

Article

Advanced Hydro-Geospatial Modeling for Groundwater Potential Zoning in the Baro River Watershed: Geographic Information System and Remote Sensing Approach

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Abstract

Groundwater is vital for ecosystems and livelihoods in sub-Saharan Africa, particularly in Ethiopia, dubbed the “water tower of Africa.” Despite its significance, many areas face water scarcity due to data scarcity and an uneven distribution of resources. The Baro River watershed, covering over 23,000 km² in Southwestern Ethiopia, poses a critical study area that has been largely overlooked. A hydro-geospatial modeling framework, utilizing remote sensing (RS), Geographic Information Systems (GIS), and Multi-Criteria Decision Analysis (MCDA) via the Analytical Hierarchy Process (AHP), was employed to map Groundwater Potential Zones (GWPZ) across the region. Nine environmental parameters were assessed for their impact on groundwater recharge, with rainfall as the primary influencer. The analysis involved reclassifying and weighting each factor, yielding a Consistency Ratio (CR) of 0.067, well below the acceptable threshold of <0.10, indicating reliable results. The resulting groundwater potential map classified zones into five categories: very high, high, moderate, low, and very low potential. High-potential zones are predominantly located in the Gambella lowlands, benefiting from favorable groundwater infiltration conditions in fractured volcanic and alluvial deposits. In contrast, low-potential areas correspond to steep slopes with dense drainage. The findings reveal significant groundwater development opportunities, with over 90% of the watershed exhibiting moderate to very high potential, suggesting effective water management strategies through the integration of GIS and AHP for enhanced groundwater evaluation.

Keywords: AHP; Baro river watershed; GRASS GIS; groundwater potential zone; MCDA; remote sensing



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1. Introduction

Groundwater is one of the most important and dynamic natural freshwater resources for sustaining ecosystems and serving as a significant buffer against the variability of surface water due to climate change [1–3]. Population growth, industrialization, and episodic droughts have led to higher demands for groundwater in various worldwide areas [4,5]. In sub-Saharan Africa, in countries with little surface water infrastructure, groundwater is the primary source of residential water supply consumption and irrigation demands [6–8]. Furthermore, the non-uniform distribution of groundwater resources is controlled by complex geomorphic, anthropogenic, and climatic interactions [9,10].

Ethiopia, often referred to as the “Water Tower of Africa,” has an abundance of surface water but is experiencing localized water scarcity [11,12]. Groundwater occurs in diverse

geological settings across the country, such as high-elevation volcanic plateaus and low-lying sedimentary basins [13–15]. However, recent studies suggest that to be climate resilient, basin authorities such as the Upper Blue Nile basin, Omo-Gibe basin, and Awash basin are increasingly shifting from surface water to groundwater-based projects [16–18]. Even though the Baro River watershed is a large-scale watershed, its subsurface potential is mostly unreported and understudied despite these consequences [19].

The interplay of surface runoff and groundwater affects aquatic ecosystems and resource availability in sub-Saharan catchments, informing management strategies [20]. The Baro River watershed covers approximately 23,000 km² in the southwest Ethiopian highlands and is of great hydrological importance. It is a large tributary of the Nile system that has a substantial annual rainfall (1200–2200 mm/yr.) and flows into the alluvial plains of the Gambella region from broken volcanic mountains [1,21]. Although the surface water is abundant, the regional groundwater potential remains poorly understood. The application of conventional hydrogeological methods such as exploratory drilling and geophysical sounding (VES) is challenging, costly, and time-consuming in large and complex terrains [22,23].

Hydro-geospatial modeling has emerged as an effective and cost-saving solution to address these challenges [24,25]. Groundwater potential zones (GWPZ) can be delineated by integrating the latest version of Geographic Information Systems (GIS) and remote sensing (RS) [2,3,8,9,17–19,24]. Delineating GWPZ requires consideration of several issues, including the balancing of various conditioning factors [3,10,26,27]. The Analytic Hierarchy Process (AHP) is a subcategory of Multi-Criteria Decision Analysis (MCDA) [10,26,28,29], which is the best method for this. Recent advances in hydrological modeling and GIS land-use analysis reveal that integrating thematic layers is effective for exploring subsurface potential in various landscapes [30]. However, applying these multi-criteria geospatial overlay methods in sub-Saharan Africa faces major challenges, including limited hydrogeological monitoring networks, low thematic spatial resolutions, and subjective parameter weighting in AHP pairwise comparisons [5,7,13].

Previous studies in Ethiopian catchments typically employed six or seven groundwater conditioning factors in conventional hydro-geospatial modeling [2,11,14,25]. This study advances the methodology by integrating nine important parameters that were shown to be relevant in the hydrological aspects: lithology, slope, lineament density, land use/land cover (LULC), curvature, rainfall, geology, soil, Topographic Wetness Index (TWI), and drainage density. These factors collectively determine the natural water retention capacity of the watershed, which influences groundwater infiltration, storage, and long-term aquifer sustainability [31]. Primary and secondary porosity and the rate of runoff vs. infiltration controlled by slope and TWI were represented by lineament density and lithology [15,32]. This study explores localized secondary porosity in fractured volcanic formations, emphasizing cross-layer structural analysis between lithology and lineament density, a factor often neglected by traditional models. To enhance groundwater potential zonation in data-scarce regions, it employs single-parameter sensitivity analysis, hydrological literature, and SWAT+ modeling cross-validation, with a GIS-MCDA technique designed for the Baro River watershed. The research differentiates between recharge and storage mechanisms in primary and secondary porosity, offering valuable insights for data-poor basins in sub-Saharan Africa. Its aim is to identify groundwater potential zones using a hydro-geospatial modeling approach, leveraging Geographic Information Systems (GIS) and remote sensing (RS) to synthesize environmental variables, particularly through open-source software like GRASS GIS 8.4.0.

On the terrestrial water balance, the main hydraulic input is rainfall, while the water availability in soil moisture and in deep infiltration is strongly linked with the actual evapotranspiration [33]. High near-surface evaporation loss in arid and semiarid environments [34,35], low recharge potential due to high evapotranspiration, and shallow water table conditions that do not allow for groundwater recharge and may result in overestimation of recharge if not included [33,36]. The water balance between runoff and evapotranspiration and between evapotranspiration and precipitation depends on properties of the land surface, which are coupled to the climatic forcing by atmospheric demand and precipitation. Hence, incorporating the climate outputs with land surface characteristics is required to minimize the error in water balance estimation for groundwater potential and recharge studies [37]. In the absence of comprehensive drill data, the work used a multi-step theoretical validation approach to ensure consistency of GWPZ. A statistical sensitivity analysis is given to test the stability of the model and the effect of every environmental theme layer on the final results by carefully omitting some distinct theme layers as provided by [5,27,38]. Second, to verify regional alignment and provide a solid scientific foundation for groundwater management without the need for conventional well-depth measurements, the results were finally compared with earlier research by [19], a geophysical survey in the Baro-Akobo-Sobat Basin.

The study aims to develop a high-resolution hydro-geospatial modeling framework for groundwater potential zoning for the Baro River watershed, which has been previously understudied using remote sensing-derived datasets, GRASS GIS, and the Analytical Hierarchy Process (AHP). The main contributions of this study include: (i) integrating nine groundwater conditioning factors; (ii) analyzing groundwater recharge and storage while distinguishing between alluvial and fractured volcanic aquifers; (iii) utilizing open-source GIS workflows; and (iv) validating results through sensitivity analysis, hydrological literature, and SWAT+ groundwater modeling.

2. Materials and Methods

The writers used artificial intelligence in this work solely for graphical merging of several author-generated graphs or images, not for data generation, gathering, analysis, or interpretation.

2.1. Baro River Watershed Regional Settings

2.1.1. Physiography and Hypsometry

The Baro River catchment is a big tributary of the Sobat-White Nile system, and it is located in southwest Ethiopia. The area is approximately more than 23,000 km² in the river basin (Figure 1) [19,39,40]. The regional hydraulic potential is related to the hypsometric gradient. In groundwater recharge modeling, the topographic slope (β) is determined by the slope of the digital elevation model (DEM) in both the x and y directions [19].

