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Source: Air, Soil and Water Research, 18(1)

Published By: SAGE Publishing

URL: https://doi.org/10.1177/11786221241312806

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Air, Soil and Water Research
Volume 18: 1–17
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DOI: 10.1177/11786221241312806

Groundwater Potential Assessment Using Integrated Geospatial and Analytic Hierarchy Process Techniques (AHP) in Chemoga Watershed, Upper Blue Nile Basin, Ethiopia

Samuel Berihun Kassa[1], Fasikaw Atanaw Zimale[2], Arega Mulu[3], Tadege Aragaw Worku[4], Mindesilew Lakew Wossene[1], Taye Minichil Meshesha[1], Yoseph Buta Hailu[1], Tadele F. Aman[4], Mekash S. Kifelew[4] and Habtamu Asrat Mekonnen[1]

[1]Department of Hydraulic and Water Resources Engineering, Debre Markos Institute of Technology, Debre Markos University, Debre Markos, Ethiopia. [2]School of Civil and Water Resource Engineering, Institute of Technology, Bahir Dar University, Bahir Dar, Ethiopia. [3]Department of Hydraulic and Water Resources Engineering, College of Engineering and Technology, Injibara University, Injibara, Ethiopia. [4]Department of Hydraulic and Water Resource Engineering, Debre Tabor University, Debre Tabor, Ethiopia.

ABSTRACT: Groundwater is an invaluable natural resource that sustains human life and supports the economic development of nations. However, its unsustainable utilization has emerged as a critical issue, particularly in developing countries. This study investigates the groundwater potential of the Chemoga watershed to address these challenges. Conventional groundwater assessments have typically relied on labor-intensive and time-consuming field surveys, which are resource-demanding and often fail to provide accurate estimates due to the inherent complexity of groundwater systems. In response, this research utilizes geospatial and analytic hierarchy process (AHP) techniques to assess groundwater potential in the Chemoga Watershed, aiming to overcome these challenges. Eight critical biophysical and environmental factors: geology, slope, rainfall, land use/land cover (LULC), soil type, elevation, lineament density, and drainage density were selected for analysis using Saaty's AHP methodology. Data was gathered from satellite imagery, existing thematic maps, local water offices, and national meteorological agencies. The integration of these thematic maps was performed through a weighted overlay analysis using ArcGIS 10.8, which resulted in the delineation of groundwater potential zones (GWPZ). The model was validated by cross-referencing the generated GWPZ with existing data from dug wells and boreholes. The results reveal five groundwater potential zones: very high (0.73%), high (24.39%), moderate (43.38%), poor (31.25%), and very poor (0.25%). The most suitable zones are in the south, southeast, and southwest of the watershed, particularly near Debre Markos Town. These high-potential zones were validated with a significant 81.5% match to ground truth data from shallow wells. The findings of this study provide crucial insights for decision-makers, enabling the formulation of more effective groundwater management strategies. By identifying cost-effective and suitable well sites, this research contributes to ensuring a sustainable water supply for Debre Markos Town.

KEYWORDS: Chemoga watershed, Debre Markos Town, Groundwater potential, Geospatial, Analytic Hierarchy Process

RECEIVED: October 7, 2024. **ACCEPTED:** December 23, 2024.

TYPE: Research Article

CORRESPONDING AUTHOR: Samuel Berihun Kassa, Debre Markos University College of Technology, PO Box 269, Debre Markos, Ethiopia. Email: samuelberihun321@gmail.com

Introduction

Water, a vital natural resource necessary for the survival of humans, animals, and plants, is unevenly distributed both on the earth's surface and below surface (Olalekan et al., 2019; Wassie, 2020). However, during the last few decades intensive anthropogenic and industrial activities have had a negative effect on the resource (Karunanidhi et al., 2024). There exist considerable variations, in terms of both quantity and quality, in natural water, whether surface or underground (Akhtar et al., 2021). Groundwater, as one of the most valuable natural resources, plays a vital role in supporting human life and economic development (Li, 2017). Due to its sustained availability and exceptional natural quality, it serves as a crucial water supply source in both urban and rural areas of any country (P. Kumar & Thakur, 2018). Globally, groundwater is used for agricultural purpose (43%), domestic use (36%), and 27% for industrial (Sankar et al., 2023). In developing countries, ground water is the main provider of water mainly rural communities (Karunanidhi et al., 2024). The increasingly evident issue of unsustainable groundwater consumption is a significant concern, particularly in developing countries such as Ethiopia (Cobbing et al., 2019; Gaye & Tindimugaya, 2019).

Globally, groundwater contributes approximately 22% to the world's freshwater supply and constitutes nearly 97% of all liquid freshwater accessible for human consumption (Lall et al., 2020). In Africa, groundwater capacity was estimated to be 100 times greater than that of annual freshwater sources, which makes it a very crucial resource (Ozegin et al., 2024a). However, mismanagement of this critical resource has led to issues such as water shortages and pollution (Foster et al., 2013). As demands for groundwater continue to grow, especially in rapidly urbanizing regions, addressing these challenges has become a priority. In addition to this, unethical extraction and inappropriate application of policies related water are also

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contributing factors on amount and quality of groundwater (Ozegin et al., 2024b). To ensure the sustainable use of groundwater, it is crucial to adopt advanced geospatial tools for continuous assessment and monitoring of groundwater resources, particularly in ecologically sensitive areas (Hussein et al., 2017).

In Ethiopia, traditional hydrogeological investigations have primarily relied on in situ measurements, which are often not feasible due to the time, labor, and financial resources required (Gedam & Dagalo, 2020; Hussein et al., 2017). Traditional field surveys have long been the cornerstone of groundwater exploration, involving methods such as yield testing, depth measurements, and manual data collection. These approaches, while valuable, often lack a structured methodology, leading to inconsistencies and inefficiencies in the data collected (Kanta et al., 2018). In groundwater exploration, yield testing involves measuring the discharge rate of wells to assess the aquifer's ability to sustain water extraction (Etikala et al., 2019). Some common techniques used in traditional field surveys include the "dipmeter method" for determining groundwater levels, the "bucket test" for yield estimation, and "piezometer installations" to monitor water table fluctuations. These methods, while foundational, have notable limitations. First, they often lack the capacity to provide a comprehensive view of groundwater conditions over large or inaccessible areas (Hussein et al., 2017). The labor-intensive nature of manual measurements makes these techniques costly and prone to human error, leading to potential inaccuracies in the data (Gedam & Dagalo, 2020; Hussein et al., 2017). Additionally, traditional methods may not account for temporal or spatial variations in groundwater levels, limiting their ability to capture dynamic changes in aquifer behavior (Bhattacharya et al., 2020; Mukherjee & Singh, 2012). Furthermore, such surveys typically rely on limited spatial sampling, which may not provide a sufficiently detailed representation of groundwater conditions across broader regions.

This reliance on conventional approaches has frequently resulted in low-yield or dry wells, undermining efforts to sustainably harness groundwater resources (Hussein et al., 2017). In the Amhara region of northwestern Ethiopia, this challenge is compounded by its role as a recharge area, characterized by a high elevation difference compared to other regions of the country (Tamesgen et al., 2023; Yenehun et al., 2020). This creates a complex problem where there is a mismatch between water resource availability and community needs, especially in areas with complex hydrogeological conditions. In the East Gojjam Zone, these issues are even more pronounced. The reliance on traditional hydrogeological investigations has hindered the identification of suitable groundwater potential zones (GWPZ), leading to unsuccessful drilling attempts and poorly functioning water points (Gedefaw et al., 2022). This inefficiency not only escalates the costs of groundwater development but also exacerbates water scarcity issues in urban centers like Debre Markos Town. To address these challenges, a shift from conventional approaches to modern, integrated methodologies that incorporate tools like the analytical hierarchy process (AHP) is needed to effectively assess and prioritize groundwater potential areas.

As reported by Mekuriaw and Gokcekus (2019), the population grew from approximately 49,297 in 1994 to 107,433 in 2016/2017 and is now estimated to have reached 262,497 in 2019/2020. This rapid population growth, along with the expansion of industrial and institutional sectors, has led to a significant increase in water demand for both domestic and non-domestic uses (Mekuriaw & Gokcekus, 2019). Debre Markos Town, situated between the Chemoga and Jedeb watersheds, relies on groundwater for 95% of its water supply (Ketemaw et al., 2021). However, the growing demand has worsened the existing water scarcity issue. In response, governmental and non-governmental organizations have made efforts to improve water availability by drilling boreholes, developing water points, and constructing hand-dug wells. Unfortunately, nearly half of these wells have recast, perpetuating the town's water supply challenges (Ketemaw et al., 2021).

