Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Spring Discharge Variation and Groundwater Distribution in the Kulfo River Basin, Southern Ethiopia

Tekle Bangu
Arba Minch University
Tariku Degife
tarikudegife2015@gmail.com

Arba Minch University
Dejene Getnet
Arba Minch University
Teklehaimanot Teklearegay
Arba Minch University
Muralitharan Jothiman
Arba Minch University

Case Report

Keywords: Spring discharge, Groundwater occurrence, Spatial variation, Fault density, Fractured aquifer, Kulfo River basin

Posted Date: June 18th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9842624/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Discover Sustainability on October 13th, 2026. See the published version at https://doi.org/10.1007/s43621-026-04945-5.

Spring Discharge Variation and Groundwater Distribution in the Kulfo River Basin, Southern Ethiopia

Tekle Bangu[1*], Tariku Degife[1], Dejene Getnet[1] ,Teklehaimanot Teklearegay[1], Muralitharan Jothiman[1*]

[1]Department of Geology, College of Natural and Computational Sciences, Arba Minch University, Arba Minch, Ethiopia.

Corresponding Authors: Email Adress:tarikudegife2015@gmail.com/tariku.degife@amu.edu.et(T. Degife) and teklugeobbb@gmail.com(T. Bangu)

Abstract

Spring discharge is an important indicator of groundwater occurrence, movement, and distribution, particularly in structurally complex volcanic terrains where borehole information is limited. This study assesses the implications of spatial variation in spring discharge on groundwater occurrence and distribution in the Kulfo River basin, Southern Ethiopia. A total of 92 perennial springs were considered, and selected springs were examined in relation to lithology, faults, physiography, drainage, and groundwater flow conditions. Spring discharge in the basin varies from very low values in the upper catchment to high discharge in the lower rift-floor area, especially around the Arba Minch spring system. The upper basin contains numerous low-yield springs, whereas the lower basin is characterized by fewer but highly productive springs. Spatial analysis shows that spring locations are strongly clustered, with a Nearest Neighbor Ratio of 0.526, indicating non-random groundwater emergence controlled by localized hydrogeological conditions. Moran's I analysis indicates weak but statistically significant positive spatial autocorrelation of spring yield, while hotspot analysis identifies high-discharge groundwater zones mainly associated with fault-controlled and structurally connected areas. Ordinary Least Squares regression shows that fault density is the only statistically significant predictor of spring yield, confirming the dominant role of faults and fractures in groundwater occurrence, movement, and discharge. The fractured rift-floor basalt, fractured trap-series basalt, and Quaternary alluvial deposits are the most important groundwater-bearing units in the basin. The study concludes that groundwater occurrence in the Kulfo River basin is mainly controlled by structural connectivity, lithological variation, and physiographic setting. The findings provide useful guidance for groundwater exploration, spring protection, and sustainable water resource management in the basin. This study contributes to SDG 6: Clean Water and Sanitation, particularly sustainable groundwater management, by identifying spring-discharge patterns and groundwater potential zones in the Kulfo River basin. It

also supports SDG 13: Climate Action by providing hydrogeological information useful for improving water-resource resilience under climate variability.

Key words: Spring discharge; Groundwater occurrence; Spatial variation; Fault density; Fractured aquifer; Kulfo River basin

Introduction

Groundwater is one of the most important natural resources for domestic water supply, irrigation, industrial development, ecosystem maintenance, and streamflow regulation. In many regions, particularly in developing countries and semi-arid environments, groundwater development provides a relatively reliable and cost-effective means of improving water security and supporting socio-economic development (Elshall et al., 2020; Frappart & Merwade, 2022; Graaf et al., 2019; Mukherjee et al., 2024). According to Neven & Zoran (2010), groundwater has contributed significantly to poverty reduction, food security, and sustainable water supply through its direct use for drinking water, agriculture, and industry. Despite its importance, groundwater is generally hidden from direct observation, except where it appears at the surface through springs, seepage zones, caves, mines, or artificial abstraction points such as wells (Masaoka et al., 2016; Nishimura et al., 2022; Steiakakis et al., 2023). As described by Ralph C. Heath (1983), the groundwater environment is mostly concealed below the land surface; therefore, its occurrence, storage, movement, and discharge must be understood through indirect indicators such as geological, geomorphological, hydrological, and hydrogeological indicators.

Groundwater occurs within subsurface openings, pores, fractures, joints, faults, weathered zones, and other permeable geological formations that can store and transmit water. These water-bearing formations, commonly referred to as aquifers, release groundwater naturally through springs and baseflow or artificially through wells and boreholes (Gebru et al., 2025; Lachassagne et al., 2021; Ojoawo & Adagunodo, 2023). Springs are among the most visible and practical indicators of groundwater occurrence because they represent natural discharge points where groundwater emerges from the subsurface to the land surface. Groundwater discharge through springs is especially important in mountainous, volcanic, and structurally complex terrains, where the construction of high-yield wells may be difficult and where springs often serve as the main source of water for local communities (Keegan-Treloar et al., 2022; Maria et al., 2024; Nigate et al., 2020; Sapkota et al., 2024).

A spring is a natural point of groundwater emergence where subsurface water flows onto the land

surface in sufficient quantity to form a seep, pool, or stream. Church (1996) described springs as part of the underground route of the water cycle, linking groundwater systems with surface-water systems. Spring discharge commonly reflects the hydraulic condition of the aquifer, the elevation difference between recharge and discharge areas, the permeability of the host rock, the nature of geological structures, and the degree of connection between fractures and groundwater storage zones. In fractured and volcanic terrains, springs commonly occur where faults, joints, lithological contacts, weathered zones, or impermeable barriers force groundwater to the surface (Briški et al., 2020; Maria et al., 2024; Medici et al., 2023).

The spatial distribution and discharge variation of springs are therefore useful indicators for understanding groundwater occurrence, movement, and potential zones. Spring discharge variation refers to differences in spring yield across locations, elevations, lithologies, geological structures, recharge conditions, drainage patterns, and physiographic settings (Lamacová et al., 2024; Nhu et al., 2020; Setiawan et al., 2023). In areas with limited borehole data, spring discharge mapping provides an important approach for evaluating groundwater occurrence and distribution. Springs with perennial flow, especially during the dry season, indicate sustained groundwater storage and hydraulic connectivity within the aquifer system (Kouassi et al., 2024; Mostowik et al., 2021; Tóth et al., 2022). Conversely, springs with low or seasonal discharge may indicate shallow groundwater circulation, limited fracture connectivity, low aquifer storage, or weak recharge conditions (Kouassi et al., 2024; Mostowik et al., 2021; Tóth et al., 2022).