The steep slopes of the highlands accelerate surface runoff, and the lowland areas increase surface residence time (T_r), promoting deep percolation into the saturated zones [41]. To differentiate between low-velocity and high-velocity runoff, high-resolution data is needed to identify the discontinuity features in the topography [15].

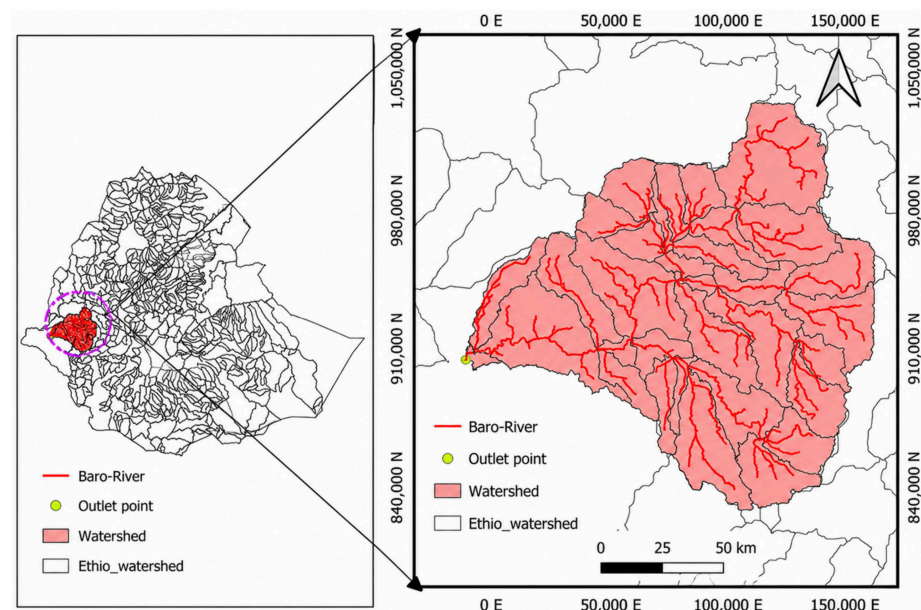


Figure 1. Baro River watershed study area map.

2.1.2. Hydrology and Drainage Network

The drainage system is influenced by tributaries of the Baro River watershed, including the Birbir, Geba, and Sor rivers [1,39,40,42]. After displaying a discrete dendritic system in the upper regime of the watershed, the drainage systems in the alluvial plains (lowlands of the watershed) changed to meandering forms, which are indicative of consistent resistance in the volcanic bedrock [2,4,43–45]. Parameters used to assess the hydrological efficiency of a watershed are: drainage density (D_d) is calculated by stream length/total area (Equation (1)) [10,26].

$$D_d = \frac{\sum_{i=1}^n L_i}{A} \quad (1)$$

where L is stream length, and A is area (23,000 km²). The prioritized area (low drainage density) in the approach to modeling indicates high surface permeability and infiltration potential [2]. Contrary to this, the dissected highlands of the Baro River watershed have high drainage density values, caused by the high runoff coefficient and impermeable surface of dense drainage networks [14].

2.1.3. Comparison of Geology and Land Use/Land Cover

Geology: The Baro River watershed comprises three distinct hydrogeological units described in Figure 2.

Basement rocks (Precambrian age) (Ranked 1–2): The origin of the Precambrian basement rocks with insignificant primary porosity is represented by the localized outcrops; the groundwater is constrained to the localized fracture zones and worn mantles [39,40,42].

Tertiary volcanic (Ranked 3–4): Mainly rhyolites and basalts in the highlands of the watershed, lacking substantial primary inter-granular porosity. Groundwater storage in the subsurface is controlled by secondary porosity (faults, joints, and vesicles). Accordingly, in the vertical recharge setting, these fractures at the surface appear as lineaments [4,22,24].

Quaternary alluvial deposits (Ranked 5) are unconsolidated sediments with considerable primary porosity that are present in Gambella's lowlands with high hydraulic permeability and significant sedimentary thickness, making them high-productive aquifer zones [39,40].

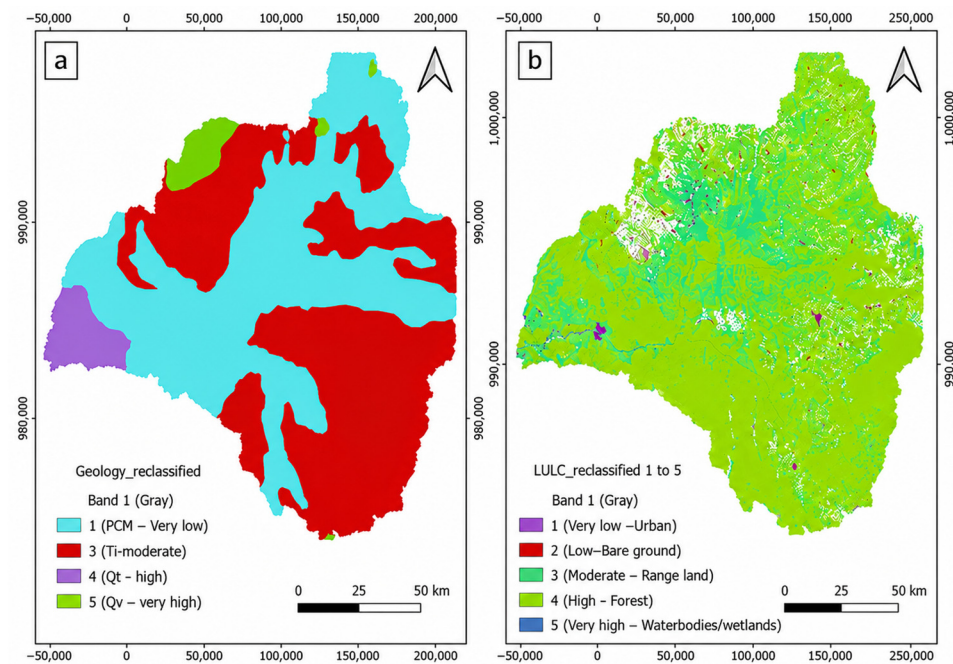


Figure 2. Comparison of (a) geology and (b) land use/land cover.

Land use/land cover (LULC): Dynamically controls surface hydraulic roughness, evaporation demand, and runoff attenuation [46,47] across the Baro River watershed. In Figure 2 and Table 1, which were obtained from ESRI Sentinel-2 high resolution (30 m), the watershed was divided into six land cover zones.

Table 1. LULC classifications of the Baro River watershed.

Category	Spatial Area (km ²)	Area Coverage (%)	Roughness & Infiltration	Influence on Evapotranspiration (ET) & Runoff	Rank (Ri)
Wetlands	1840	8	Very high moisture retention; slow percolation.	High local AET; acts as regional discharge/recharge sink.	5
Dense Forest	6670	29	High canopy interception; deep root-channel macro-porosity.	High transpiration; suppresses flash surface runoff.	4
GRASS	4830	21	Moderate roughness; uniform soil cover.	Moderate ET; balanced runoff and infiltration.	3
Cultivated Land	8280	36	Variable surface roughness; moderate infiltration capacity.	Seasonal ET dynamics; moderate-to-high runoff potential.	3
Bare Ground	230	1.00	Low hydraulic roughness; soil crusting promotes runoff.	Low ET; minimal infiltration allowance.	2
Impervious	160	0.70	Extremely low permeability; high artificial imperviousness.	Negligible ET; maximizes urban surface runoff generation.	1

2.2. Data Type and Collection

The reliability of hydro-geospatial modeling for the assessment of groundwater potential zones (GWPZ) in data-scarce areas such as the Baro watershed necessitates the integration of high resolutions and several sources of remote sensing products [48,49]. The study watershed's (23,000 km²) topography, pedologic, spectral, and climatic variations were recorded using a multisensory inventory. To improve computational accuracy and

consistency, all layers were projected using EPSG: 32637-WGS84/UTM ZONE 37 and harmonized at 30 m resolution.