Several methodologies exist for locating and mapping groundwater resources. Recently, digital satellite data has proven valuable in providing quick and useful baseline information on factors influencing groundwater occurrence and movement (Anusha et al., 2022; Nag & Ghosh, 2013; Krishna et al., 2017). Updated information on geology, land cover, lineaments, and other controlling factors is essential for identifying groundwater potential areas (Bhattacharya et al., 2020; Mukherjee & Singh, 2012). The necessary parameters from surface and subsurface approaches should also be integrated to have ground water potential of higher reliability precision in an area (Ilugbo et al., 2023; Olubusola et al., 2023; Ozegin et al., 2024b). Groundwater resource assessment is a critical task requiring robust decision-making methodologies to address complex and multi-faceted factors, with various techniques such as MCE, AHP, and Fuzzy Logic being employed to address water scarcity and assist in evaluating groundwater potential and recharge zones (Kanta et al., 2018; Leyew et al., 2022; Raja & Aneesh, 2023; Rajasekhar et al., 2021). Among these AHP has been widely utilized due to its ability to handle subjective judgments and prioritize diverse criteria effectively (Ifediegwu, 2022; Pinto & Shrestha, 2017). Unlike Fuzzy Logic, which emphasizes handling uncertainty and imprecise data through membership functions, AHP leverages pairwise comparisons to derive weighted criteria based on expert input, thereby making it more intuitive and user-friendly for applications requiring stakeholder engagement (Salaken et al., 2017; Tang et al., 2024). Similarly, while Multi-Criteria Evaluation (MCE) provides a flexible framework for integrating diverse datasets, it often lacks a systematic mechanism to quantify the relative importance of criteria an issue effectively addressed by AHP's structured decision hierarchy (Jrmorales & Vries, 2021). AHP's strength lies in its systematic approach to decomposing complex problems into smaller, manageable components, which enables decision-makers to assign relative importance to criteria through

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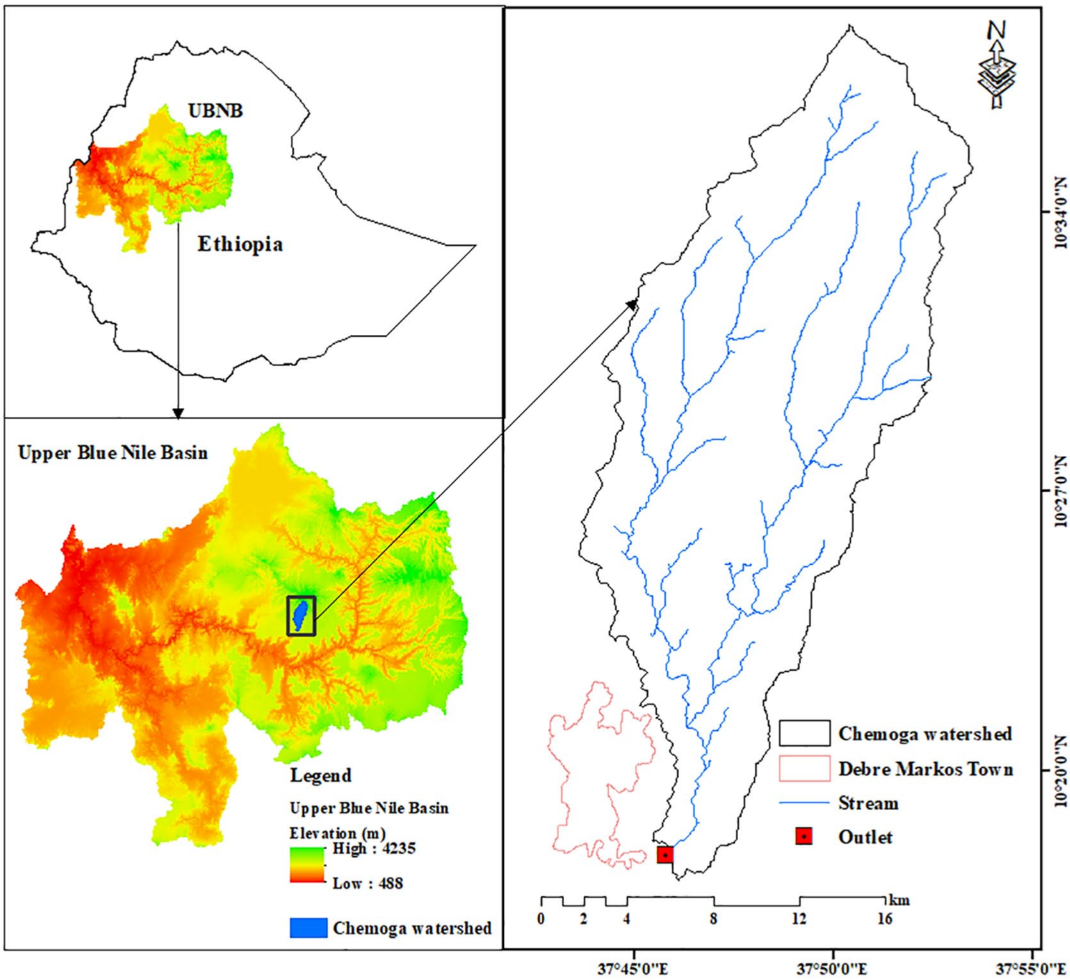

Figure 1. Location map of the study area.

pairwise comparisons. This structured process is particularly well-suited for integrating expert judgment, ensuring that decisions are grounded in domain-specific knowledge and experience (Ifediegwu, 2022; Pinto & Shrestha, 2017). By synthesizing these comparisons into a cohesive framework, AHP not only prioritizes factors effectively but also provides a robust mechanism for ranking alternatives, making it a preferred choice for groundwater assessments (Akbari et al., 2021; Pinto & Shrestha, 2017).

To address these issues, integrating advanced geospatial techniques with the AHP presents a promising solution for improving groundwater exploration. By systematically assessing GWPZ in the Chemoga watershed, these tools can effectively reduce the risk of poor well yields and enhance groundwater development efforts. The main objective of this study is to assess the groundwater potential of the Chemoga watershed by integrating geospatial analysis with the AHP. Specifically, the study has two key goals: first, to identify and characterize the factors influencing the distribution of groundwater potential zones within the watershed, and second, to delineate and classify these zones based on the identified factors. This systematic approach will enable a thorough evaluation of groundwater resources, supporting informed decision-making for sustainable water management.

Materials and Methods

Study area description

The Chemoga watershed is situated in the east Gojjam zone Northwestern Highlands of Ethiopia and represents one of the primary headstreams of the Blue Nile Basin within the Choke Watersheds (Figure 1), which is source of more than 270 springs and 60 rivers (Adane, 2023). Located approximately 300 km northwest of Addis Ababa, the watershed covers an area of 354 km^2, bounded by longitudes 37°44′E to 37°53′E and latitudes 10°18′N to 10°39′N. The major woredas within the watershed include Debre Markos, Gozamen, Sinan, and Anaded. It begins in the northern part of Sinan woreda, extends west into Anaded woreda, and lies south of Gozamen woreda and Debre Markos Town. The watershed is characterized by complex topography, varied land features, and diverse agroecological environments. Due to the heterogeneous land characteristics, which include significant variations in elevation, slope, and local climate, the study watershed contains three distinct

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Table 1. Types of Software Use.

NO.	SOFTWARE USED	VERSION	DESCRIPTION
1.	Arc GIS	10.8	For image preprocessing and thematic map generating
2.	Google Earth	–	For image preprocessing
3.	Excel	2019	For rainfall data preparation
			For AHP calculation
4.	R-Studio	3.6.3	For data processing and document preparation

agroecological environments: Wet Wurch, Moist Dega, and Moist Weyna Dega (Meshesha et al., 2024a). The soil within the watershed is predominantly characterized by clay and clay loam textures, while cropland and woodland comprise the dominant land use and land cover types. Topographically, the watershed exhibits significant variation, ranging from elevations of 2,255 to 3,911 m. The Chemoga watershed's geology comprises diverse lithological units, including Quaternary eluvial sediment, various basalt flows (Debre Markos, Lumame, Rob Gebeya, Arat Mekeraker, and Kutye), and formations from the Choke shield volcano group (Figure 5). Notably, Debre Markos Town is encompassed within the boundaries of the Chemoga watershed.

Methods

Data preparation

GIS and remote sensing (RS) techniques (Table 1) were employed to delineate the groundwater potential of the Chemoga watershed using the analytic hierarchy process (AHP). The process involved collecting and preparing geospatial data, which included layers for soil, geology, elevation, slope, land use and land cover, drainage, lineament, and rainfall (Table 2). These layers were systematically prepared for predicting groundwater zones, following multiple stages tailored to nature and type of available data. The methodologies utilized in this process included digitization, geo-referencing, projection, reclassification, and interpolation, among others.

Data analysis

Table 2. Data Use and Their Source.