Geological formation, geological structures, topographic setting, land cover, and drainage characteristics strongly influence the occurrence and distribution of groundwater. Lithology determines the primary and secondary porosity of rocks, while faults and fractures provide pathways, barriers, or storage zones for groundwater movement (Idris et al., 2018; Mihret & Wuletaw, 2025). In volcanic terrains, fractured basalt, weathered zones, joints, fault planes, and lithological boundaries commonly control groundwater flow (Idris et al., 2018; Mihret & Wuletaw, 2025). Similarly, hydrogeological studies in structurally controlled terrains show that faults may act as conduits that transmit groundwater, barriers that obstruct flow, or as combined conduit-barrier systems, depending on their orientation, aperture, filling material, and relationship with surrounding lithology (Mihret & Wuletaw, 2025; Scibek et al., 2016).

Complex volcanic geology, active tectonic structures, variable topography, and numerous perennial springs characterize the Kulfo River basin, located in the southern sector of the Rift Valley Lakes Basin of Ethiopia (Ayana et al., 2022; Jothimani et al., 2022; Yisehak et al., 2020). The basin contains trap-series basalt, rhyolite-ignimbrite units, rift-floor basalt, weathered volcanic rocks, and Quaternary alluvial deposits (Abrar et al., 2021; Ayenew et al., 2008; Mengistu et al., 2021). These geological units have different capacities to store and transmit groundwater. The fractured rift-floor basalt and fractured trap-series basalt are particularly important because they host many of the springs and groundwater flow paths in the basin (Abrar et al., 2021; Ayenew et al., 2008; Mengistu et al., 2021). The area is also affected by faults and lineaments related to the tectonic evolution of the Main Ethiopian Rift. These structures influence groundwater occurrence by creating fracture networks, escarpments, barriers, and conduits that control the emergence and discharge of springs (Abrar et al., 2021; Ayenew et al., 2008; Mengistu et al., 2021).

In the Kulfo River basin, spring discharge varies considerably from the upper to the lower parts of the catchment. The upper part of the basin contains numerous springs with generally low discharge, while the lower part contains fewer but higher-yielding springs, including the Arba Minch or Forty Springs system (Aragaw & Gnanachandrasamy, 2021; Bonetto et al., 2021; Hulluka et al., 2023). The presence of many perennial springs in the upper basin also indicates groundwater storage and movement within fractured and weathered volcanic rocks, although the lower discharge values suggest more localized, shallow, fracture-controlled flow systems (Aragaw & Gnanachandrasamy, 2021; Bonetto et al., 2021; Hulluka et al., 2023).

Previous hydrogeological understanding of the area indicates that groundwater occurrence in the basin is controlled by the combined influence of geology, fault systems, physiographic position, and drainage conditions (Oyda et al., 2025; Temesgen et al., 2023). However, descriptive field observations alone are insufficient to fully explain the spatial patterns of spring occurrence and discharge variation. To better understand the controlling factors, it is necessary to integrate field-based hydrogeological investigations with geospatial analysis, digital elevation models, satellite imagery, geological mapping, spring discharge data, and spatial statistical methods (Iván et al., 2020; Keegan-Treloar et al., 2022; Seelig et al., 2024). Such an integrated approach helps to identify whether springs are randomly distributed, clustered in structurally favorable zones, or spatially associated with particular hydrogeological factors (Iván et al., 2020; Keegan-Treloar et al., 2022; Seelig et al., 2024).

In this study, spring discharge is used as a key indicator of groundwater occurrence and distribution in the Kulfo River basin. The study integrates field investigations, spring inventory, geological and structural mapping, digital elevation data, satellite imagery, drainage analysis, and spatial statistical techniques to evaluate the implications of spatial variation in spring discharge on groundwater occurrence. In addition to conventional geological and hydrogeological interpretation, the study applies spatial analyses such as Kernel Density Estimation, Nearest Neighbor Analysis, Moran's I spatial autocorrelation, Getis-Ord Gi* hotspot analysis, and Ordinary Least Squares regression (Ahmad et al., 2021; Ahmad et al., 2023; Islam et al., 2021). These methods provide quantitative support for identifying spring clustering, yield autocorrelation, groundwater discharge hotspots, and the relative influence of controlling factors such as fault density, lineament density, stream density, rainfall, slope, elevation, lithology, land use/land cover, and NDVI (Embaby et al., 2024; Li et al., 2020; Nhu et al., 2020).

The main objective of this study is therefore to assess the implications of spring spatial discharge variation on groundwater occurrence and distribution in the Kulfo River basin, Southern Ethiopia. Specifically, the study aims to: identify the spatial distribution and discharge variability of perennial springs; evaluate the geological, structural, topographic, and drainage controls on spring occurrence; classify groundwater potential zones based on spring discharge and hydrogeological conditions; and quantify the spatial relationship between spring yield and controlling environmental factors. The results are expected to provide useful information for groundwater exploration, spring protection, sustainable water-resource development, and future hydrogeological planning in the Kulfo River basin. Groundwater is directly linked to achieving the Sustainable Development Goals (SDGs), especially SDG 6: Clean Water and Sanitation, which emphasizes access to safe water and the sustainable management of water resources. In groundwater-dependent regions such as the Kulfo River basin, understanding spring discharge, aquifer conditions, and structural controls is essential for improving water security, protecting natural springs, and supporting sustainable groundwater development. The study also relates to SDG 13: Climate Action, because reliable groundwater information is necessary for adapting to rainfall variability, dry-season water stress, and future climate-related water scarcity.

Materials and methodology

Study area

The Kulfo River basin is located in Southern Ethiopia, within the southern sector of the Rift Valley Lakes Basin, and drains toward Lake Chamo near Arba Minch. The study area lies approximately between 313000–346000 m E and 653500–691000 m N in UTM coordinates (Fig 1) and covers about 453 km². Elevation ranges from about 1100 m to 3456 m above mean sea level, producing strong physiographic variation from highland plateau and escarpment areas to intermediate slopes and lower rift-floor plains. This topographic contrast controls surface drainage, groundwater recharge, groundwater flow direction, and variations in spring discharge. The upper catchment is rugged and deeply dissected, with many low-discharge springs and spring-fed streams. In contrast, the lower catchment near Arba Minch features gentler slopes, alluvial deposits, regional faults, and high-yield groundwater discharge.

The drainage system is mainly controlled by topography, lithology, and tectonic structures. Several spring-fed tributaries, including Baba, Ambule, Gulundo, Wobale, and Yeremo, originate in the upper catchment and join downstream to form the main Kulfo River. Geologically, the basin is dominated by volcanic rocks related to the Main Ethiopian Rift, including trap-series basalt, rhyolite–ignimbrite units, rift-floor basalt, weathered and fractured volcanic rocks, and Quaternary alluvial deposits. The fractured trap-series basalt and rift-floor basalt form important groundwater-bearing units, while the alluvial deposits in the lower basin also provide productive aquifers. Structurally, the area is affected by NNW–SSE- and NNE–SSW-trending faults and lineaments, which act as groundwater conduits, barriers, and storage zones depending on their geometry, fracture connectivity, and relationships with surrounding lithology.