2.2.1. Topographic Data

Topography is an important element of the hydrological cycle, and it regulates the flow between the rapid runoff and infiltration processes. The terrain data were high-resolution (30 m) data that were provided by the OpenTopography webpage. The GRASS algorithm (r.fill.dir) was used to preprocess the raw Digital Elevation Model (DEM) data in QGIS by removing false spikes and filling sinks to ensure a hydrologically reasonable surface [50].

A projected 30 m DEM was used to extract several GWPZ factors, including:

Slope gradient (β): The velocity of surface runoff is directly related to slope. Lower slopes will enable the water to remain on the surface for longer periods of time, an aspect that will promote the process of infiltration [51].

Topographic Wetness Index (TWI): After sinks were filled and the DEM's flow directions were determined, the Topographic Wetness Index was computed to determine the local topography-based locations where water prefers to accumulate (Equation (2)).

$$TWI = \ln\left(\frac{\alpha}{\tan\beta}\right) \quad (2)$$

where α is the local upslope contributing area /contour length, and β is the slope angle.

Curvature: Flow across the surface is accelerated and decelerated using the r.slope.aspect GRASS module from the DEM curvature calculation.

Lineament density (L_d): The lineament density, which represents structural weakness (fractures/faults) used for principal conduits for groundwater transport, was successfully calculated using line density from the GRASS module [52]. Computed using Equation (3) below:

$$L_d = \frac{\sum L_{lin}}{A} \quad (3)$$

where $\sum L_{lin}$ is the total length of identified lineaments (cumulative sum of length of all mapped).

2.2.2. Lithology and Land Use/Land Cover Data

To determine the Groundwater Protection Zone (GWPZ) for the study area, surface properties, including land use and land cover (LULC), were integrated with subsurface geological properties through modeling. This integration utilized vector-based geographical data alongside high-resolution land cover images. The combination of high-resolution land cover imagery and vector-based geological data enabled the modeling of both subsurface and surface properties in the research area, which were essential for defining the GWPZ.

Geology: Structural and lithological information from Ethiopia-Geoportal was utilized to assess the hydrogeological potential of the watershed. This assessment involved defining primary permeability and aquifer storage capacity, thereby characterizing the region's water resource potential effectively [6].

LULC: The land use and land cover data from existing remote sensing-derived products-ESRI Sentinel-2 were publicly available to provide data on the land use and land cover, which affects the surface hydraulic roughness and the tendency to evapotranspiration [46]. The study used the LULC data as an input for one of the nine thematic groundwater conditioning factors for groundwater potential zoning; reclassification was made by QGIS after downloading the data from the sources.

2.2.3. Soil and Climate Data

The recharge input of the system was determined based on the distribution of rainfall across the region by CHIRPS (<https://www.chc.ucsb.edu/data/chirps> (accessed on 15 January 2026)) and the physical properties of the soil by FAO.

Soil: FAO had a shapefile containing soil data. Soil texture and drainage class parameters were used to calculate the surface interface's infiltration capacity (<https://www.fao.org/soils-portal> (accessed on 15 January 2026)).

Rainfall is the primary source of groundwater recharge, as determined by Climate Hazards Group Infrared Precipitation with Station data (CHIRPS). The mean annual rainfall was computed using data from 12 gridded meteorological stations (Gambella, Bure, Uka, Yibdo, Dembidolo, Mettu, Shebel, Guliso, Simbo, etc.) in the delineated study area. Inverse Distance Weighting (IDW) interpolation techniques were used to compute aerial precipitation [47].

To account for the impact of evapotranspiration, the precipitation input from the macroclimatic model was combined with the characteristics of land use/land cover in data-scarce areas, using Multi-Criteria Decision Analysis (MCDA) [53,54]. High-resolution surface hydraulic properties and localized transpiration demands from the LULC layer from ESRI Sentinel-2. High-density vegetation and wetlands have high actual evapotranspiration (AET) and reduce water infiltration to deep aquifers [55]. When the weightage of the land use land cover parameter with high evapotranspiration is reduced, the model achieves a significant balance between gross precipitation input and atmospheric loss to the system [53,54]. The data type, sources and characteristics of datasets used in this study are summarized in Table 2.

Table 2. Summarized data type and sources.

Data Category/Type	Specific Layer	Primary Sources	Access URL/Portal
Land cover	LULC	ESRI Sentinel-2	https://livingatlas.arcgis.com/landcover/ (accessed on 15 January 2026)
Elevation	DEM	OpenTopography/ALOS PALSAR/	https://opentopography.org/ (accessed on 15 January 2026)
Geological	Lithology, Lineament density	EthiGeoportal	https://ethiopia.africageoportal.com/ (accessed on 15 January 2026)
Pedological	Soil texture, type	FAO	https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/ (accessed on 15 January 2026)
Climatic	Mean annual rainfall	CHIRPS	https://www.chc.ucsb.edu/data/chirps (accessed on 15 January 2026)

2.3. Geospatial Resources Analysis Support System (GRASS) GIS

The hydro-geospatial modeling in the Baro River watershed has been performed by the GRASS GIS 8.x (Geospatial Resources Analysis Support System) environment. It can be used with more flexibility than traditional GIS applications with GUIs, such as ArcGIS 10.7 [50], due to its open-source modular structure, high accuracy of the raster engine even for very large watershed discretization, and good ability to process topological data structures.

Groundwater potential zones need to be modeled to achieve proper hydrological characterization of the study area, which involves applying proper processing lines or techniques to convert basic topography data into important hydrological factors or predictors [5,17,24]. The workflow started with using the *r.fill.dir* GRASS module to remove

the sinks in order to create a hydrologically consistent surface. The groundwater recharge zones were then identified (or located) to calculate the flow accumulations and drainage networks using the *r.watershed* module. Additionally, the *r.slope.aspect* module in GRASS was used to govern surface residence time (a gentle slope offers vertical percolation), where the local evapotranspiration and soil moisture retention are influenced by aspects, in order to comprehend the infiltration potential of the study area's slope gradient (β). Using a combination of these output results, in particular the upslope contributing area (α) of *r.watershed* and slope gradient of *r.slope.aspect*, one can compute the Topographic Wetness Index (TWI) in order to map or define the spatial distributions of potential zones and groundwater vulnerability throughout the study area watershed [49,50,56].

2.4. Multiple Criteria Decision Analysis (MCDA)

This interaction among climate, geology, topography, soil, and LULC governs the complexity of groundwater occurrence in the study area and needs multiple decision-making frameworks. The Analytical Hierarchy Process (AHP) was used to weigh and incorporate several environmental factors into a single potential map.

2.4.1. Development of Factor Architecture

Based on the impact of recharge, storage, and transitions, this study identified nine environmental primary variable elements that were identified from Ethiopian highlands literature (usually utilizing 6 to 7 factors only) [1,2,9,11,14,15,40,57]. Each of these was considered as a theme rating (1–5) from very low to very high potential by the authors of QGIS (GRASS). The following features were used: rainfall (orographic effects) [22,58], lithology (geology) (defines aquifer storage capacity and hydraulic conductivity) [32,58], lineament density (structural conduits, fractures, and faults) [57,59], slope (control infiltration to runoff ratio) [7], drainage density (inverse indicator of permeability) [2], soil texture (infiltration rate and soil atmosphere interface) [15], Topographic Wetness Index (TWI—quantifies topographic controls) [38], curvature (decelerate flow and concentrate flows) were used. Although water retention capacity was not treated as a separate groundwater conditioning factor, it is implicitly represented through the integrated effects of slope, geology, land use/land cover, drainage density, and topographic characteristics used in the GIS-AHP framework [8,60].

