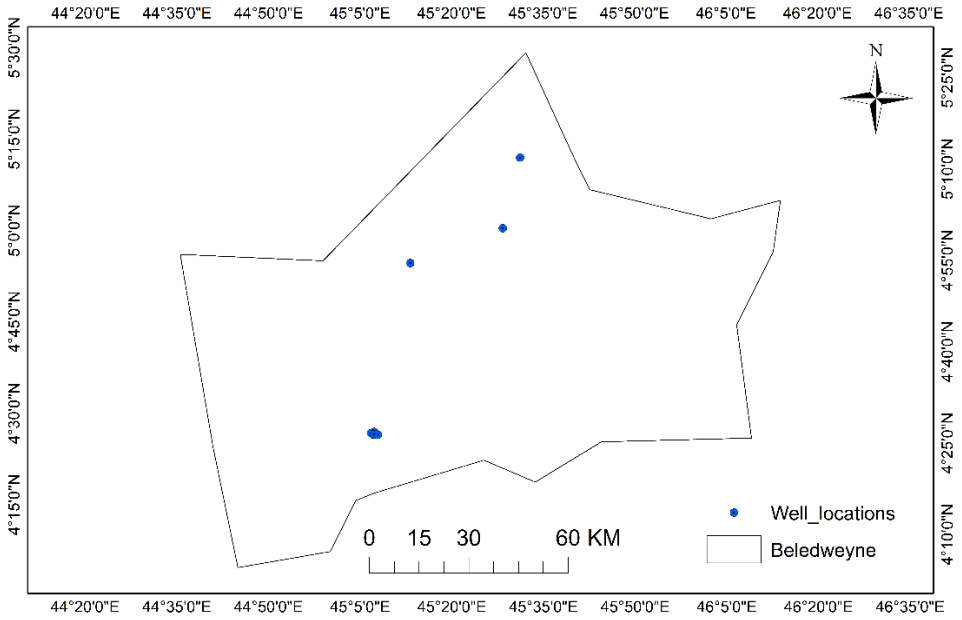


Figure 10: Spatial Distribution of Boreholes and Dug Wells Used for Groundwater-Potential Validation in Beledweyne District, Somalia

Table 6. Groundwater Potential Zones

Sr. No.	Potential Zone	Percentage
1	Very Low	1.34%
2	Low	42.84%
3	High	36.52%
4	Very High	19.30%

Table 7. Groundwater-Validation Wells in Beledweyne District. Source: FAO SWALIM (2026), Somalia Water Sources Information Management System, https://swims.faoswalim.org/

Well ID	Source type	Well name	Settlement	Latitude (°N)	Longitude (°E)
7078	Borehole	Not reported	Not reported	5.0062580	45.4727310
7105	Borehole	Not reported	Not reported	5.1996470	45.5202960
8335	Borehole	Not reported	Not reported	4.9111314	45.2204378
7428	Dug well	Jaaburi	Xaawataako	4.4419000	45.1223000
7693	Dug well	Waadi	Bulada	4.4490000	45.1217000
7695	Dug well	Towfiq 1	Xaafada Afaraad	4.4458000	45.1130000
7701	Dug well	Sagal	Siigalow	4.4416000	45.1212000
7703	Dug well	Cisman Cagey	Buloyacqub	4.4410000	45.1317000
7707	Dug well	Farah Gedi	Howlwadaag	4.4410000	45.1317000
7712	Dug well	Malele	Kooshin	4.4410000	45.1212000
7717	Dug well	Ahmed Cadar	Xaawataako	4.4460000	45.1239000
7718	Dug well	Beder Water Supply	Buloyacqub	4.4410000	45.1317000
7722	Dug well	Tawakal	Kooshin	4.4422000	45.1214000

5. Conclusion

This study used GIS, remote sensing, and AHP to delineate groundwater-potential zones in Beledweyne, Somalia. Six thematic layers—rainfall, geology, slope, drainage density, lineament density, and soil type—were integrated through a weighted-overlay model. The model classified 36.52% of the study area as high potential and 19.30% as very high potential. These zones provide priority areas for field investigation and may support borehole siting, managed recharge, and water-resource planning. They do not, however, confirm aquifer yield, sustainable abstraction, or water quality.

Local authorities and water managers can use the map as an initial screening tool alongside hydrogeological surveys, pumping tests, groundwater-level monitoring, and water-quality

analysis. Decisions should also account for flood exposure, contamination risk, community demand, and environmental safeguards.

Future research should report complete data provenance and model parameters, test sensitivity to alternative weights, quantify validation against well yield or groundwater depth, and incorporate aquifer thickness, recharge, land use, evapotranspiration, and water-quality information.

Ethics Approval and Informed Consent

This study analyzed geospatial and environmental data and did not collect personal data from human participants; human-participant ethics approval and informed consent were therefore not applicable.

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None

Conflict of Interest

The authors confirm that there is no conflict of interest related to the manuscript.

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