The basin's climate and hydrology are influenced by elevation variation, topography, and seasonal rainfall. Higher-elevation areas receive relatively greater recharge and support perennial spring flow and the development of head water streams. The lower rift-floor area receives groundwater from the upper catchment through structurally controlled subsurface flow paths. During the dry season, perennial springs become particularly important indicators of groundwater storage and aquifer productivity because they continue to discharge even when direct surface runoff is reduced. Therefore, dry-season spring discharge is a useful proxy for identifying groundwater potential zones in the basin. Land use and land cover in the study area vary from highland cultivated lands and vegetated slopes to settlement areas, riverine vegetation, and lowland alluvial plains. Vegetation is commonly denser in spring-emergence zones, fault-controlled depressions, and moist valley floors. These vegetated areas may indicate shallow groundwater occurrence or zones where groundwater reaches the surface.

However, vegetation alone does not fully control spring distribution; rather, it reflects the combined influence of moisture availability, geomorphic position, lithology, and structural controls.

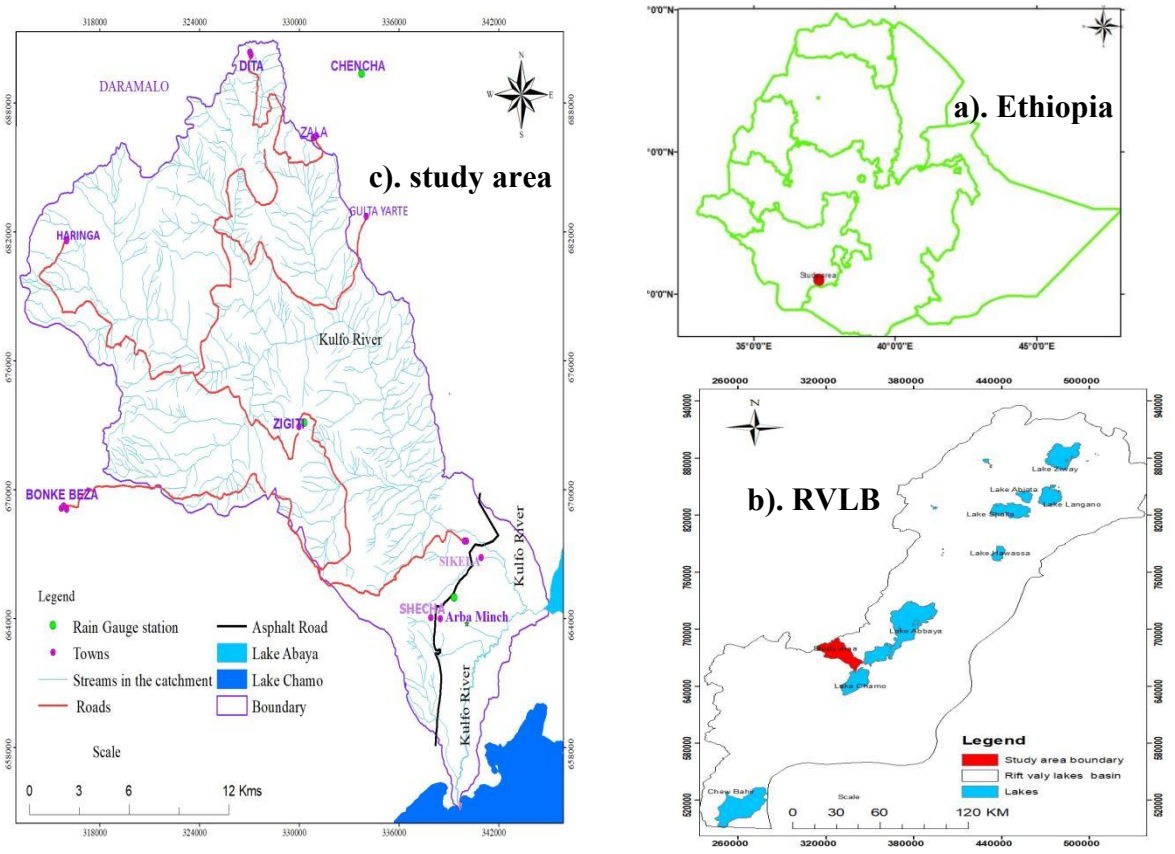


Fig.1 Location map of study areas in the Chamo lake basin showing kulfo river drainage system and accessibility to local area

a) Map of Ethiopia **b)**. map of rift valley lake basin (RVLB) **c).** Study area

Data collection and preparation

In this study, multiple geospatial datasets were used to analyze groundwater spring distribution and its controlling factors. The datasets include elevation, slope, normalized difference vegetation index (NDVI), rainfall, lithology, land use/land cover, lineament density, fault density, stream density, and spring yield data. All datasets were obtained in raster and vector formats and processed in a GIS environment using Google Colab and Python-based geospatial libraries. All raster datasets were converted to a common coordinate reference system (CRS) and resampled to a uniform spatial

resolution to ensure spatial consistency. Spring locations were extracted from the spring yield raster using valid-pixel masking, and corresponding environmental variables were sampled at the same spatial coordinates.

The study used spring discharge measurements to assess spring distribution and discharge variation from the perspective of groundwater occurrence. The 92 perennial springs are used, and 9 springs are reselected for detailed study and validation (Table 1). These springs are investigated from the viewpoints of Geology, physiographic location, geologic structure, and river drainage system. The volumes of these springs are measured using in situ point measurements, except for Arba Minch (40 springs). The inventory of water points in the area and the analysis of collected data are used to understand the area's hydrogeological conditions. Springs and boreholes are the groundwater sources identified in the area. The field study was conducted using a geological hammer, a Brunton compass, a GPS, a digital camera, and a topographic map. Using these materials, the field description of spring openings and locations has been characterized. Using secondary data, field studies, DEMs, and satellite images, geologic units and structures were identified. The collected data were processed using ArcGIS 10.3 and Surfer 10.

Raster preprocessing and standardization

To ensure comparability among datasets, all raster layers were standardized to a common grid system. Invalid values, such as NoData, infinities, and extreme outliers, were removed using data-cleaning procedures. Mathematically, normalization of variables was performed using the following eq 1:

$$Z = \frac{(X - \mu)}{\sigma} \qquad (1)$$

Where: X = original value, μ = mean of variable, σ = standard deviation.