Analytic Hierarchy Process (AHP) was chosen for the study due to its systematic approach in integrating various thematic parameters with distinct physical characteristics [28,61]. This method is commonly employed in groundwater potential mapping, facilitating the inclusion of expert insights via pairwise comparisons. The Consistency Ratio (CR) promotes objective consistency, enhancing the accuracy of factor weighting and comparisons. A CR of 0.067 confirms that subjective judgment in pairwise comparisons is minimized.

2.4.2. Analytic Hierarchy Process (AHP) and Consistency Verification

The AHP approach, developed by [28,61], was used to assign the relative weight of these nine criteria by using the Pairwise Comparison Matrix (A). Each component was compared with each other, and the comparison was made on a scale of 1 to 9, in which 1 is equal importance, and 9 is extreme importance [28]. To ascertain the impact of the nine environmental elements, four condensed steps of the AHP approach were used.

Because of the variation among individual geological formations, the technique used in the study is a cross-section between lineament density layers (used as one of the groundwater conditioning factors to represent structural discontinuities) and lithology layers as opposed to assuming each formation was homogeneous. In fractured zones, for instance, another volcanic (Tertiary) layer was given a rank of 4 due to its secondary porosity and

infiltration rate characteristics, whereas in an un-fractured zone it was given a lower rank. This method suggests that it is capable of representing localized structural deformations and has a strong representation of aquifers.

Step 1: Pairwise Comparison Matrix (A): The reciprocal matrix is compared to scales developed by [28] and can be calculated using Equation (4) (Table 3) below.

$$\alpha_{ij} = \frac{1}{\alpha_{ji}} \quad (4)$$

LULC had a lower weight in the analysis, although it impacts recharge via infiltration and evapotranspiration. However, its regional influence is deemed less significant compared to factors such as rainfall, geology, lineament density, and slope gradient, as supported by AHP weights from expert comparisons and prior studies.

Step 2: Normalization and weight computation (W): The matrix was normalized by dividing each cell by the total of the columns, and the relative weights (W_i) were obtained by averaging the rows of the normalized matrix (Equation (5)) (Table 4).

$$\bar{a}_{ij} = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}} \text{ and } w_i = \frac{\sum_{j=1}^n \bar{a}_{ij}}{n} \quad (5)$$

Step 3: Consistency verification (CR): To assess the judging reliability, the Consistency Ratio (CR) was computed. A valid model is shown by $CR < 0.10$ (Table 4) (Equation (6)).

$$CI = \frac{\lambda_{max} - n}{n - 1} \text{ and } CR = \frac{CI}{RI} \quad (6)$$

where $n = 9$ and $RI = 1.49$.

Table 3. Pairwise Comparison Matrix.

Factor	R	G	L	S	D	So	Lu	T	C
Rainfall (R)	1	2	3	4	5	6	7	8	9
Geology (G)	1/2	1	2	3	4	5	6	7	8
Lineament (L)	1/3	1/2	1	2	3	4	5	6	7
Slope (S)	1/4	1/3	1/2	1	2	3	4	5	6
Drainage (D)	1/5	1/4	1/3	1/2	1	2	3	4	5
Soil (So)	1/6	1/5	1/4	1/3	1/2	1	2	3	4
LULC (Lu)	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3
TWI (T)	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2
Curvature (C)	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1

Table 4. Normalized matrix, weights, and consistency analysis.

Factor	R	G	L	S	D	So	Lu	T	C	Weight (Wi)
Rainfall	0.35	0.43	0.41	0.36	0.31	0.28	0.24	0.21	0.2	0.31
Geology	0.18	0.21	0.27	0.27	0.25	0.23	0.21	0.19	0.18	0.25
Lineament	0.12	0.11	0.14	0.18	0.19	0.18	0.17	0.16	0.16	0.16
Slope	0.09	0.07	0.07	0.09	0.12	0.14	0.14	0.14	0.13	0.11
Drainage	0.07	0.05	0.05	0.04	0.06	0.09	0.1	0.11	0.11	0.08
Soil	0.06	0.04	0.03	0.03	0.03	0.05	0.07	0.08	0.09	0.05
LULC	0.05	0.04	0.03	0.02	0.02	0.02	0.03	0.05	0.07	0.04
TWI	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.04	0.02
Curvature	0.04	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.01
Parameters	$\lambda_{max} = 9.78$		CI = 0.097		RI = 1.45		CR = 0.067		Valid	

2.4.3. Statistical Sensitivity Analysis Framework (SSAF)

The study explored hydro-spatial modeling and assessed the impact of groundwater conditioning factors on a final groundwater index through single-parameter map removal sensitivity analysis. The variation index (S_i) [62] for each parameter was calculated using Equation (7), focusing on the output map's changes with the removal of specific thematic layers from the MCDA.

$$S_i = \left| \frac{\frac{GWPZ}{N} - \frac{GWPZ'}{N}}{GWPZ} \right| \times 100 \quad (7)$$

where S_i is the variation index (%) resulting from the removal of thematic layer i , $GWPZ$ is the groundwater potential index obtained from $N = 9$ parameters, and $GWPZ'$ is the updated groundwater potential index obtained from $N = 8$ parameters.

2.5. Overlay Analysis and Raster Algebra

Using raster calculators in the GRASS GIS module (*r.mapcal*), which enable sophisticated, pixel-based map algebra, the $GWPZ$ was synthesized via Weighted Linear Combinations (WLC) (Equation (8)) as the final approach to modeling the hydro-geospatial characteristics of the research area. Because it is effective at preserving the statistical subtleties of the AHP weights throughout the whole study area and capable of performing floating-point operations with high accuracy, this module is preferable to basic overlay tools [28,61].

$$GWPZ = \sum_{i=1}^n (W_i \times R_i) \quad (8)$$

where $GWPZ$ is the final groundwater potential index for each cell, W_i is the relative weight of factor i , and R_i is the reclassified rating of factor i .

3. Results and Discussion

The results of hydro-geospatial modeling provide a thorough spatial synthesis of the nine environmental parameters influencing groundwater potential and occurrence in the Baro River watershed research area. The detailed reclassified thematic layers and their subsequent integrations with the final Groundwater Prospect Zone ($GWPZ$) map will be shown in this part.

3.1. Thematic Factors Reclassifications and Analysis

With scientific insights from various prior findings [2,3,11,25], this section presents the chosen analysis of the nine parameters with rank, area proportions, geographic zoning, and detailed descriptions (Figures 3 and 4 and Table 5). These parameters are integrated by the GRASS GIS environment.

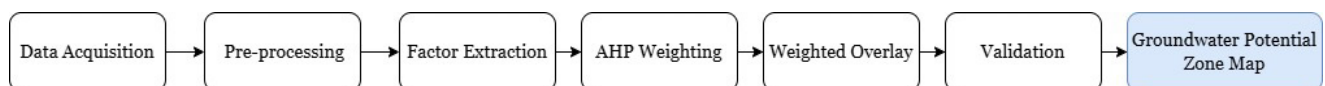


Figure 3. Methodological framework of hydro-spatial modeling of $GWPZ$: Data acquisition, including DEM from OpenTopography, LULC from Sentinel-2, CHIRPS rainfall, and geology/lithology, is outlined. Preprocessing and final mapping utilized GRASS modules (e.g., *r.slope.aspect*, *r.fill.dir*). Thematic weight derivation is conducted using AHP, followed by WLC overlay. Mapping validations used single-parameter sensitivity, hydrogeological literature, and SWAT+ base flow dynamics, all represented in the flow chart.