NO.	DATA TYPE	SOURCE	OUTPUT LAYER
1.	Rainfall	Annual rainfall from Ethiopian Meteorology Institute (EMI)	Rainfall map
2.	Soil	Food and Agricultural Organization	Soil map
3.	Geological	Geological Survey of Ethiopia	Geology map
4.	DEM	30 m × 30 m resolution from United State of Geological Survey (USGS)	Drainage, Slope, and Elevation map
5.	LC	United State of Geological Survey	LULC map
6.	Lineament	Geological Survey of Ethiopia	Lineament map
7.	Yield and depth	Debre Markos Town, Gozamen, Sinan, and Anaded woreda	Validation

The methodology involves creating thematic layers such as geology, elevation, lineament density, slope, drainage density, soil, rainfall, and land use/land cover using geospatial techniques and the AHP. Landsat-8 imagery was utilized to delineate the Land Use/Land Cover (LULC) in the area, while soil, lineament, and lithology data were identified and classified through digitization from existing maps and field surveys, which served as input for ArcGIS data processing. Spatial analysis tools in ArcGIS 10.8 were employed to derive slope, elevation, and drainage density from the DEM. Additionally, the rainfall map was produced using the Inverse Distance Weighting (IDW) interpolation method. To assess the relationship between rainfall and groundwater recharge effectively, it is essential to analyze annual average rainfall data. High rainfall amounts typically indicate higher groundwater recharge potential, resulting in zones of high groundwater potential (GWP), while low rainfall suggests reduced groundwater recharge, correlating with low GWP zones (Raja & Aneesh, 2023). Regions with consistently low rainfall may be less permeable to groundwater accumulation (Yenehun et al., 2020). For this study, the rainfall map was constructed using annual average rainfall data obtained from the Ethiopian Meteorology Institute (EMI). Data was collected from six rain gauge stations (Rebu Gebeya, Debre Markos, Dingay Ber Amanuel, Aneded, and Yejube) for the years 2008 to 2020. To accurately estimate spatial rainfall distribution, point measurements were imported into GIS software, enabling interpolation across the study area. Given the inherent challenges in extrapolating point measurements to larger areas, increasing the density of the monitoring network can enhance the quality of spatial rainfall estimation. For this analysis, two rain gauge stations (Rebu Gebeya and Debre Markos) were employed for rainfall interpolation using Inverse Distance Weighting (IDW) and Ordinary Kriging methods. Based on the root mean square error (RMSE) results, IDW was chosen for interpolating precipitation data, as it yielded lower RMSE values compared to ordinary kriging. The IDW algorithm estimates cell values by averaging the values of nearby sample data points. Additionally, the Thiessen polygon method was applied to determine the areal depth of precipitation within the catchment (Figure 2). This method accounts for the variability in rainfall intensity and duration by assigning weights to the data collected from

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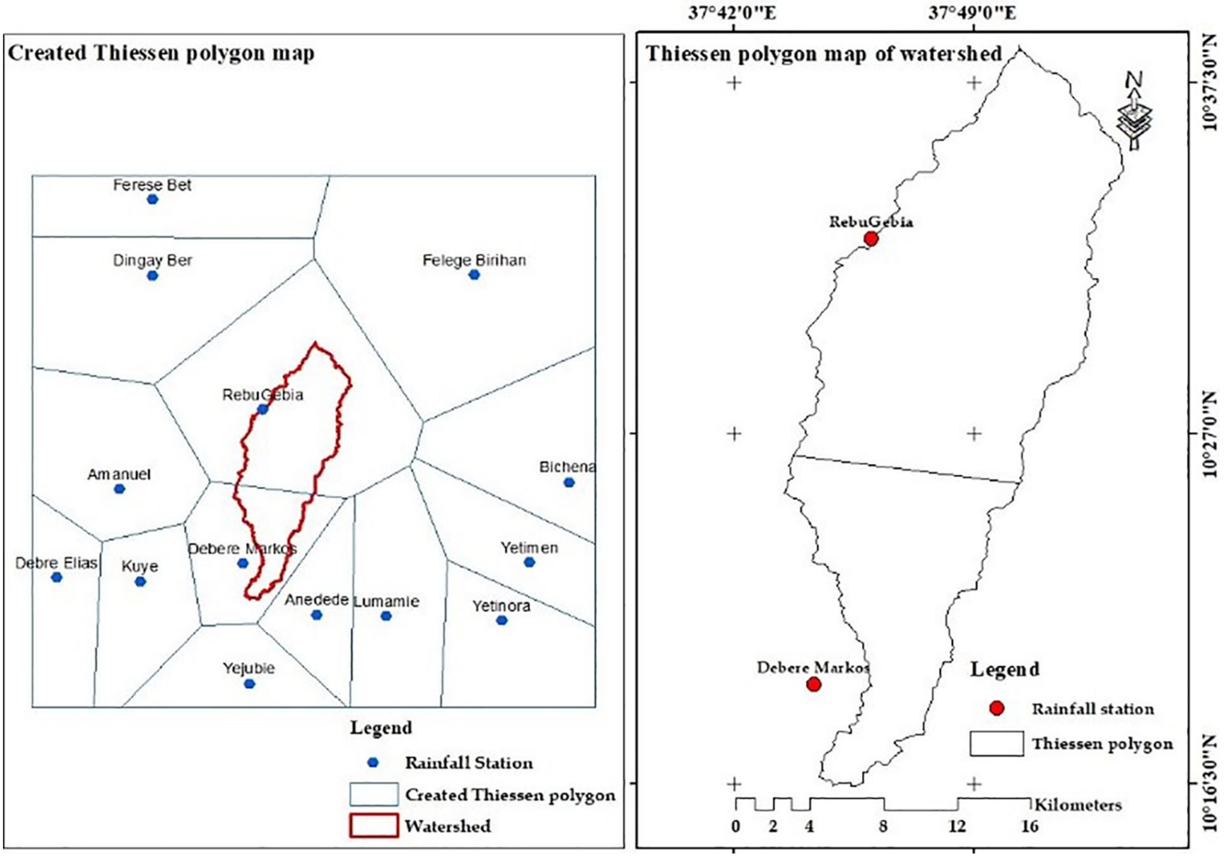

Figure 2. Thiessen polygon map of study area.

each rain gauge station based on the area it represents. The method is particularly suitable in cases where rain gauge stations are sparse relative to the size of the basin and in moderately rugged terrain. In this study, 14 stations (Amanuel, Debre Markos, Yetinora, Debre Elias, Dingay Ber, Kuye, Yetimen, Aneded, Felege Birihan, Ferese Bet, Rebu Gebeya, Yejubie, Bichena, and Lumame) were mapped to create a network of triangles, with perpendicular bisectors forming polygons around each station. The resulting polygons define the boundaries for rainfall representation in the study area.

The methodology for this study for groundwater potentiality mapping involves the qualitative classification of eight thematic layers elevation, geology, land use/land cover (LULC), soil, drainage density, lineament density, slope, and rainfall based on groundwater potential into five categories: Very High, High, Moderate, Poor, and Very Poor. Weights and ranks for each layer were determined using expert judgment and prior studies, reflecting their relative significance in groundwater potential assessment (Saaty, 2004).

All thematic maps were converted into raster format and integrated through a weighted overlay method using ArcGIS 10.8. For assigning weights, geology and elevation were given higher importance, while rainfall and LULC were assigned lower weights due to their lesser influence on groundwater potential. Following this, individual ranks were attributed to sub-variables within each layer, with higher ranks corresponding to features indicating higher groundwater potential (e.g. water bodies in LULC) and lower ranks for features with lower potential (e.g. bare land or built-up areas).

The weighted overlay method was then applied, combining ranked and weighted thematic maps to calculate the Groundwater Potential Index (GWPI). This process culminated in the generation of a final groundwater potential map (Figure 12), which visually represents areas of varying groundwater potential based on the integrated thematic layers. This approach ensures comprehensive spatial analysis, identifying regions with the highest and lowest groundwater recharge potential.

Integration of thematic layers using weightage overlay analysis

The AHP is a method of measurement involving pairwise comparisons and relies on expert judgment to establish priority scales (Saaty, 2004). This process utilizes a comparative scale ranging from 1 to 9 (Table 3), indicating the relative importance of one criterion over another. AHP stands out as one of the most effective techniques in multi-criteria decision making (MCDM), assisting decision-makers in addressing complex problems or conflicts involving multiple internal criteria (Pinto

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Table 3. Saaty's 1 to 9 Scale of Preference Between Two Parameters in AHP.

LESS IMPORTANT				EQUALLY IMPORTANT	MORE IMPORTANT			
EXTREMELY	VERY STRONGLY	STRONGLY	MODERATELY	EQUAL	MODERATELY	STRONGLY	VERY STRONGLY	EXTREMELY
1/9	1/7	1/5	1/3	1	3	5	7	9

Table 4. Random Consistency Index.

MATRIX SIZE	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table 5. Pairwise Comparison of the Factors That Affect Groundwater Potentiality.

THEMATIC		1	2	3	4	5	6	7	8	WEIGHT	WEIGHT (%)
		GEO	EELVN.	LD	SL	SO	DD	RF	LULC		
1	Geo	1	2	2	3	2	4	5	9	0.27	26.79
2	Elevn.		1	2	3	3	2	5	7	0.21	20.88
3	LD			1	2	3	3	3	5	0.16	15.69
4	SL				1	3	3	3	6	0.13	12.80
5	SO					1	1/3	3	5	0.08	8.54
6	DD						1	2	3	0.09	8.02
7	RF							1	5	0.05	5.06
8	LULC								1	0.02	2.22
Total										1	100

& Shrestha, 2017). In this study, after gathering available layers through remote sensing (RS) data and other pertinent resources, all layers were analyzed within ArcGIS and converted into raster data format. Utilizing inter-criterion and intra-criterion weights were determined for the layers and their respective classes. Finally, employing ArcGIS 10.8 and the Raster Calculator toolbox, the layers were overlaid to generate potential maps and delineate groundwater zones (P. Kumar et al., 2016; Melese & Belay, 2022; Mishra et al., 2020).