Kernel Density Estimation (KDE)

Kernel Density Estimation was used to analyze the spatial intensity of spring and lineament distributions. KDE estimates the probability density of spatial features using eq 2.

$$f(x) = (1 / (n \times h)) \Sigma K\left(\frac{(x - xi)}{h}\right) \qquad (2)$$

Where: f(x) = density at location x, n = number of points, h = bandwidth, K = kernel function xi = observed locations

Nearest Neighbor Analysis (NNA)

Nearest-neighbor analysis was used to determine whether the spring distribution is clustered, random, or dispersed. The Nearest Neighbor Ratio (R) is shown in eq 3:

$$R = \frac{Do}{De} \quad (3)$$

Where: R = nearest neighbor ratio, Do = observed mean distance, De = expected mean distance

Expected distance is calculated using eq 4:

$$De = \frac{0.5}{\sqrt{\rho}} \quad (4)$$

where ρ is point density.

Interpretation: R<1: clustered distribution, R=1: random distribution, R>1: dispersed distribution

Moran's I (Spatial Autocorrelation)

Global spatial autocorrelation was assessed using Moran's I statistic to evaluate the spatial dependence of spring yield using eq 5.

$$I = \left(\frac{n}{W}\right) \times \frac{[\Sigma\, wij\, (xi - \bar{x})(xj - \bar{x})]}{[\Sigma\, (xi - \bar{x})^2]} \quad (5)$$

where:n = number of observations, jxj = values at locations i and j, $\bar{x}$ = mean value, wij = spatial weight, matrix, W = sum of all weights.

Moran's I measures whether values that are similar cluster spatially.

Interpretation:

- I>0: clustering
- I=0: random pattern
- I<0: dispersion

Statistical significance was tested using permutation-based p-values.

Getis-Ord Gi* hotspot analysis

Hotspot and coldspot detection was performed using the Getis-Ord Gi* statistic (eq 6).

$$Gi^* = [\, \Sigma\, wij\, xj - \bar{x}\, \Sigma\, wij\,] \,/\, \sqrt{[\, (\, \Sigma\, xj^2 / n - \bar{x}^2\,) \times (\, n\, \Sigma\, wij^2 - (\Sigma\, wij)^2\,) / (n - 1)\,]} \quad (6)$$

Where: xj = attribute value, wij = spatial weight, $\bar{x}$ = mean, n = number of observations

Ordinary Least Squares (OLS) Regression

$$Y = \beta 0 + \beta 1X1 + \beta 2X2 + \beta 3X3 + \ldots + \beta nXn + \varepsilon$$

Where:
Y = spring yield
β0 = intercept
βn = regression coefficients
Xn = explanatory variables
ε = error term

R-squared

$$R^2 = 1 - \left(\frac{SSres}{SStot}\right)$$

Where:
SSres = residual sum of squares
SStot = total sum of squares

Adjusted R-squared

$$R^2adj = 1 - \left[\frac{(1 - R^2)(n - 1)}{(n - k - 1)}\right]$$

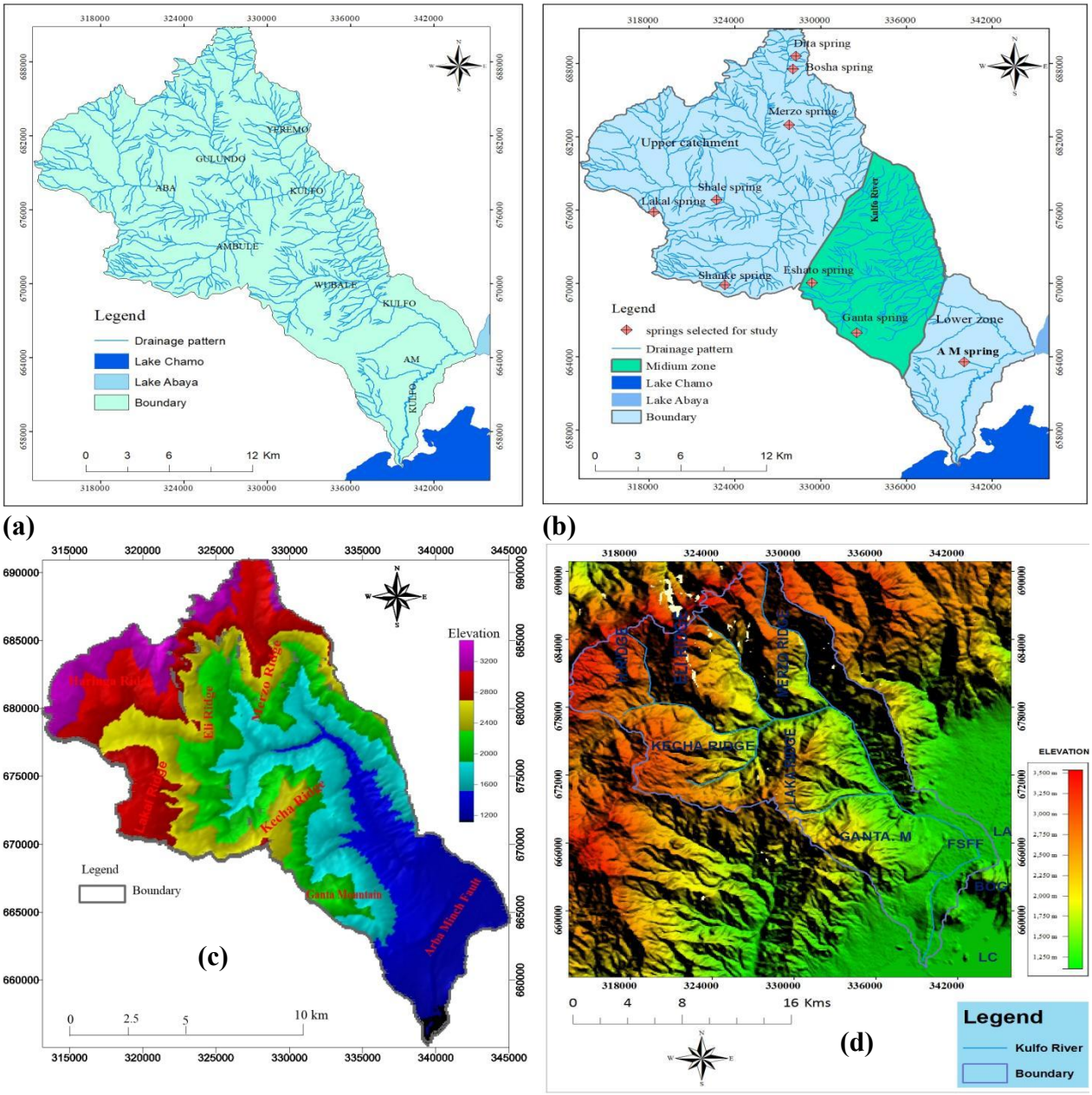
Where:
n = number of observations
k = number of predictors