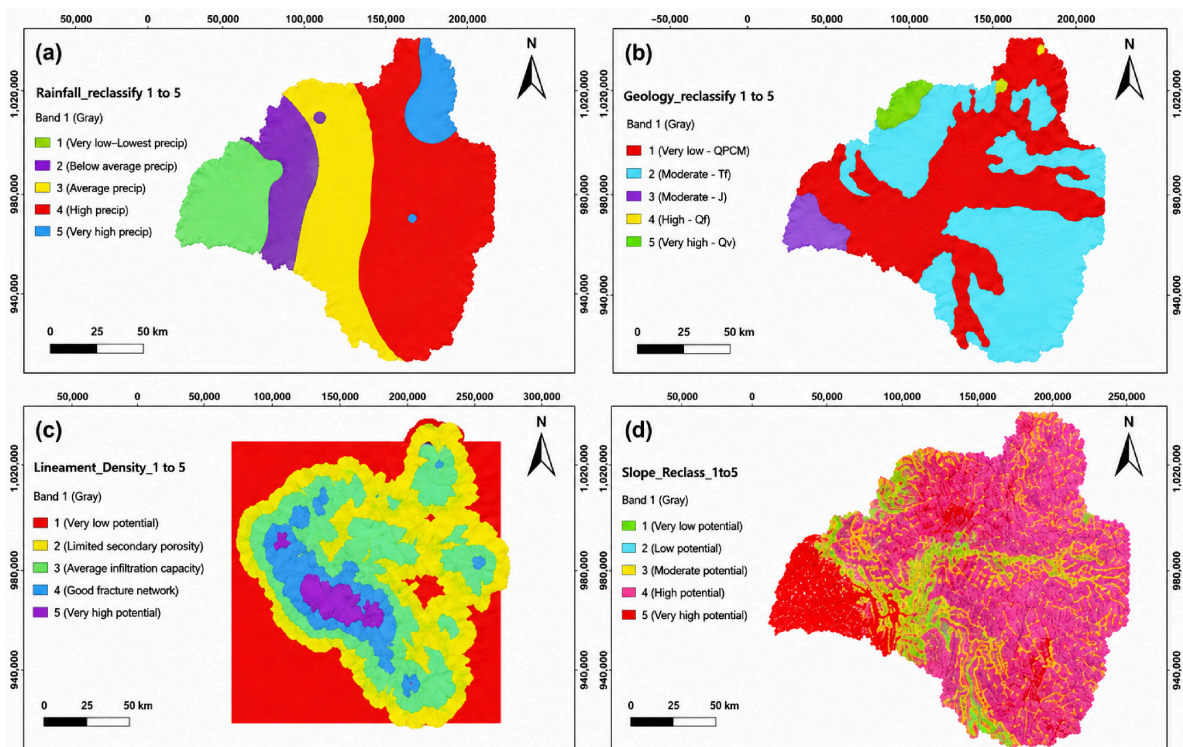


Figure 4. Reclassification and spatial distribution of the main factors: (a) precipitation, (b) geology/lithology, (c) lineament density, and (d) slope (surface).

Table 5. Single-parameter map removal sensitivity analysis summary.

Thematic Layer	Assigned AHP Weight (Wi)	Mean Variation Index (Si, %)	Sensitivity Rank
Rainfall	0.31	2.41	1
Geology (Lithology)	0.25	1.85	2
Lineament Density	0.16	1.22	3
Slope Gradient	0.11	0.94	4
Drainage Density	0.08	0.68	5
Soil Texture	0.05	0.45	6
LULC	0.04	0.38	7
TWI	0.02	0.31	8
Curvature	0.01	0.15	9

Rainfall: Rainfall is a key input for regional hydrology and the main source of ground-water recharge [1,2,14,21,32,45] in the Baro River watershed. The Southeast region has substantial moisture availability, as shown by the mean annual precipitation of the area with notable orographic effects from Figure 3 and Appendix A Table A1. This maximum moisture availability of zoning for deep percolations, which makes up 6.05% of the entire watershed area, was rated at 5 (extremely high). On the other hand, due to high-potential evapotranspiration and restricted infiltration, which account for 13.29% of the total area, the western lowlands of the watershed have the lowest precipitation available, represented by a rank of 1. Rainfall is designated as the primary function for recharging in the AHP model, and its weight is 0.31 (Table 3). This result showed that rainfall plays a significant role in deep percolations, which is consistent with regional water balance analysis by [21], geo-chemical and isotope validation by [1] and recent findings by [44] for hydrological extremes in the Baro-Akobo basins and other basins in Ethiopia, such as Upper Blue Nile (Chemoga watershed) for GWPZ delineation by [2] and drought-prone area analysis by [32].

Vertical recharge from local precipitation is limited by plains in the western part of Gambella [1]. The very high groundwater potential in this low-lying area persists despite the high-potential evapotranspiration. The variations are due to the difference in storage capacity of the quaternary alluvial deposits and the hydrologically active area of high primary porosity in the east and the fractured highland escarpments as a source of groundwater flow regions [1]. Then, the geometry of the basin and the underground geological properties are important modulating factors that protect the aquifer from localized losses by evaporation from the atmosphere [19].

Geology (Lithology): The geological architecture defines the subsurface environment's principal permeability and aquifer storage capacity [13]. Precambrian basement rocks, Tertiary volcanic rocks, and quaternary alluvial deposits (found in river valleys, covering 2.97% of the watershed and ranked as 5 due to their highest permeability and storage capacity due to their unconsolidated nature) make up the complex lithology of the Baro River watershed, which is mapped from Figure 4b and Table A1 (Appendix A). Due to exceptional secondary porosity resulting from fracture networks, 49.82% of the lithology covered by weathered volcanic found in eastern plateaus was graded as 4. Due to their non-porous nature and function as a regional aquitard [19], the remaining 45.2% of the area was made up of enormous bedrocks that were primarily found in eastern highlands and were ranked 1. These results were compared with those of other studies conducted in the Baro River watershed and other river basins in Ethiopia, such as the hydrogeological characterization of the Baro River basins by [1] which revealed that quaternary alluvium is the most prominent unit; other researchers discovered that weathered volcanic and alluvial deposits in the Upper Omo Gibe basins by [11] were prioritized for GWP; and, in the Chemoga River, water lithology is the second significant factor in geospatial and AHP modeling by [2]. Lithology holds 0.25 model weights (Table 4).

Lineament density (L_d): In hard-rock settings, lineaments, structural flaws like faults and fractures, act as the main channels for groundwater movement. The top level, ranked by 5 (tectonic faults with 2.85% of the watershed), offered considerable secondary porosity [22], as shown by the geographical distributions of the lineament density shown in Figure 4c and the characterization of L_d in Table A1 (Appendix A). In total, 7.68% of the watershed has fracture networks that enhance permeability and high-density zones at the highland borders [24,39], which are graded as 4. Compact strata with minimal structural porosity, especially in the western plains (41.72%), were classed as low density [4]. Lineament density has a model weight of 0.16 (Table 4).

Slope: One important factor that establishes the limits between surface runoff and vertical infiltration is slope gradient. The large hypsometric gradient in the research region is seen in Table A1 (Appendix A) below. The Gambella plains, which made up 30.22% of the basins, had a 0–2% slope and a level topography. Because it maximizes the water residence period and promotes deep percolations to saturated zones, this location received a score of 5 (very high). With a rating of 4 (high) and moderate slopes (2–8%), 43.73% of the higher pediments are covered by high infiltration with minimal erosion danger. In the eastern escarpments, more than 35% of the slope, which is categorized as steep slopes and classed as 1, produces fast surface runoff that stops infiltration into subseries. Table 4 shows the weighted topographic slope of 0.11.

Drainage density (D_d): Drainage density is an inverse measure of permeability; a well-developed stream network efficiently removes water as runoff from a high-density area [1,22]. The research area's dissected highlands have a very high drainage density (ranked 1), which replicates the zone of impermeable surfaces that quickly drain water away, as seen in Figure 5 and noted in Table A1 (Appendix A) below. On the other hand, 4.74% of the research area is situated in western lowlands with spatially low drainage

density (ranked 5), making it more water-absorbing than sheds. In total, 51.66% of the research area's internal watershed is covered by the most extensive areas with moderate drainage density [13,63]. The hydrological efficiency of watersheds is determined by these parameters, which have model weights of 0.08.