Saaty gave a measure of consistency called Consistency Index (CI) as a deviation or degree of consistency using the following *Equation 3*.

$$\mathrm{CI} = \frac{\lambda_{max} - \mathrm{n}}{\mathrm{n} - 1} \tag{1}$$

where $\lambda_{\max}$ is the largest eigenvalue of the pairwise comparison matrix and n is the number of classes. The value of $\lambda_{\max}$ is given by the *Equation 2*. Based on the principal Eigenvalue, obtained from the summation of products between each element of the Eigenvector and the sum of columns of the reciprocal matrix:

$$\begin{aligned} \lambda_{max} &= 3.39{*}0.27 + 5.01{*}0.21 + 6.70{*}0.16 + 10.17{*}0.13 \\ &\quad + 15.53{*}0.08 + 14.17{*}0.09 + 22.2{*}0.05 + 41{*}0.02 \qquad (2) \\ \lambda_{max} &= 8.80 \end{aligned}$$

Consistency ratio (CR) is a measure of consistency of pairwise comparison matrix and is given by the *Equation 4*.

$$\mathrm{CI} = \frac{\lambda_{max} - \mathrm{n}}{\mathrm{n} - 1} = \frac{8.80 - 8}{8 - 1} = 0.114 \tag{3}$$

Where RI is the ratio index, the value of RI for different "*n*" values is given in Table 4.

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} = \frac{0.114}{1.41} = 0.081 \tag{4}$$

The RI values corresponding to various n values were provided, with RI=1.41 for n=8 as shown in Table 5. The consistency ratio was then calculated, resulting in CR=0.081, which is below 0.1, indicating that the assigned weights are valid for further analysis (Gedam & Dagalo, 2020; Kanta et al., 2018;

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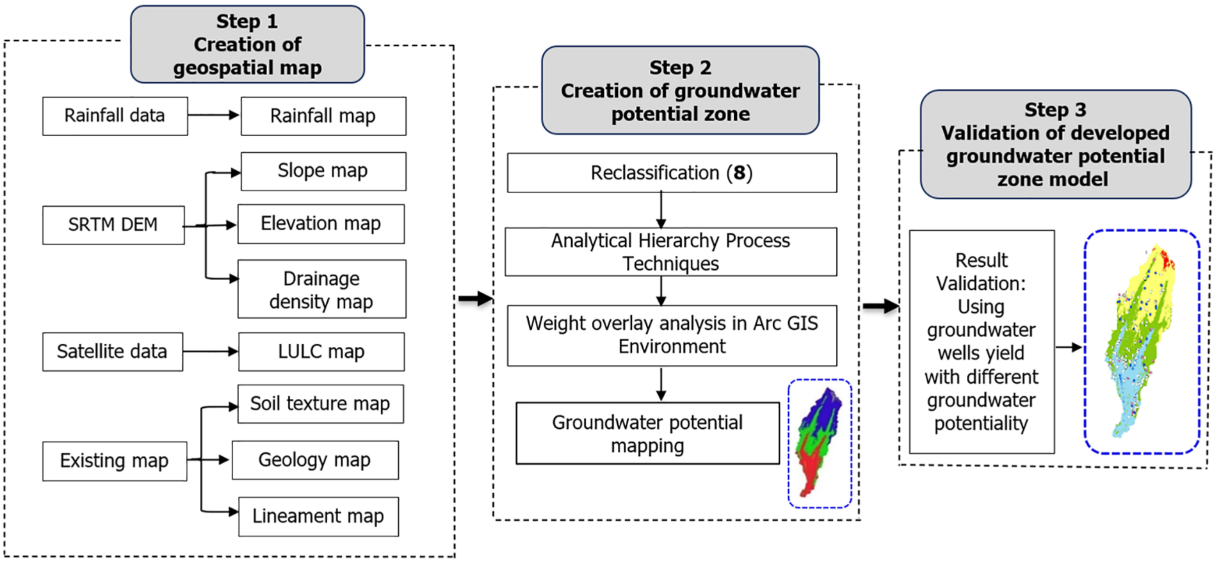

Figure 3. Conceptual framework of the study.

Raja & Aneesh, 2023). Since 0.12%<CR<10%, it suggests a high level of consistency in the pairwise comparisons, affirming the validity of the weights: 26.79% for geology, 20.88% for elevation, 15.69% for lineament density, 12.80% for slope, 8.02% for drainage density, 8.54% for soil, 5.06% for rainfall, and 2.22% for land cover, respectively. This study was conducted in 2022, and one of the main activities involved data collection through administering questionnaires for focal group discussions with the local community in three Woredas (Anded, Gozamen, and Sinan) and one administrative town (Debre Markos). Specific thematic values are presented in Table 5, with the weights determined based on inputs from questionnaires distributed among various stakeholders in each sub-watershed (Woreda and the administrative town). These locations represent the upstream to downstream segments of the watershed. Additionally, the weights were informed by researchers' judgment and insights from previous groundwater studies.

After determining relative weights for each of the factors, the criteria for groundwater potential for each pixel were calculated using the mathematical *Equation 6*:

$$\mathrm{GWPI} = \sum_{\mathrm{n}=1}^{8} W_i * X_i \qquad (5)$$

where: GWPI is the Ground Water Potential Index, i: is a pixel number in the raster, n is the number of the factors, W_i: is the weight assigned to each factor, and X_i: the groundwater potentiality raster file of each factor:

Groundwater potential index (GWPI) was computed after checking all criteria as follows:

$$\begin{aligned} GWPI = {} & (0.268 * Geology) + (0.209 * Elevation) + \\ & (0.157 * Lineament\ density) + (0.128 * Slope) + \\ & (0.0854 * Soil) + (0.0802 * Drainage\ density) + \\ & (0.0506 * Rainfall) + (0.022 * Land\ use\ land\ cover) \end{aligned} \qquad (6)$$

The overall methodology was summarized as in Figure 3.

Results

Factors to determine groundwater potential zone

The integration of several thematic layers, essential for identifying groundwater occurrence, led to the development of a groundwater potential map utilizing GIS technology. This study focused on eight critical criteria elevation, geology, lineament density, slope, soil type, rainfall, drainage density, and land use/land cover (LULC) to assess potential groundwater zones within the Chemoga watershed. Each thematic map, or factor map, used in the groundwater prospectivity assessment is described briefly below, highlighting its contribution to understanding groundwater availability in the study area. The findings demonstrate how these integrated criteria collectively influence groundwater potential, offering insights into the hydrological dynamics of the region.

Slope

Slope is a critical factor influencing groundwater occurrence, as infiltration rates are inversely related to the steepness of the terrain. The slope map of the study area was generated from a 30 m resolution DEM using the spatial analysis tool in ArcGIS 10.8. The slope values in the study area ranged from 0° to 55.7°. Based on these findings, the slopes were categorized into five

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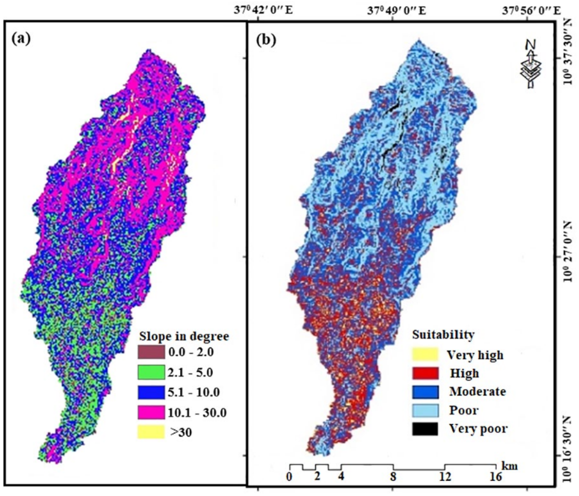

Figure 4. (a) Classified slope map in degree and (b) slope map for GWPZ suitability.

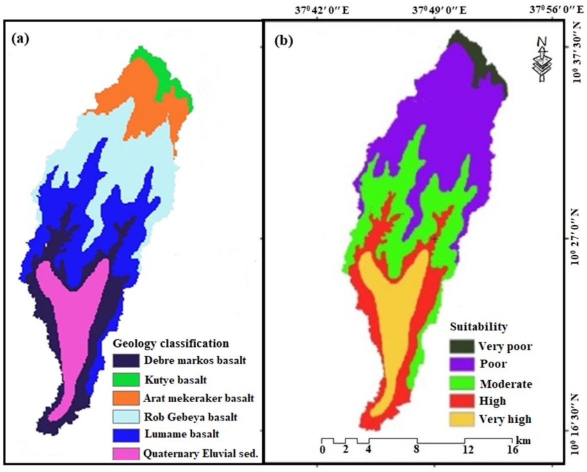

Figure 5. (a) Geology map classification and (b) reclassified geology map for GWPZ suitability.

classes: flat (0.0°–2.0°), gentle (2.1°–5.0°), moderate (5.1°–10.0°), steep (10.1°–30.0°), and very steep (Figure 4). The very steep slopes, exceeding 30°, comprised 1.15% of the area and were primarily located in the northern region. The central part of the study area exhibited moderate to steep slopes, accounting for 71.43% of the total area, with slope ranges of 5.0° to 10.0° and 10.1° to 30.0°, respectively. In contrast, the southern portion and areas along the main river featured flat to gentle slopes (0.0°–2.0° and 2.1°–5.0°), making up 27.42% of the study area. Steeper slopes significantly impact the surface and subsurface flow patterns of rainwater, thereby affecting its recharge into groundwater storage (Appels et al., 2015; Mishra et al., 2020; Yenehun et al., 2020). Regions with flat to gently sloping terrain are classified as having very high to high potential for groundwater storage due to their nearly level topography, which promotes slower surface runoff. This allows ample time for rainwater to infiltrate the soil and replenish groundwater reserves (Ahmad et al., 2020; Murmu et al., 2019; Singh et al., 2013). Conversely, the areas with very steep slopes in the northern part are considered to have poor groundwater potential, attributed to increased runoff, reduced infiltration, and limited rainfall recharge (Manap et al., 2013). Slopes exceeding 30° pose significant constraints on groundwater favorability, as they are often associated with the absence of springs.