Table 1. Selected and measured springs discharge and its geographic location

S.No	Springs name	X	Y	Elevation	Yield(l/s)	Yield (l/min)	Sample code
1	Arba Minch	340032	663604	1220	130	7800	S1
2	Ganta	332495	665984	2211	1.5	90	S3
3	Lakal	318304	675874	2874	0.08	4.8	S4
4	Shanke	323281	669897	2560	0.3	18	S5
5	Gum'ee	328227	688642	2974	0.2	12	S6
6	Bosha kashe	328055	687570	2920	0.6	36	S7
7	Merzo	327766	683002	2732	0.4	24	S8
8	Shale	322670	676872	2237	0.2	12	S10
9	Eshato	329380	670071	2390	4.4	264	S11

Physiographic setting and drainage system

Tectonic faulting is a controlling factor in shaping the physiographic features of an area. The Kulfo River catchment is characterized by gravity-flow-dominated springs, resulting in streams and subrivers in the upper part and the main river in the middle to lower parts. The upper Part is controlled by



numerous springs that form streams, which in turn feed five sub-rivers, including Baba, Ambule, Gulundo, Wobale, and Yeremo. These rivers join together to form the Kulfo River.

Fig. 2 Thematic Maps shows **(a).** Drainage pattern, **(b).** Parts of the catchment **(c)**. Physiographic location and (d) satellite image of the study area

All of streams make transitional zone with groundwater at spring point. The springs selected for validation are located in the three river classes.

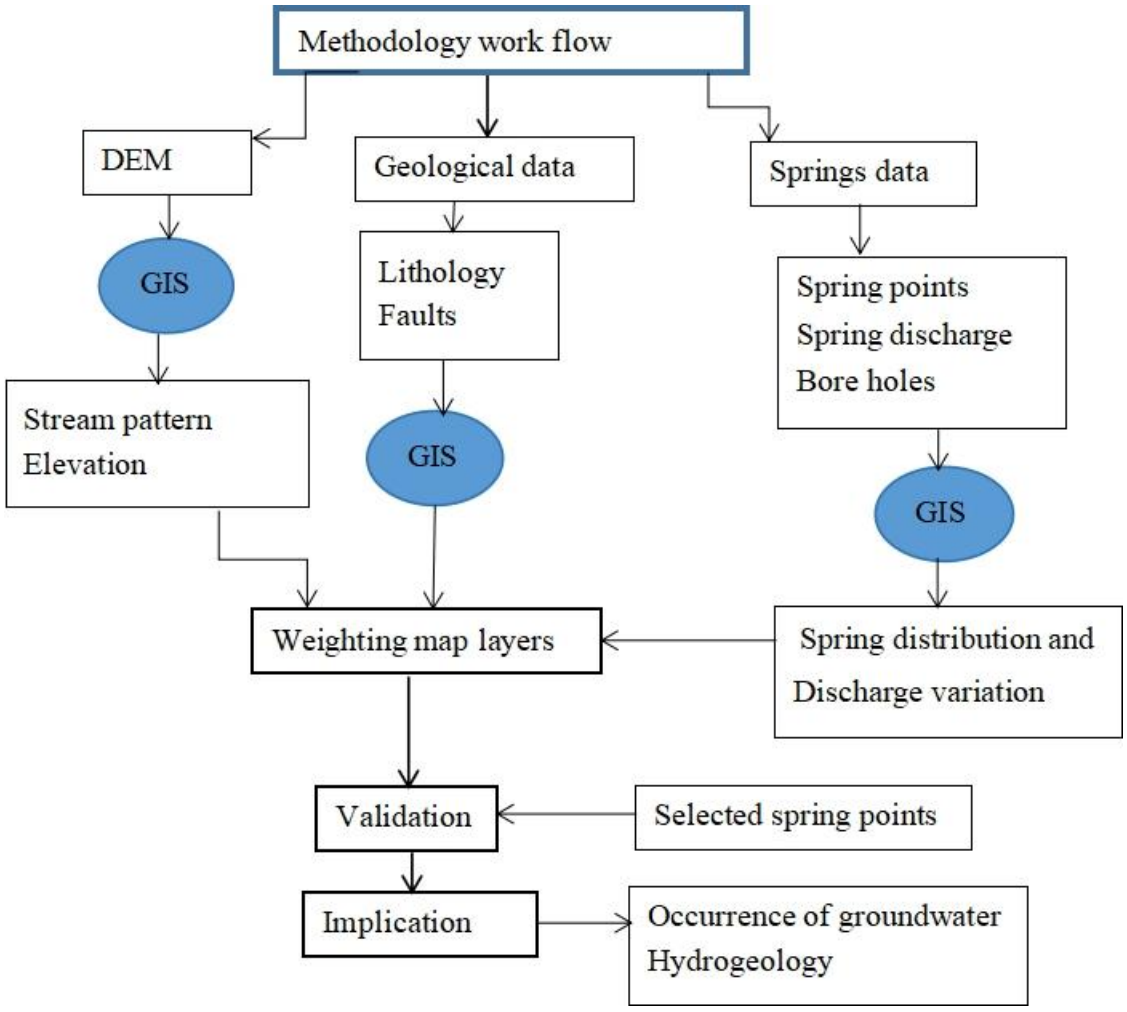


Fig.3. Conceptual framework developed to perform targeted objective

Geology

Geologically, the Kulfo River basin is mostly volcanic, erupted during the Oligocene- Pliocene-Pleistocene period (Zanettin, 1978), and exposed in the plateaus, rift margins, and rift floors of the MER system. Five lithological units have been identified and mapped based on field studies. This includes trap series (basalt and rhyolite-ignimbrite), rift-floor basalt, and alluvial deposits (Fig. 4). Trap-series basalt is older basalt in the rift valley (Zanettin et al., 1974), which was emplaced in a plateau topographic section. Trap series basalt is predominantly observed over the study area. It defines

a boundary for all lithologies mapped in the area shown in fig. 1. Rift floor basalt is a younger formation formed during the Quaternary period and characterized by the emission of alkali basalts and the accumulation of fluviatile and lacustrine deposits (Zanettin, 1974). Vesicles with open fractures and joints characterize the Quaternary rift-floor basalt. An alluvial deposit in the lower section of the area is composed of various sizes of alluvial sediment, ranging from clay to boulder size, reconstructed from basalt fragments. Based on borehole logs around Arba Minch city, the total thickness of the alluvial deposit ranges from 42 to 110 m below the surface.