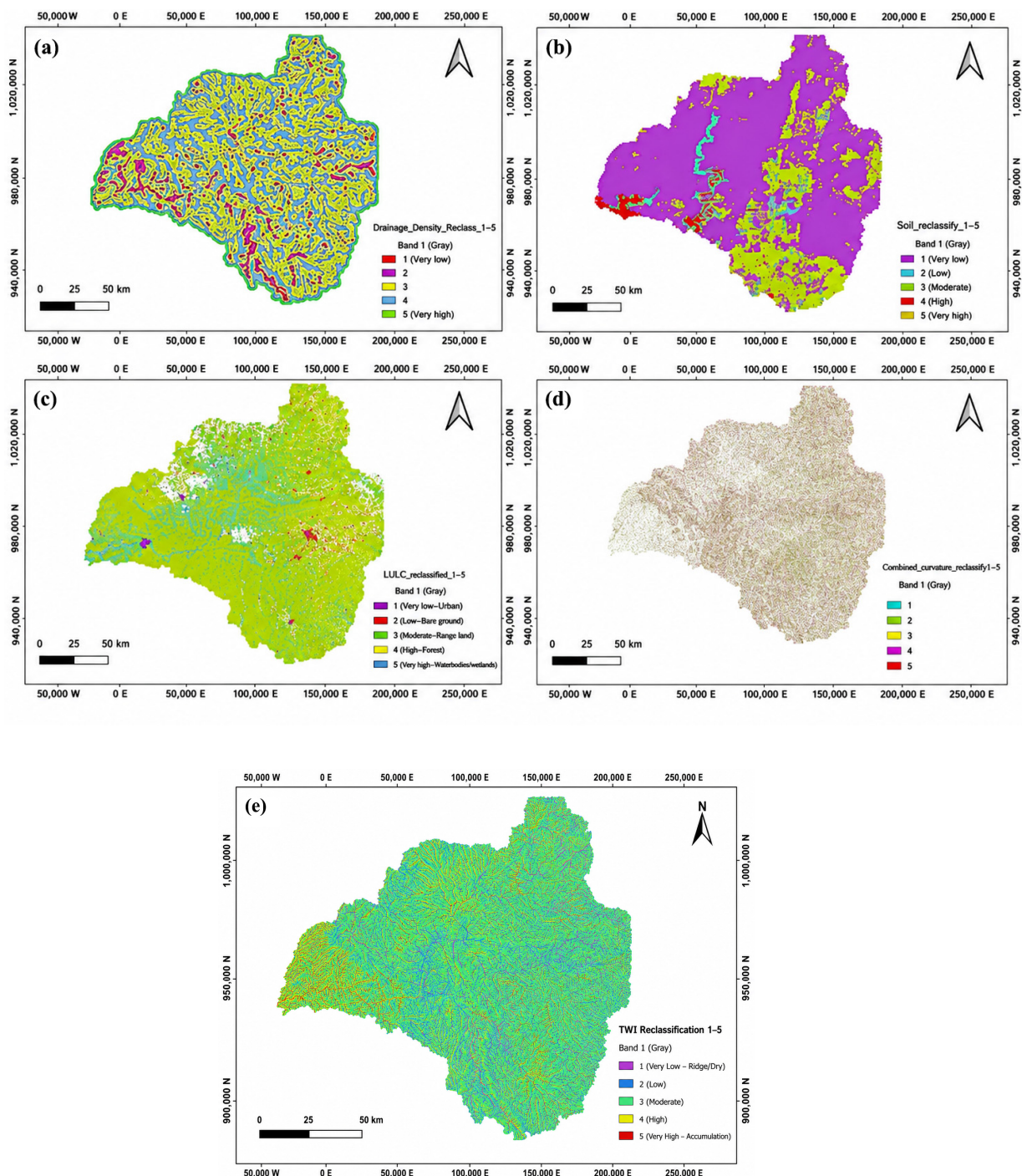


Figure 5. Reclassified raster data layers showing (a) drainage density (b) soil (c) land use/land cover (LULC) (d) curvature and (e) topographic parameters (TWI).

Soil and LULC: Soil texture and land use and land cover (LULC) serve as essential surface regulators for groundwater recharge by regulating infiltration rates and hydraulic roughness throughout the research region. From below, Figure 5b and Table A1 (Appendix A) show that the lowland regions are mostly covered by 30.20% of the area of sandy and alluvial soils (ranked 5), which permit strong hydraulic conductivity, while

ranked 4 (sandy loams) facilitate vertical seepage throughout 43.8% of the pediments. On the other hand, thick clays (ranked 1) at highland peaks prevent infiltration and cause excessive surface runoff. The majority of the land covered by forest and woodland (72.73% of the area, ranked 4) uses root systems to encourage deep percolation, while 1.43% of the land covered by urban areas (ranked 1) forms impermeable surfaces that completely prevent recharge. LULC patterns interact with soil qualities [22,39].

TWI and Curvature: Surface curvature and the Topographic Wetness Index (TWI) enhance the identification of water accumulation zones and flow dynamics. The TWI rank 5, covering 15% of western floodplains, indicates high saturation potential and moisture retention. Figure 5e shows valley bottoms rated 4 and concave depressions rated 5, serving as key points for surface water convergence and recharge. These features indicate significant groundwater prospects through the integration of favorable vegetative cover, soil texture, and concave topography in floodplains and lower pediments.

3.2. Groundwater Potential Zoning (GWPZ)

In complicated African catchments, the integration of WLC with GRASS GIS has demonstrated strong consistency with modern multi-criteria GWPZ mapping frameworks in delineating regional groundwater potential zones [64]. The final GWPZ map was produced by the Weighted Linear Combination (WLC) module using pixel-based raster algebra (r.mapcal). The r.mapcal GRASS module was employed to ensure precise performance operations [50,64]. Figure 6 below shows the groundwater potential distribution of the Baro River watershed. The classification was done by their capacity to replenish aquifers and generate sustainable yields through a combination of hydrological, climatic, lithological, and geomorphological factors.

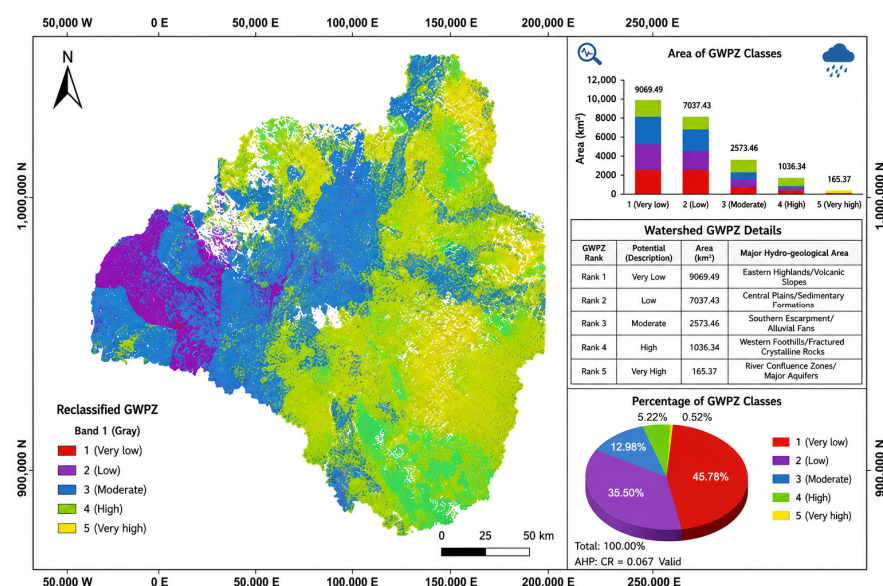


Figure 6. Spatial distribution of groundwater potential zones in the Baro River watershed: final groundwater potential map classified into five categories, with varying percentage shares across a 23,000 km² area. The map indicates moderate to high storage in the lowlands and structural recharge in the eastern volcanic highlands.