Geology

Geology is a critical factor in identifying and assessing groundwater potential zones, as it significantly influences both the quantity and quality of groundwater within a given area (Hussein et al., 2017). The geological composition determines the porosity and permeability of aquifer rocks, which are essential for groundwater occurrence (Kanta et al., 2018).

According to the Ethiopian Geological Survey, the lithologic units within the study area consist of Tertiary and Quaternary volcanic rocks, as well as Quaternary superficial deposits (Tadesse et al., 2003). The Tertiary volcanic rocks primarily comprise basalt, with minor occurrences of rhyolite, trachyte, and pyroclastssic tuff, alongside sedimentary formations. Specifically, the Tertiary lava flows, identified as flood basalts, are dated between 25.3 and 29.4 million years ago, while the Choke shield volcano has an age range of 22.4 to 23 million years (Tadesse et al., 2003). The geology of the Chemoga watershed is characterized by several distinct lithological units, including Quaternary eluvial sediment (Qe), Debre Markos basalt (TV3), Lumame basalt flow (TV4), and various formations from the Choke shield volcano group, such as Rob Gebeya basalt (TCV1), Arat Mekeraker basalt (TCV2), and Kutye basalt (TCV3; Figure 5). However, these lithological units do not hold equal significance in determining groundwater availability. To better assess groundwater potential, lithologic units that favor groundwater storage and accumulation were assigned higher weights (Ahmad et al., 2020; Lall et al., 2020). This weighting was based on a comprehensive evaluation of factors such as permeability, porosity, textural properties, the formation of weathered or fractured zones, and groundwater yield potential of various rock types (Pinto & Shrestha, 2017). The lithological units were then ranked accordingly, leading to the following prioritization: eluvial sediment > Debre Markos basalt > Lumame basalt > Rob Gebeya basalt > Arat Mekeraker basalt > Kutye basalt (Gessesse et al., 2019; Melese & Belay, 2022).

Rainfall

Rainfall is a critical factor governing the availability of water for infiltration into groundwater zones, thus directly influencing groundwater potential (Gedam & Dagalo, 2020; Ifediegwu, 2022; Mukherjee & Singh, 2012). As a major hydrological parameter, rainfall not only serves as the primary source for

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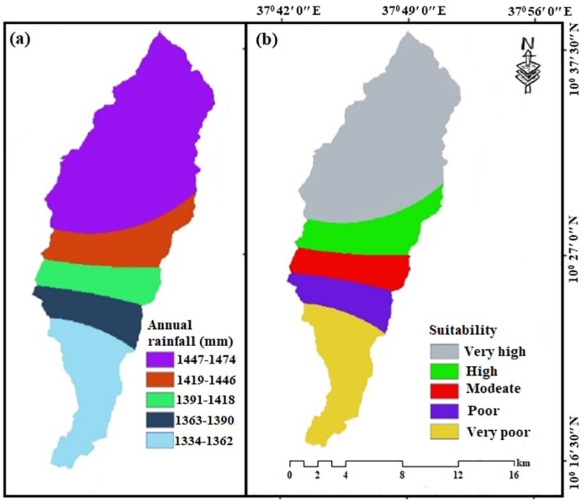

Figure 6. (a) Annual rainfall map classification and (b) rainfall map for GWPZ suitability.

groundwater recharge (Etikala et al., 2019) but also varies significantly based on environmental factors such as topography, vegetation, and surface geology. These factors ultimately affect the quantity of water that percolates into the ground.

The rainfall map (Figure 6) was categorized into five classes using equal-interval classifications: very poor (1,334–1,362 mm), poor (1,363–1,390 mm), moderate (1,391–1,418 mm), high (1,419–1,446 mm), and very high (1,447–1,474 mm). The southern and southeastern parts of the study area receive very poor rainfall, while the central region experiences rainfall ranging from poor to high. In contrast, the northern part benefits from very high rainfall. High rainfall areas are prioritized for their positive impact on groundwater potential. Based on the mean annual rainfall and its contribution to groundwater recharge, relative ranks were assigned to each rainfall class. The northern part of the watershed receives a higher amount of rainfall, indicating a greater potential for groundwater recharge and resulting in zones of high groundwater potential. In contrast, the lower rainfall levels in the southern region correspond to reduced groundwater recharge, which is associated with relatively lower groundwater potential (Ahmad et al., 2020; Melese & Belay, 2022; Murmu et al., 2019).

Soil

Soil plays a crucial role in governing the infiltration capacity of a region, making it a vital natural resource for delineating potential groundwater zones and enhancing groundwater recharge (B. D. Kumar & Jayappa, 2013; Senanayake et al., 2016). The properties of soil significantly influence the interaction between runoff and infiltration rates, which in turn regulates the permeability levels that dictate groundwater potential (Arya et al., 2020; P. Kumar et al., 2016). Specifically, the texture and hydraulic characteristics of the soil are key factors in estimating infiltration rates, with grain size largely determining the infiltration capacity. Sandy soils and coarse sandy clays are favorable due to their light texture and superior infiltration rates. Conversely, clay soils are classified as poor for groundwater recharge, as they exhibit poor drainage, slow permeability, severe erosion, and low hydraulic conductivity (Mirus, 2015).

In this study, the soil map was generated from existing soil databases and reclassified according to the Food and Agricultural Organization (FAO, 1998) classification system (Table 6), as described by the Universal Soil Data Analysis (USDA) in ArcView shapefile format. The clipped soil map revealed four predominant soil types in the study area: loam to clay, clay to silt loam, clay loam, and clay. In terms of groundwater potential, sandy soils were assigned higher weights, clay soils lower weights, and loamy soils intermediate weights (Arya et al., 2020; P. Kumar et al., 2016). Clay covers 15.1% of the study area, predominantly found in the southern, eastern, and central parts of the watershed, and is characterized by the highest runoff potential and very low infiltration rates. Clay loam covers 40.9% of the study area, primarily located in the northern and central parts of the watershed, exhibiting moderate infiltration rates. Clay to silt loam comprises 39.6% of the study area and is also found in the northern and central parts of the watershed, associated with relatively high runoff and low infiltration rates. Lastly, loam to clay covers a small portion of the study area (4.4%) in the eastern region, demonstrating high infiltration rates and consisting of moderately fine to moderately coarse textures. Weightings and ranks were assigned based on the infiltration and porosity rates of the various soil types. In the Chemoga watershed, loam to clay soils received a high rank

Table 6. USDA Textural Classes of Soils Based on the USDA Particle Size Classification.

COMMON NAMES	GENERAL TEXTURE	SAND (%)	SILT (%)	CLAY (%)	TEXTURE CLASS	INFILTRATION RATE(cm hr^{-1})
Loamy soils	Medium texture	23 to 52	28 to 50	7.27	Loam to clay	1.3
Loamy soils	Medium texture	20 to 50	74 to 88	0 to 27	Clay to silt loam	1.05
Loamy soils	Moderately fine texture	20 to 45	15 to 52	27 to 40	Clay loam	0.8
Clayey soils	Fine texture	0 to 45	0 to 40	40 to 100	Clay	0.05

Source. USDA Textural classes of soils, 2012.

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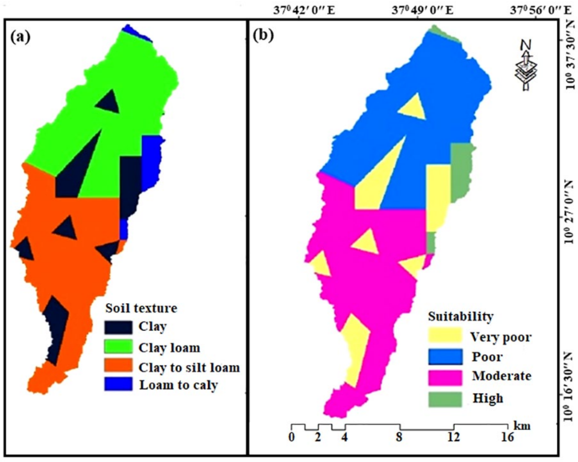

Figure 7. (a) Soil texture map and (b) soil texture map for GWPZ suitability.

due to their relatively high infiltration rates, while clay soils were assigned a low rank because of their poor infiltration capacity (Figure 7).