Fault: The area consists of NNW-SSE- and NNE–SSW-trending blocks of fault lineaments and volcanic rock joints (fig. 4). The presence of dominant fractures and normal faults in the study area is due to extensional tectonic movement during the evolution of the main Ethiopian rift. Faults dominantly observed and identified are classified as minor and major, characterized by groundwater conduits and barrier lines. There are two major faults in the upper crust of the northwestern and north-eastern parts, with strikes of N305W and N46E, respectively. In the lower, two major faults are identified with the same strike directions, N35E and N31E, called the upper Arba Minch fault and the spring-formed fault, respectively (fig. 4). The Arba Minch fault is a large, long fault extending to the southwest and northeast of the study area. In addition to the Arba Minch fault, the Abaya fault dam and Egzer Dildy fault in the rift floor form common fence-like escarpments and the entire rift valley forest on the full graven (fig.4). These faults, conceptualized as a groundwater barrier as well as a surface water dam in the study area, are shown in (fig.5a,b,c).

Based on the topographic face constructed up and down-throw block of fault along escarpments, fault penetration is estimated by producing a geologic cross-section along lines a,b, and c (fig.5). The up and down-throw of faults observed on the surface sheet show depth of fault penetration below the earth's surface. The deep-penetrated fault has long lineaments and large, steep-to-gentle-sloped escarpments, which are identified as the Kecha, Haringa, Ganta, Lakal, Merzo, and Arba Mich faults. The faults observed are shown in the cross-section map along lines A-A', B-B', and X-X' (fig. 5). The line b and c sections unify the upper, intermediate, and lower classes of study and indicate the fault line pattern, geology, and spring locations. The section along Y-Y' (fig. 5c) shows shallow fault penetration, especially in the margin of the rift valley, which indicates geology is highly deformed to form disturbed land escape. The areas with highly weathered geology on the mountain, the surface water divide, and the intermediate zone have

shallow fracture penetration. But along river channels in the upper class and the rift floor in the lower zone, deep-penetrated faults occur. The fault plain penetration is an implication of groundwater occurrence and movement.

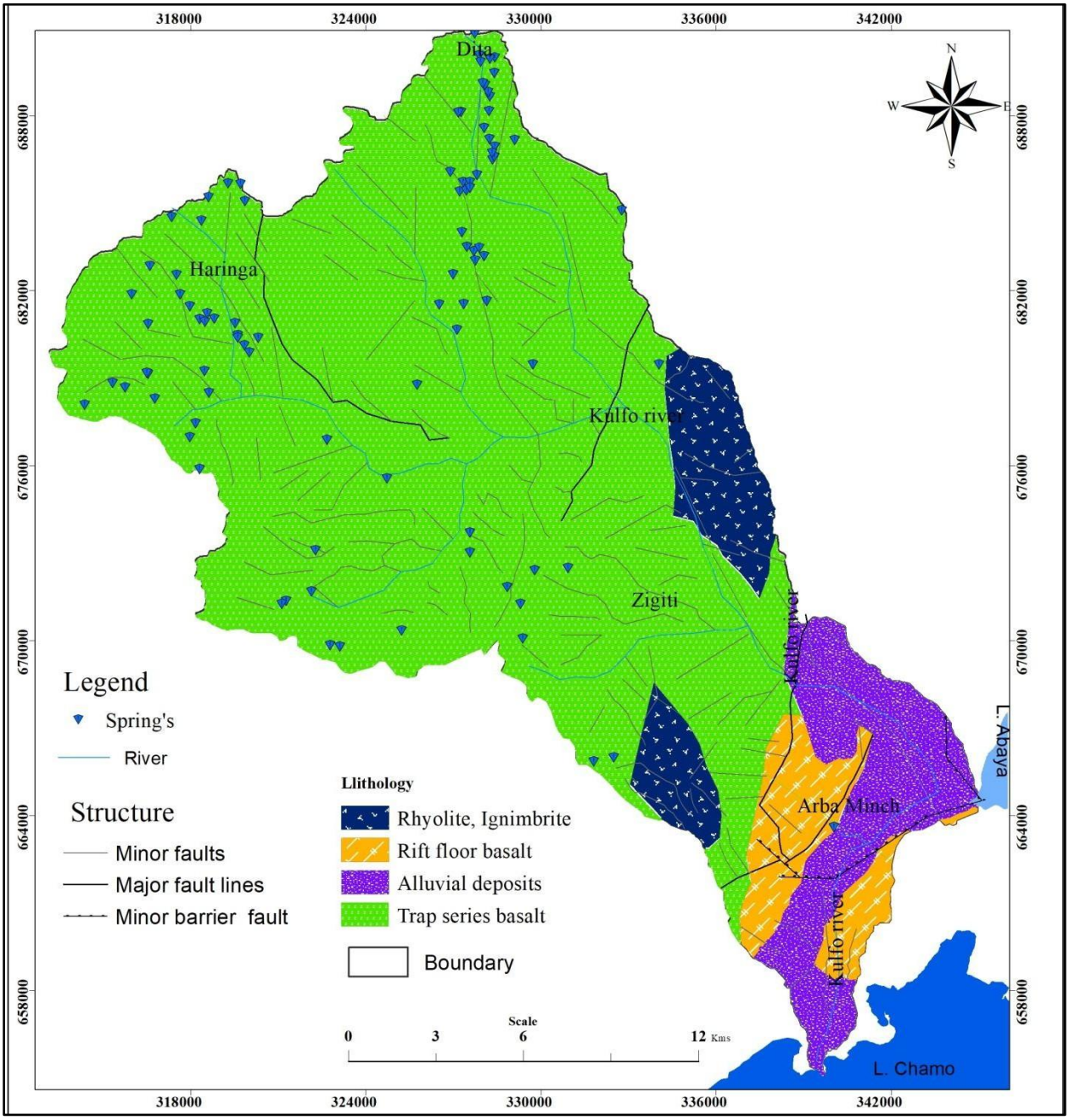


Fig. 4 Geological map of the study area, consisting of five lithologic units and regional faults that store and conduit groundwater to the surface as springs.

To detect the fault role in groundwater movement, springs are located on the cross-section face at their exact geographic positions. As observed on the line section, most springs are located at the foot of the mountain range or escarpment. However, their distribution is not the same along the three-line section. Joints in water-bearing volcanic rock play a significant role by receiving and transmitting water freely to the natural spring chamber. Some springs on the margin of a mountain in basaltic rock with small discharge are produced by joints, aided by a local barrier fault.

A joint is a fracture group with no measurable displacement in the rock body. Its lineament is not merging, keeping the original line. Joints in water-bearing volcanic rock play a role by receiving and transmitting water freely to the natural spring chamber. Some springs on the margin of a mountain in basaltic rock with small discharge are produced by joints, aided by a local barrier fault.