Very high potential (Zone 5): These are mostly found in the northern Gambella lowlands, which have a flat slope to maximize residence time for deep percolations. They are distinguished by a large region of quaternary alluvial sediments that give high primary porosity [65].

High potential (Zone 4): Expansive regions, which are primarily found in the Eastern and Southern volcanic highlands, are areas of secondary porosity created by cracks and joints. The systems are more susceptible to seasonal rainfall variability than lowland alluvial aquifers because of the presence of broken networks in geometry, which result in minimal storage even when maximum rainfall occurs.

Moderate potential (Zone 3): The center and eastern parts of the watershed are referred to as transition areas and fall into moderate potential (Zone 3); there is a balance between highland runoff and lowland deposition. The strong lineament-driven recharge from the volcanic highlands makes this area less porous than that of the Gambella plains, which has a consistent and moderate inflow yield [22].

Low to very low potential (Zones 1 and 2): The western and northwest portions of the research area comprise large Precambrian basement rocks, with low to very low potential (Zones 1 and 2). In contrast, with the high slope and limited permeability, most of the annual rainfall in this area will lead to rapid surface runoff instead of aquifer recharge, as would occur in the permeable alluvial lowlands.

This study enhances groundwater potential mapping in the Ethiopian Rift and Nile basins by identifying dual recharge-storage dynamics at a large watershed. While prior research mainly focused on lowland alluvial storage, this analysis recognizes nine factors that control high-potential recharge zones in fractured volcanic escarpments of the eastern highlands. This robust scientific foundation supports targeted water resource management by distinguishing between precipitation-driven highland recharge and sediment-hosted lowland storage. The hydrogeological profile analysis and groundwater distribution (Figure 6) show that over 90% of the examined region has moderate to high groundwater potential. The region's primary potential zone was made up of broken volcanic hills and alluvial sediment plains. The result will offer a solid hydro-geospatial foundation for water resource management in the basin and other data basins. This study advances large-watershed groundwater potential zone (GWPZ) mapping by incorporating additional environmental factors and leveraging cutting-edge GIS tools, including GRASS modules within QGIS 3.40.15. It newly identifies high-potential fractured volcanoes in the southeastern region, building on [66]. Previous research accurately delineated high-yield zones in smaller western alluvial plains, attributing this to their flat topography and sediment deposits [67].

Overall, the GWPZ shows moderate to extremely high stability for 90% of the watershed. Geology-derived sustainable extractability and precipitation-derived recharge potential should be separated. Actual extraction amounts are determined by the storage capacity, which is dependent on local variations in aquifer characteristics, seasonal rainfall differences, and subsoil storage capacity. The study identifies two contrasting geographical areas, namely the Eastern Volcanic Highlands and the Gambella low-lying plains, both of which have maximum rainfall, but the Eastern Volcanic Highlands has lower sustainability potential with higher slopes and rapid drainage, while the Gambella low-lying plains have high sustainability potential with unconsolidated quaternary alluvial sediments with high porosity, thickness, and high storage capacity [3,11].

From a hydrological perspective, the lowland area of the Gambella plain serves as the sink storage and terminal discharge for the Baro River watershed. Significant groundwater recharge occurs due to high precipitation from the eastern volcanic highlands, facilitating westward subsurface flow and storage within porous quaternary layers. This indicates that the high GWPZ lowlands, along with the considerable surface water volume of the Baro-Akobo-Sobat River, result from watershed-wide subsurface storage rather than merely localized precipitation. The observed spatial variation in groundwater potential indicates that features like gentle slopes, alluvial deposits, wetlands, and low drainage density

enhance water storage and infiltration [68]. Conversely, impermeable formations and steep terrain lead to rapid runoff and decreased groundwater retention [3].

3.3. Validation Framework and Sensitivity Analysis

To evaluate model reliability in the Baro River watershed, a multi-trial methodology was utilized due to limited water table depth and well yield datasets. This approach involved statistical sensitivity testing, a review of regional hydrogeological literature, and hydrological simulation with SWAT+. This approach ensures resilience and application, especially when data is limited, as is the case in Ethiopia [22].

3.3.1. Single-Parameter Sensitivity Analysis

According to the single-parameter map removal test shown in Table 5, the groundwater potential index is most sensitive to variations in rainfall (2.41%) and geology/lithology (1.85%). Lineament density (1.22%) and slope (0.94%) follow, while curvature (0.15%) and TWI (0.31%) are less significant. These results indicate that climatic factors and groundwater storage capacity primarily drive the model's spatial pattern, aligning with physical hydrological expectations.

3.3.2. Regional Hydrogeological Literature Cross-Validation

Studies conducted in the Gidabo watershed (75% moderate–high-potential) [69] and Chemoga watershed [2] are consistent with this study, which found that the Baro River watershed's high potential zones were driven by nine elements (rainfall, geology, and slope) during AHP mapping. When applied to the Omo Gibe basin, recharge and geology were identified as key factors by the ROC test, which was performed against the transmissivity value obtained from the integrated AHP-WetSpass model [11]. This shows the effectiveness of AHP in the tectono-geomorphic highlands of Ethiopia [11,14,22,57,63,70].

3.3.3. SWAT+ Model Cross-Validation

An independent approach using physically based temporal simulation outputs was added to improve the validation program for the SWAT+ model. The analysis in Figure 7 shows that the simulated groundwater recharge is correlated with the base flow and that groundwater recharge peaks determine the amount and timing of base flow. The GWPZ map integration shows that there is an active recharge process in the high-potential zones. Previous results are also confirmed by temporal trends, with high correlation between base flow responses and fluctuations in recharge, suggesting hydrologically active spatial areas [2,3,11,37,43,45]. This is an additional validation method that improves the efficiency and accuracy of the water resources model in the region.

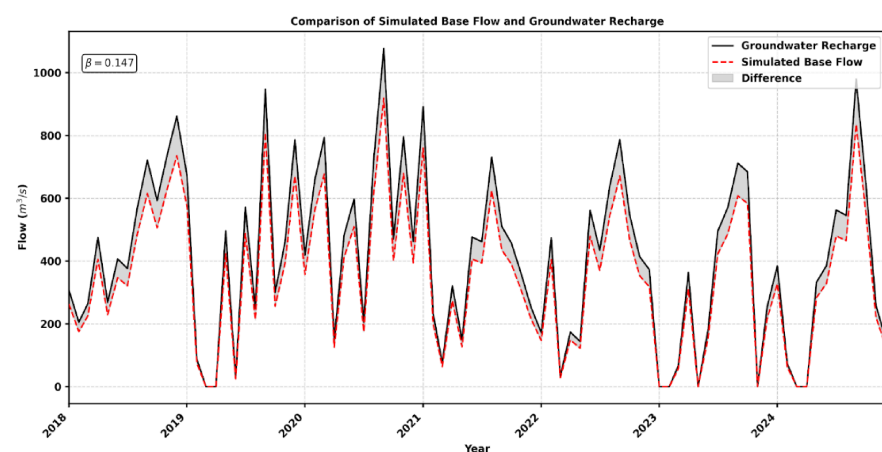


Figure 7. Groundwater recharge and base flow temporal dynamics.

3.4. Model Limitations and Evapotranspiration Dynamics

Infiltration and groundwater recharge are influenced by evapotranspiration within the catchment water balance [33]. Land use/land cover and TWI serve as implicit proxies for evapotranspiration and soil moisture retention [37]. The study highlights the lack of explicit weighting for potential and actual evapotranspiration in the AHP matrix. Particularly in the Gambella region's lowlands, high temperatures lead to elevated PET rates, and neglecting AET dynamics may result in overestimated effective recharge. Future iterations of the hydro-geospatial framework should integrate daily satellite-derived AET products to enhance net effective recharge estimation.

The accuracy of AHP-based potential mapping is constrained by the spatial scale and quality of input datasets, including satellite rainfall products and geological maps [30]. In data-poor catchments like the Baro River, small subsurface heterogeneities can lead to localized spatial uncertainty, necessitating careful interpretation when transitioning to site-specific borehole drilling.