Land use-land cover

Land cover studies provide crucial insights into groundwater demand and utilization, serving as essential indicators for site selection of potential groundwater zones (Bhattacharya et al., 2020; Ifediegwu, 2022). The type of land use and land cover significantly influences hydrological processes, including interception, soil infiltration capacity, and runoff generation mechanisms (Ahmad et al., 2020; B. D. Kumar & Jayappa 2013). In the study area, cultivated land dominates, covering 220 km^2 and constituting 61.66% of the total area. Other land cover types include bush and shrub land (11.58%, or 41.3 km^2), grassland (6.47%, or 23.1 km^2), forest (8.41%, or 30 km^2), bare land (3.53%, or 12.6 km^2), buildings (7.23%, or 25.8 km^2), and water bodies (1.12%, or 4 km^2).

The validation of land use/land cover (LULC) products is crucial for assessing data quality for both users and producers of these maps. In this study, supervised classification accuracy was determined through field surveys and reference data from Google Earth. A total of 145 sample points were utilized to evaluate classification accuracy, resulting in an overall accuracy of 96.67% and a kappa coefficient of 95.87, indicating a high level of reliability in the classification results.

Areas covered by water bodies and cultivated land received the highest suitability values, as they facilitate groundwater occurrence through enhanced infiltration. Specifically, water bodies, agricultural land, and waterlogged areas serve as excellent sources for groundwater recharge. In contrast, bare land and exposed rock surfaces are less conducive to recharge due to limited infiltration (Nag & Ghosh, 2013). Consequently, bare land and built-up areas exhibit the lowest suitability ratings (Figure 8), primarily due to the impediments to infiltration posed by rock surfaces, roads, pavements, and buildings, which cover the soil and limit groundwater potential (Bhattacharya et al., 2020; Leyew et al., 2022). In summary, bare land shows the least suitability for groundwater infiltration, whereas farmland, grasslands, shrub and bushlands, water bodies, forests, and buildings were assigned varying reclassified values based on their respective capacities for recharge and infiltration. From a land-use perspective, forests, bushlands, and grasslands are regarded as moderate sites for groundwater exploration. Among these, forests are ranked highest (Figure 8) due to their ability to reduce runoff by intercepting rainfall before it reaches the ground, thus allowing more time for infiltration and integration into the groundwater system.

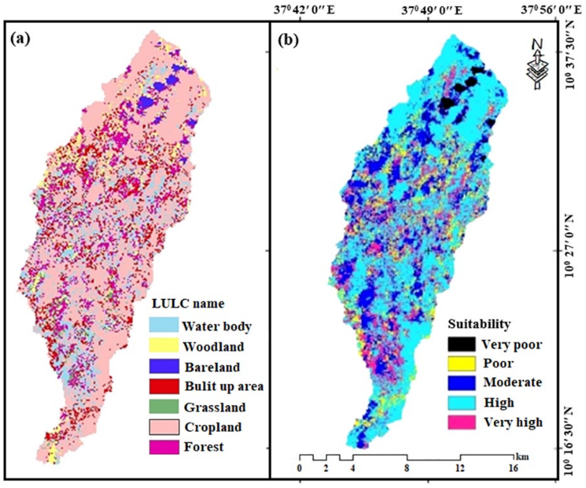

Figure 8. (a) Land use land cover classification map and (b) Land use land cover map for GWPZ.

Drainage density

Drainage density, defined as the ratio of the total length of streams within a watershed to its contributing area (Ahmad et al., 2020; Pinto & Shrestha, 2017), is expressed mathematically in Equation 7:

$$DD = \frac{L}{A} \tag{7}$$

where: DD: Drainage density, L: Total length of drainage (km), and A: Total area of watershed (km^2)

In the study area, drainage density ranges from 0 to 9 km/km^2 (Figure 9), demonstrating a clear relationship between drainage density and surface runoff. Higher drainage densities are associated with increased runoff and limited infiltration, leading to reduced groundwater occurrence (Ahmad et al., 2020). Conversely, areas with lower drainage density experience reduced runoff, allowing sufficient time for water to infiltrate into the ground, thereby promoting higher groundwater levels (Arya et al., 2020; Mukherjee & Singh, 2012). To assess groundwater potential, the drainage density

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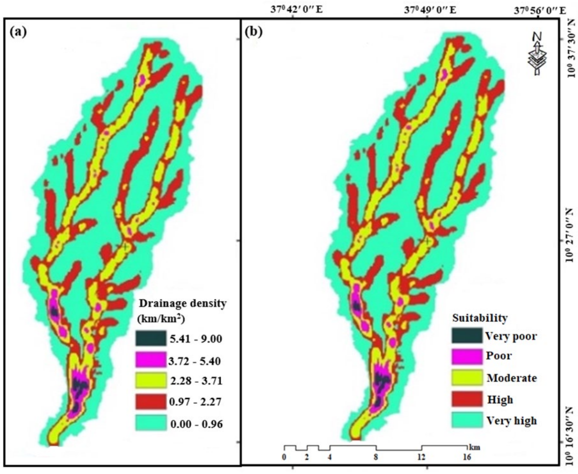

Figure 9. (a) Classified drainage density map and (b) drainage density map for GWPZ suitability.

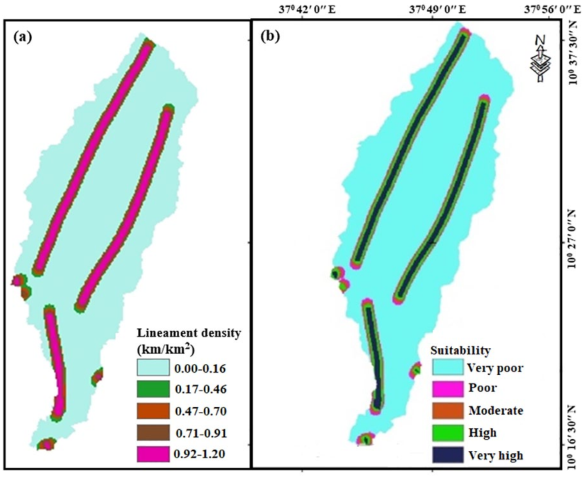

Figure 10. (a) Classified lineament density map and (b) lineament density map for GWPZ.

within the study area was categorized into five classes based on suitability rank, employing the natural break classification method. The results revealed that the southern part of the study area exhibits the highest drainage density, while moderate drainage density is observed in the western and eastern regions. Low and very low drainage densities are concentrated in the northern, western, eastern, and central parts of the study area. Notably, regions classified with very low drainage density (0–0.96 km/km^2) cover 38.72% of the area and are deemed very highly suitable for groundwater occurrence. In contrast, areas with very high drainage density (5.41–9.0 km/km^2), constituting 3.75% of the study area, are considered unsuitable for groundwater potential. Additionally, highly suitable areas with low drainage density (0.97–2.27 km/km^2) cover 24.69% of the study area, while moderate (2.28–3.70 km/km^2) and low suitability areas (3.80–5.40 km/km^2) occupy 19.25% and 13.59% of the area, respectively. From a groundwater recharge perspective, higher weightage is assigned to very low drainage density regions, whereas lower weightage is allocated to areas with very high drainage density (Leyew et al., 2022). This analysis underscores the significance of drainage density in assessing groundwater potential and informs land management strategies aimed at optimizing groundwater recharge.

Lineament density

Lineament density is a critical factor that directly correlates with groundwater potential. Lineaments, defined as linear features distinct from the surrounding terrain, are indicative of subsurface conditions and play a pivotal role in groundwater occurrence (Hussein et al., 2017; Kanta et al., 2018). This concept can be quantitatively expressed as the length of linear features per unit area within a grid, where lineament density (LD) is calculated using Equation 8:

$$LD = \frac{L}{A} \tag{8}$$

where: LD: Lineament density, L: Length of lineament (*Km*), A: Area of watershed (*km*^{2}).

In the study area, lineament density was classified into five equal interval classes: 0 to 0.16, 0.17 to 0.46, 0.47 to 0.70, 0.71 to 0.91, and 0.92 to 1.2 km/km^2. The lineament trends predominantly align along north-south (N to S), northwest-southeast (NW to SE), and northwest-southwest (NW to SW) directions (Figure 10). The highest lineament density, ranging from 0.92 to 1.2 km/km^2, is concentrated along specific lineaments, while the lowest density (0–0.16 km/km^2) is distributed throughout various parts of the study area. Higher lineament density facilitates groundwater infiltration and recharge, creating favorable conditions for groundwater development. Thus, areas with elevated lineament density are deemed suitable for groundwater potential (Hussein et al., 2017; Kanta et al., 2018). Regions with very high lineament density exhibit enhanced groundwater infiltration rates, promoting groundwater recharge, whereas areas with low lineament density experience reduced infiltration and are less suitable for groundwater recharge and discharge. Consequently, areas characterized by high lineament density are assigned higher weight values in groundwater potential assessments, highlighting their significance in groundwater exploration (Gedam & Dagalo, 2020).