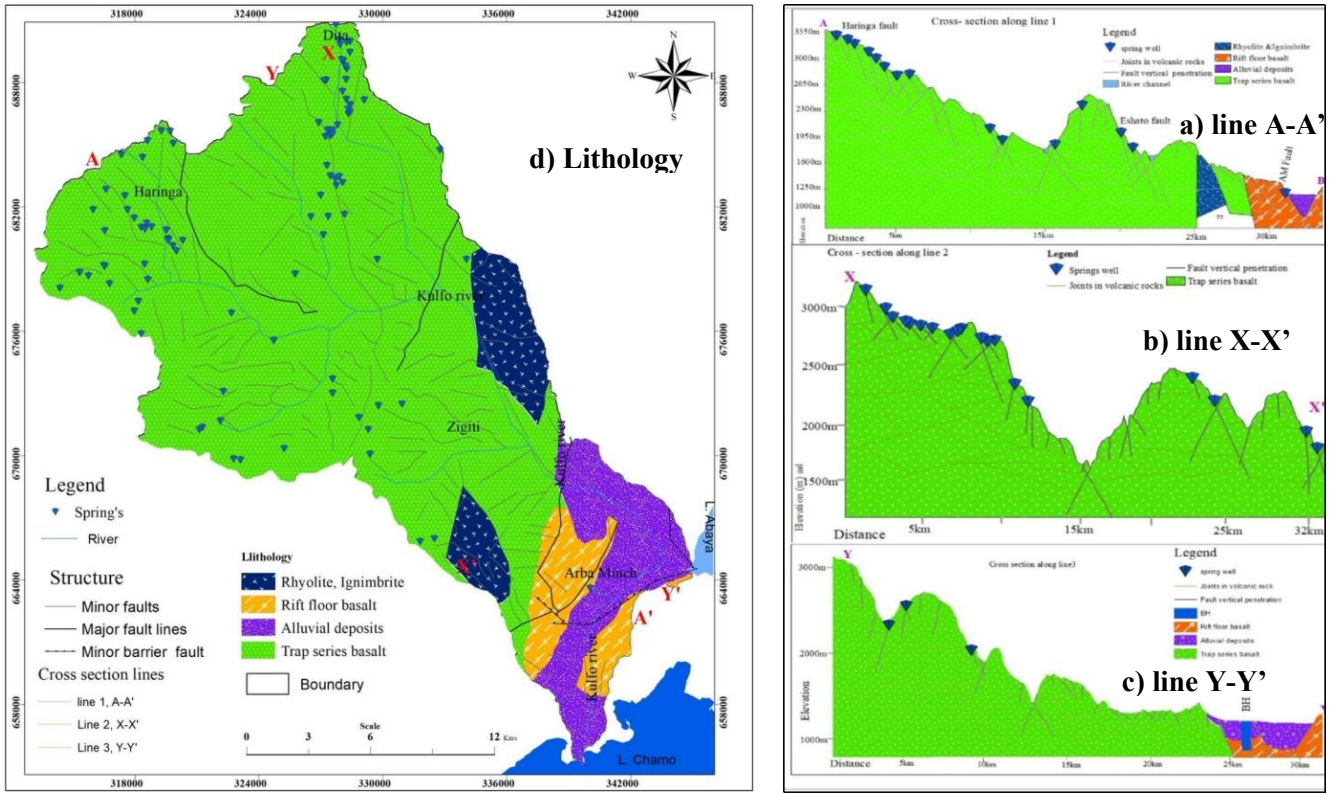


Fig. 5 maps show major faults and cross section line along X-X', A-A' and Y-Y'.

Table 2. Data sources and references

Data sources and references	Data type	Processed factors

Earth data (https://search.asf.alaska.edu)	Digital elevation model	Elevation
MoWE (https://www.mowe.gov.et)	RVLB shape file	River basin
Landsat 8 8 (https://earthexplorer.usgs.gov.et)	DEM	3D image
Arba Minch top sheet and field mapping	Geology and hydrogeology	Lithology
Gamo zone water mine and energy office	Spring discharge	Water inventory

The spring's water and its discharge variation

Spring water

A spring is a location where groundwater emerges from the Earth's subsurface in an amount large enough to form something resembling a stream. Natural springs may also discharge directly into lakes and oceans (Church 1996). It is also a natural overflow from groundwater reservoirs driven by gravity and hydraulic pressure. It is formed when groundwater is outside its natural environment (an aquifer) (fig. 6). Spring discharge is not only caused by the difference in the elevation of the hydraulic head in the aquifer and the elevation of the land surface where the discharge takes place. But it also arises from a lateral impermeable barrier in fractured rock due to faulting, which forces groundwater from greater depth to ascend through the overlying sediments and release at the surface (Neven & Zoran, 2010). Consequently, it represents a transition between groundwater and surface water in the circulation system. In the study area, there are more than 92 perennial springs that form a transition zone between groundwater and surface water. The biggest spring with maximum yield of 250 l/s and minimum yield of 130 l/s in the lower zone is called Arba Minch (forty spring), Fig.6d.







Fig.6. A field photograph shows the physical nature of some springs in the area. **a)**. Gum'ee springs around Dita Gebrel. **b)** Shale spring in the upper part of the study area **c)** Spring overflows due to gravity, **d) Arba Minch (**forty springs), the largest volume spring in the southern section of MER.

Classification of springs based on mean discharge

Table 3) shows Meinzer's classification of springs based on the mean discharge by using metric cube per second. Similarly, all springs except Arba Minch have no mean discharge. This is because only dry-season discharge has been measured for the water supply. So, this classification is used only for Arba Minch springs. Since the mean discharge of Arba Minch springs is 190 l/s, the springs are classified as 3rd-order springs.

Table 3. Meinzer's springs classification based on mean discharge

Magnitude (order)	Discharge (m3/s)
1st	>10 m3/s
2nd	1-10m3/s
3rd	0.1-10 m3/s
4th	10-100 l/s
5th	1-100 l/s
6th	0.1-1 l/s
7th	10-100 ml/s
8th	< 10 ml/s

Results

Spring distribution and discharge variation

Including Arba Minch spring, a minimum of 92 springs (annex- 1) are used in this study to indicate groundwater occurrence in the Kulfo River basin. As observed in (fig.7a), the yield varies from 0.01 – 130 l/s (fig.7a). By using all springs' minimum discharge value, the spatial potentiality of springs was interpolated to indicate groundwater (fig.7c). The Potentiality of the spring is checked by dry season discharge, which is mostly capped for the community as drinking water. In the upper east and west parts, a large number of springs are mapped, and this area is designated as a dominant springwater zone. As indicated in Figure 7 b, the large number of springs is associated with major and minor fault zones. The lower section of the area is characterized by high productive spring discharge as a result of conduit faults. Several springs are well distributed in the upper zone, and a few are located in the middle and lower parts of the study area (fig. 7d). However, yield increases from the upper to the lower parts (fig. 7a) due to groundwater flow and storage capacity. Groundwater flow from the recharge area to the discharge zone is driven by gravity and pressure, not by movement. The 130 l/s yield implies there is a productive fault that acts as a conduit for groundwater, as well as collecting water into a chamber called the collection chamber. The dark-colored part (fig. 7c) indicates that springs do not exist during the dry season.