3.5. Climate Change Adaptation

Climate variability and shifting precipitation pose serious challenges to sub-Saharan Africa's water security. In the Baro River watershed, where rain-fed agriculture and seasonal surface water are the main sources of income for the basin's population, groundwater acts as an essential buffer against climate shocks. To guarantee long-term regional sustainable resilience, groundwater potential mapping is crucial for integrated sustainable development frameworks [71]. To mitigate drought susceptibility, sustain community water supply systems, and avoid an excessive dependence on increasingly unpredictable surface flows, the high and very high-potential zones require careful management.

4. Conclusions and Recommendations

4.1. Conclusions

To design groundwater potential possibilities in the Baro River watershed, a hydro-geospatial technique that included remote sensing, GIS, and Multi-Criteria Decision Analysis (MCDA) via Analytical Hierarchy Process (AHP) was used. Nine environmental parameters were included in this study to effectively represent the complex interplay between climatic, geomorphological, and land surface characteristics that govern groundwater occurrence and movement. Significant groundwater potential is indicated by the moderate to very high groundwater potential suitability grades found in over 90% of the examined region. Because of their level topography and loose alluvial deposits that promote infiltration and groundwater recharge, the Gambella lowlands in the northern parts of the watershed have the most potential. However, the eastern and southern parts of the watershed have substantial groundwater potential, mostly in fractured volcanic strata where groundwater storage is regulated by secondary porosity. Fractured volcanic aquifers exhibit unique storage characteristics, necessitating long-term groundwater monitoring and field investigations. The GIS and AHP integration approach worked well and was appropriate for places with little data. The calculated Consistency Ratio (CR = 0.067), which shows how consistent the weighting scheme and decision-making process are, is less than the permissible threshold value of 0.10. This article has shown that despite the absence of large amounts of field information, GIS-MCDA methods can produce scientifically complete groundwater potential maps. Altogether, this study contributes to the baseline hydrological understanding of the understudied study watershed by providing a systematic, open-source, geospatial workflow that can assist water resources planners in data-limited regions.

4.2. Recommendation

According to the findings of the research, a number of specific recommendations are established to guide sustainable water resources management across Baro River catchments. Resources development must concentrate on regions that are highly viable, such as the Southern volcanic pediments and the Gambella lowlands. The use of conservation methods of water, including contour bunds and check dams, is necessary in improving the availability of groundwater, particularly in areas of high runoff. The model validation requires field verification and geophysical surveys. Basin-scale planning should include the potential of groundwater to help minimize drought vulnerability and encourage the use of surface and groundwater in an integrated manner. Having a centralized GIS database will facilitate continuous assessment and decision-making. Further study is necessary to employ hydro-geochemical and isotopic techniques to better understand how to manage groundwater flow and sustainability, especially in fractured aquifer regions.

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Abbreviations

The following abbreviations are used in this manuscript:

AET	Actual Evapotranspiration
AHP	Analytic Hierarchy Process
ANN	Artificial Neural Network
GIS	Geographic Information System
GRASS	Geospatial Resources Analysis Support System
GWPZ	Groundwater Potential Zone
IDW	Inverse Distance Weighting
MCDA	Multi-Criteria Decision Analysis
RS	Remote Sensing
SWAT+	Soil and Water Assessment Tool Plus
TWI	Topographic Wetness Index
UTM	Universal Transverse Mercator
WLC	Weighted Linear Combination

Appendix A

Table A1. Selected thematic layers, ranks, area proportion each class with detailed descriptions.

Parameter	Rank	Class	Geographic Zones (Dominant)	Area (%)	Detail Descriptions
1. Rainfall	5	Very high	SE escarpments	6.05	Max. water available for deep percolation
	4	High	NE & S highlands	44.43	Primary recharge source for the basin
	3	Average	Central Basin	25.02	Consistent but moderate seasonal recharge.
	2	Low	NW Plains	11.20	Limited contribution to the water table.
	1	Very low	Western Lowlands	13.29	High evaporation limits effective infiltration.
2. Geology	5	Quaternary Alluvium	River Valleys	2.97	Unconsolidated; highest storage and ermeability.
	4	Weathered Volcanics	Eastern Plateaus	49.82	Excellent secondary porosity via fractures.
	3	Consolidated Sed.	Transitional Slopes	1.97	Moderate ability to transmit groundwater.
	2	Semi-pervious	Mid-Basin	—	Restricts vertical movement of water.
	1	Massive Bedrock	Central Highlands	45.24	Non-porous; acts as a regional aquitard.
3. Slope	5	Flat (0–2%)	Gambella Plains	30.22	Negligible runoff; maximum infiltration time.
	4	Gentle (2–8%)	Upper Pediments	43.73	High infiltration with low erosion risk.
	3	Moderate (8–15%)	Mid-Basin	16.44	Balanced runoff and percolation.
	2	Mod. Steep (15–35%)	Highland Foot-slopes	8.06	High runoff; limited groundwater potential.
	1	Steep (>35%)	Eastern Slopes	1.55	Rapid drainage; water cannot soak into ground.
4. Lineament density	5	Very High	Tectonic Faults	2.85	Major structural pathways for flow.
	4	High	Highland Edges	7.68	Enhanced permeability via fracture networks.
	3	Moderate	Transition Zones	21.34	Sufficient conduits for localized aquifers.
	2	Low	Central Basin	26.41	Few fractures; slow horizontal transmission.
	1	Very Low	Western Plains	41.72	Compact strata; minimal structural porosity.
5. Drainage density	5	Very Low	Western Lowlands	4.74	Ground absorbs water instead of shedding it.
	4	Low	Lower Pediments	33.55	High potential for vertical recharge.
	3	Moderate	Central Basin	51.66	Moderate runoff network development.
	2	High	Upper Tributaries	9.36	Prioritizes surface flow over infiltration.
	1	Very High	Dissected Highlands	0.69	Dense stream network drains water away fast.

Table A1. Cont.

Parameter	Rank	Class	Geographic Zones (Dominant)	Area (%)	Detail Descriptions
6. Soil	5	Sandy/Alluvial	Lowland Plains	30.20	High hydraulic conductivity (K).
	4	Sandy Loams	Lower Pediments	43.80	Facilitates effective vertical seepage.
	3	Loamy Soils	Central Valleys	16.49	Balanced texture; moderate infiltration rate.
	2	Clay Loams	Mid-Highlands	7.75	High water retention but low permeability.
	1	Heavy Clay	Highland Peaks	1.76	Nearly impermeable; causes high surface runoff.
7. LULC	5	Water/Wetlands	Western Basins	0.36	Direct groundwater-surface water interaction.
	4	Forest/Woodland	Southern Highlands	72.73	Canopy and roots promote deep percolation.
	3	Cropland	Central Basin	25.79	Moderate potential; affected by compaction.
	2	Bare Land	Degraded Slopes	0.01	High evaporation and soil crusting.
	1	Built-up	Urban Areas	1.43	Impervious surfaces block all recharge.
8. TWI	5	Very High (>12)	Western Floodplains	15.00	High water accumulation & saturation potential.
	4	High (9–12)	Lower Pediments	35.00	Significant moisture retention; favors recharge.
	3	Moderate (6–9)	Central Basin	30.00	Moderate drainage and accumulation balance.
	2	Low (3–6)	Highland Slopes	15.00	High runoff potential; low water residence.
	1	Very Low (<3)	Ridge Crests	5.00	Water sheds immediately; minimal infiltration.
9. Curvature	5	Highly Concave	Deep Depressions	1.45	Maximum convergence and water accumulation.
	4	Concave	Valley Bottoms	47.20	Terrain “collects” surface water for recharge.
	3	Flat/Linear	Uniform Slopes	52.66	Neutral effect on water movement.
	2	Convex	Ridge Crests	0.76	Water diverges away; minimal accumulation.
	1	Highly Convex	Mountain Peaks	—	Immediate runoff in all directions.

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