Elevation

Elevation plays a crucial role in influencing the infiltration rate of rainfall, flow accumulation, transit, and dissipation zones, with areas of low relief closely associated with groundwater accumulation (Mallick et al., 2015). As elevation decreases, water infiltration rates tend to increase (Oh et al., 2011). Water

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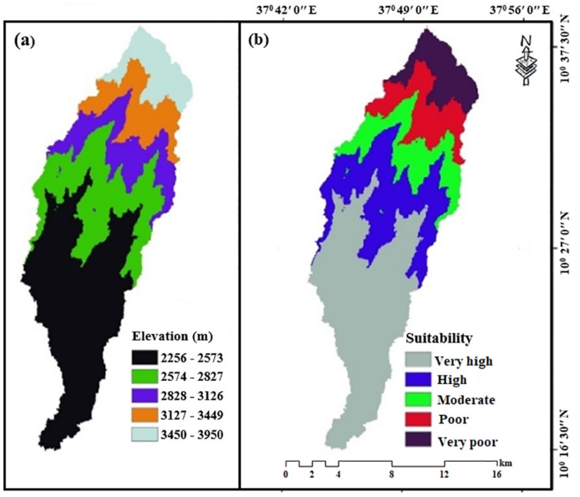

Figure 11. (a) Classified elevation map and (b) elevation map for GWPZ suitability.

tends to accumulate more readily in lower-lying areas compared to higher elevations; thus, higher elevations typically exhibit lower groundwater potential, and vice versa (Leyew et al., 2022; Oh et al., 2011).

In the study area, elevations range from 2,256 m to the highest peak at Choke Mountain, reaching 3,956 m. The elevation gradient is classified into five classes based on the natural break's classification method: elevations ranging from 2,256 to 2,573 m are categorized as "very high," 2,574 to 2,827 m as "high," 2,828 to 3,126 m as "moderate," 3,127 to 3,449 m as "poor," and 3,450 to 3,956 m as "very poor" (Figure 11).

Groundwater potential zones

The results of the groundwater potential zones (GWPZ) for the Chemoga watershed were delineated through an integrated approach using weighted multi-influencing factors in a GIS environment. By reclassifying thematic maps based on groundwater holding capacity, the ranks were assigned from 1 (very poor) to 5 (very high; Figure 12). Each thematic layer (elevation, slope, soil, land use/land cover, drainage density, lineament density, and rainfall) was reclassified, weighted, and integrated to generate the final groundwater potential map. The downstream areas of the watershed were identified as having high groundwater potential, while the northern and northeastern parts showed very poor potential. These findings highlight how the spatial variability of physical factors influences groundwater recharge in the region.

The very high GWPZ, covering only 0.41% of the watershed, is concentrated in the southwestern and southeastern areas, benefiting from flat slopes, low drainage density, and high lineament density, which enhance groundwater infiltration and recharge. Similarly, the high GWPZ spans 26.93% of the watershed and is found predominantly in the southern regions. These areas feature gentle slopes, soils with relatively high infiltration rates, and moderate lineament density, all of which contribute to higher groundwater recharge. In contrast, the moderate GWPZ, which covers 34.52% of the watershed, is characterized by steeper slopes and soils with lower infiltration capacity. Although these areas experience moderate rainfall and have basaltic formations, the combination of higher slopes and drainage density limits the overall groundwater recharge potential. Furthermore, the largest area, the poor GWPZ (36.72%), located in the central, northwestern, and northeastern regions, faces unfavorable conditions such as steep slopes and low infiltration rates. The very poor GWPZ, covering only 1.43% of the watershed, is found in the northern and northeastern parts, where very steep slopes, low infiltration rates, and high drainage density result in minimal groundwater recharge. These findings are reflected in the discussion, where it is emphasized that the southern and downstream areas of the watershed are better suited for groundwater recharge due to favorable topographic and soil conditions. Conversely, the steep, barren, and high-elevation regions in the north and northeast, with high runoff and minimal infiltration, show very poor groundwater potential. The study highlights the importance of integrating various factors using GIS to understand groundwater dynamics and inform future water resource management in the Chemoga watershed.

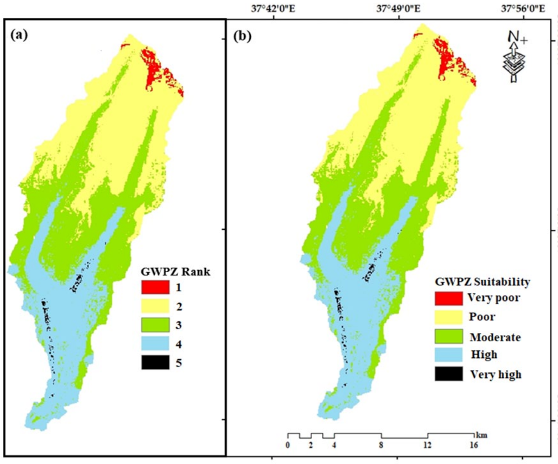

Figure 12. (a) Groundwater potential zone (GWPZ) rank and (b) GWPZ suitability map.

Validation of groundwater potential zones

Validation plays a crucial role in ensuring the reliability and accuracy of scientific research findings. In this study, after delineating and classifying the groundwater potential zones of the Chemoga Watershed, a thorough validation process was conducted using existing data from shallow wells (Figures 13 and 14). This cross-validation involved comparing the predicted groundwater potential zones with field data on well yield and depth, following methods established in previous studies (B. D. Kumar & Jayappa 2013; Melese & Belay, 2022; Singh et al., 2013). The shallow well data, including point measurements of yield and depth, were overlaid onto the

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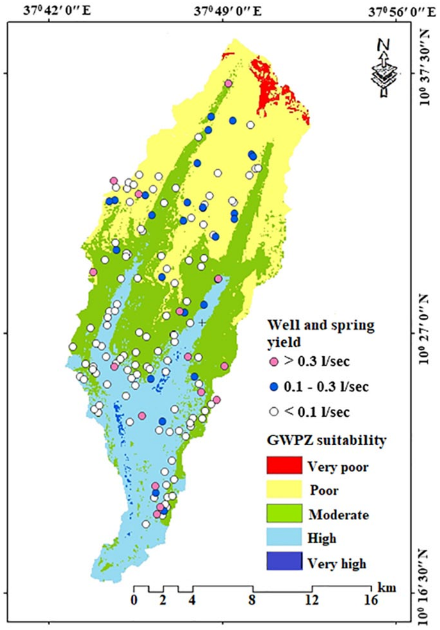

Figure 13. Distribution of wells and springs with yield across GWPZ.

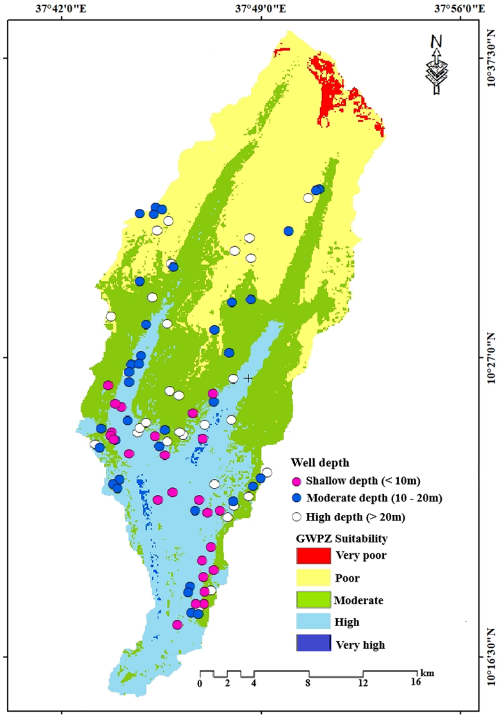

Figure 14. Distribution of wells and springs with depth across GWPZ.

groundwater potential map. The comparison revealed that approximately 81.5% of the existing wells fell within zones that matched the predicted groundwater yield and depth ranges (Table 7). This strong correlation underscores the robustness of the geospatial and analytical hierarchy process (AHP) techniques used in this study. The results suggest that the integration of these methodologies provides an accurate representation of groundwater potential across the watershed. Moreover, the high agreement between the predicted groundwater zones and the actual well data indicates that the approach employed is highly reliable. This level of accuracy offers a valuable tool for decision-makers, enabling them to better identify, monitor, and manage groundwater resources in the Chemoga Watershed. The validation confirms that the results of this study can serve as a practical guide for future groundwater exploration and sustainable management efforts in the region (Table 8).

Discussion

The sustainability of groundwater resources is increasingly challenged by rising demand and unmanaged usage, necessitating accurate assessments of groundwater potential to ensure long-term viability. In Ethiopia, traditional methods of evaluating groundwater potential have relied on in situ measurements, which are often impractical due to constraints of time, labor, and resources (Hussein et al., 2017; Woldearegay et al., 2024). To address these challenges, this study employed a more efficient approach by integrating geospatial data with Analytical Hierarchy Process (AHP) techniques to assess the groundwater potential of the Chemoga Watershed.

A pairwise comparison method was utilized to assign weights to various factors influencing groundwater potential. The resulting weight percentages provide valuable insights into the relative importance of these factors, guiding future groundwater management strategies. As outlined in Table 5, geology emerged as the most influential factor, with a weight of 26.79%. Geological characteristics, such as rock formations, permeability, and the capacity of underlying layers to store and transmit water, play a fundamental role in determining groundwater potential (Gessesse et al., 2019; Hussein et al., 2017; Melese & Belay, 2022). This underscores the significance of geology in controlling aquifer properties such as porosity and permeability (Kanta et al., 2018). Elevation, with a weight of 20.88%, is the second most influential factor in groundwater potential due to its direct impact on water infiltration and hydrological dynamics. Lower elevations promote water accumulation and storage, while higher elevations increase surface runoff and reduce infiltration. The southern and central parts of the watershed, with lower elevations, are expected to have higher groundwater potential (Figure 11). Despite relatively higher rainfall in the upstream region, the significant elevation difference (1700 m) leads to increased runoff and reduced infiltration in higher areas (Meshesha et al., 2024b). This study area characterized by complex topography (Meshesha et al., 2024a) further amplifies elevation's influence on hydrological processes, with higher areas serving as recharge zones but contributing to limited groundwater discharge downstream (Gedefaw et al., 2022). Lineament density, with a weight of 15.69%, is another important factor in groundwater potential assessment, as fractures and structural features in the Earth's surface enhance permeability and provide pathways for water recharge. Areas with a higher density of lineaments provide more pathways for water to infiltrate and

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Table 7. Wells and Springs Matched With Their Corresponding Classes of GWPZ.

WELLS DATA	GW SUITABILITY	# OF WELLS	OVERLAY	NON OVERLAY	% OVERLAY	% NON-OVERLAY
Hand dug wells	High	36	25	11	69.4	30.6
	Moderate	27	20	7	74.1	25.9
	Poor	13	10	3	76.9	23.1
Total		76	55	21	72.4	27.6
Manual drilling	High	2	2	0	100	0
	Moderate	8	8	0	100	0
Total		10	10	0	100	0
Protected springs	High	11	8	3	72.7	27.3
	Moderate	21	15	6	71.4	28.6
	Poor	19	14	5	73.7	26.3
Total		51	37	14	72.5	27.5
Springs development	High	1	1	1	100.0	100.0
	Moderate	3	2	1	66.7	33.3
	Poor	4	3	1	75.0	25.0
Total		8	6	2	75.0	25.0
Shallow wells	High	4	4	0	100	0
	Moderate	2	2	0	100	0
	Poor	2	1	1	50	50
Total		8	7	1	87.5	12.5
Overall matched					81.5	18.5

Table 8. Validation of Groundwater Potential (GWP) Map.

NO.	WELLS DATA	NO. OF WELLS OVERLAY	SUITABILITY OF GWP	AVERAGE YIELD (l/s)	AVERAGE DEPTH (m)
1.	Hand dug wells	55/76	High (25)	0.100	10.9
			Moderate (20)	0.047	12.8
			Poor (10)	0.025	18.2
2.	Manual drilling wells	10/10	High (2)	0.080	11.0
			Moderate (8)	0.030	21.0
3.	Shallow wells	7/8	High (4)	2.000	50.5
			Moderate (2)	1.500	57.0
			Poor (1)	1.250	64.0
4.	Spring	43/59	High (9)	0.673	
			Moderate (17)	0.355	
			Poor (17)	0.106	
Overall matched		81.50%			

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recharge groundwater systems (Opoku et al., 2024). The study identified regions with the highest lineament density (ranging from 0.92 to 1.2 km/km^2), primarily in specific lineament zones, which create favorable conditions for groundwater recharge (Opoku et al., 2024; Tamesgen et al., 2023). The slope, contributing 12.80% to the total weight, highlights the influence of terrain steepness on infiltration and runoff. Steeper slopes, particularly those exceeding 30° (1.15% of the area, primarily in the northern region), increase runoff and limit water retention, while flatter areas enhance infiltration. The central region, with moderate to steep slopes (5.1° to 30.0°), comprises 71.43% of the area, whereas the southern region and areas near the main river feature flat to gentle slopes (0.0° to 5.0°), covering 27.42% (Figure 4). Flat to gently sloping areas, with slower surface runoff, are highly conducive to groundwater recharge, allowing more time for rainwater infiltration (Appels et al., 2015; Mishra et al., 2020; Yenehun et al., 2020). In contrast, steep slopes hinder groundwater storage by accelerating water flow (Ahmad et al., 2020; Murmu et al., 2019; Singh et al., 2013). Soil texture, with a weight of 8.54%, is moderately important in determining groundwater recharge potential. Soil characteristics, such as texture and permeability, play a critical role in influencing land infiltration capacity. A reclassified soil map identified various soil types, including loam, clay, silt loam, clay loam, and clay (Figure 7). Clay soils, predominant in the study area, exhibit low permeability, limiting recharge potential. While soil type is important, its influence is less significant compared to geological or topographical factors within the watershed. The predominance of clay-to-clay loam soils aligns with findings from (Gedefaw et al., 2022) emphasizing the constraints posed by low-infiltration soils on groundwater recharge in the region. Drainage density, weighted at 8.02%, significantly affects groundwater potential, as higher drainage density leads to faster water flow and reduced infiltration rates. Areas with lower drainage density (38.72%), primarily in the northern, western, eastern, and central regions of the watershed (Figure 9), are more favorable for groundwater availability (Arya et al., 2020; Mukherjee & Singh, 2012). Despite its relatively lower weight (5.06%), rainfall remains an important factor, particularly in the northern and northeastern parts of the watershed (Figure 6), where higher rainfall supports groundwater recharge (Gedam & Dagalo, 2020; Ifediegwu, 2022; Mukherjee & Singh, 2012). Lastly, Land Use/Land Cover (2.22%) plays a minor role, but areas with natural vegetation, such as forests and grasslands, facilitate water infiltration, while impervious surfaces obstruct it. Nag & Ghosh (2013) emphasized that water bodies and cultivated land promote groundwater occurrence by supporting infiltration, while bare land and built-up areas obstruct it. Figure 8 shows that only a small portion of the watershed is covered by bare land and built-up areas (10.76%), suggesting that forests, bushlands, and grasslands which cover much of the area are moderate sites for groundwater exploration due to their ability to facilitate infiltration. Overall, the assessment of groundwater potential zones in the Chemoga Watershed indicates that areas with high (26.93%) and very high (0.41%) groundwater potential are concentrated in the southern and southwestern regions. These zones benefit from favorable conditions such as lower elevation, higher rainfall, suitable soil types, and higher lineament density, which collectively enhance groundwater recharge and storage capacity.

Conclusion

The assessment of groundwater potential has become increasingly crucial in the face of rising population pressures and urbanization, particularly in regions like the Chemoga Watershed. This study presents an efficient and cost-effective methodology by integrating geospatial analysis with the AHP to assess groundwater potential. By synthesizing various existing methods, this approach offers a robust framework that optimizes time, resources, and data requirements, making it highly effective for assessing large and inaccessible areas in a short time.

Key groundwater indicators such as geology, rainfall, drainage density, lineament density, elevation, soil type, land use/land cover (LULC), and slope were integrated to classify GWPZ. Geology, elevation, lineament density, and slope emerged as the most influential factors, while rainfall and LULC had relatively lesser impacts. Elevation was given greater influence than rainfall due to its critical role in hydrological processes, particularly in this study area, which is characterized by significant topographical variation. The weighted thematic maps ensured a precise classification of the groundwater potential into five zones: very high (0.73%), high (24.39%), moderate (43.38%), poor (31.25%), and very poor (0.25%). The most favorable groundwater zones were found in the southern, southeastern, and southwestern parts of the watershed, particularly near Debre Markos Town, while the northern and central areas showed limited recharge potential.

The methodology's effectiveness was validated with existing shallow well data, yielding an 81.5% match, confirming its reliability for groundwater assessments. The study's findings highlight that region with lower elevations, moderate slopes, higher lineament density, and favorable soil types exhibit the highest potential for groundwater recharge. These insights are invaluable for managing groundwater resources in the Chemoga Watershed, particularly in areas around Debre Markos Town, where groundwater recharge potential is optimal. A limitation of this study is that no statistical analysis, such as multicollinearity checks, was applied to minimize the influence of correlated parameters on the results. This absence of statistical testing could potentially lead to either overestimation or underestimation of the significance of certain factors in determining groundwater potential. To address this limitation, future studies could incorporate statistical techniques to refine the weighting process, thereby enhancing the reliability and accuracy of the groundwater potential assessment.

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Acknowledgements

We sincerely thank the Ethiopian Meteorological Institute (EMI) and the Geological Survey of Ethiopia for providing the essential rainfall, geology, and lineament data that were crucial to this study.

Author Contributions

Samuel Berihun Kassa: Writing—Original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, and Conceptualization. Fasikaw Atanaw Zimale: Writing—review & editing, Supervision, Resources, Methodology, and Conceptualization. Arega Mulu: Writing—review & editing; Tadege Aragaw Worku: Writing—review & editing; Mindesilew Lakew Wossene: Writing—review & editing; Taye Minichil Meshesha: Writing—review & editing; Yoseph Buta Hailu: Writing—review & editing; Tadele F. Aman: Writing—review & editing; Mekash S. Kifelew: Writing—review & editing; Habtamu Asrat Mekonnen: Writing—review & editing. All authors have read and agreed to this version of the manuscript.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

Data Availability Statement

All the data used for this research work are available from the author upon request.

ORCID iDs

Samuel Berihun Kassa https://orcid.org/0009-0004-5618-9743
Mekash S. Kifelew https://orcid.org/0000-0001-7671-4569

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