To evaluate the spatial relationship between spring occurrence and hydrogeological controlling factors, fault density, lineament density, rainfall, and NDVI maps were prepared and compared with spring locations. The fault-density map shows that many springs are concentrated in areas of high to moderate fault density, indicating the strong influence of fault-controlled permeability on groundwater emergence. In contrast, the lineament-density map shows that lineaments are more dispersed and do not uniformly coincide with spring locations, suggesting that not all lineaments are hydraulically active. Fig. 7. Spatial relationship of spring locations with surface environmental factors: (a) rainfall distribution map and (b) NDVI

Rainfall shows a general spatial variation from relatively high values in the upper part of the basin to lower values toward the lower rift-floor area. However, high spring discharge does not occur only in the highest rainfall zones, indicating that recharge alone does not control spring yield. The NDVI map shows moderate vegetation variability, with vegetation mainly reflecting surface moisture and land-cover conditions. Therefore, rainfall and NDVI are interpreted as secondary factors, while fault density and structural connectivity are the main controls on spring occurrence and discharge variation.

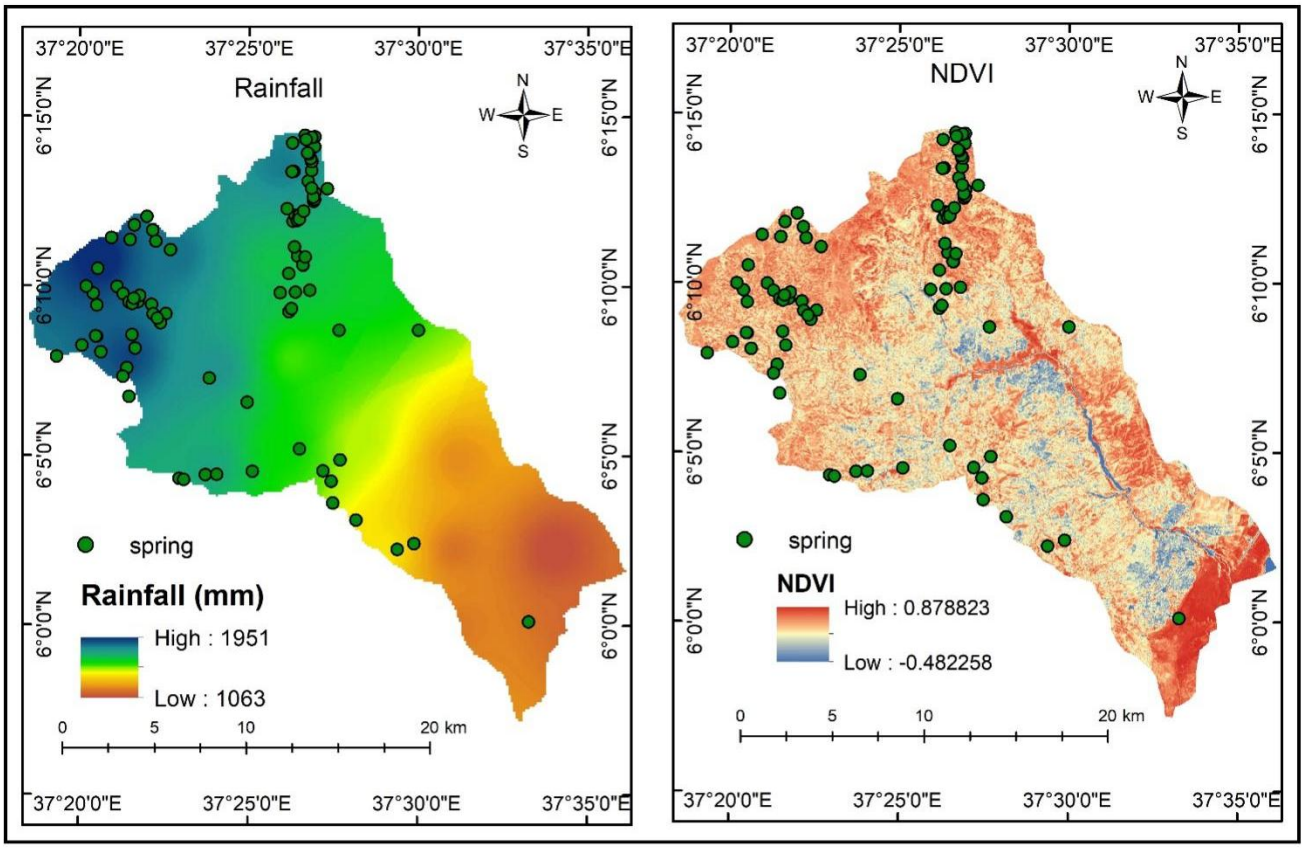


Fig. 7. Spatial relationship of spring locations with surface environmental factors: (a) rainfall distribution map and (b) NDVI map of the Kulfo River basin.

Hydrogeology

The origin, flow, and chemical composition of groundwater are controlled by the lithology, distribution, thickness, and structure of the hydrogeological units through which it moves (UNESCO, 1972). The nature of the groundwater system, occurrence, movement, and distribution of water in the aquifer below the Earth's surface is very complex. However, by using different parameters and approaches and considering subsurface openings, a hidden water resource in the underground environment is identified on the hydrogeological map. The rift valley lake basin in MER comprises two portions: the northern (Lake Ziway to Hawassa) and the southern (Lake Abaya to Lake Chew Bahir). The nature of the aquifer system across the northern-to-southern portion of RVLB is variable, reflecting hydraulic properties that range from regional to local scales. Kulfo river basin is one of the sub-basins in Lake Chamo, and its hydrogeology varies from the upper to the lower portions. Numerous seasonal and perennial spring water and groundwater reservoirs characterize it. Tectonic fractures and normal

faults highly govern the aquifer system of this basin. Fig. 8. Shows spring distribution and discharge variation in the Kulfo River basin: (a) groundwater flow direction and spring-discharge classes, (b) interpolated spring-discharge variation, (c) 3D physiographic surface model, and (d) spring distribution in relation to lithology, drainage, and faults.

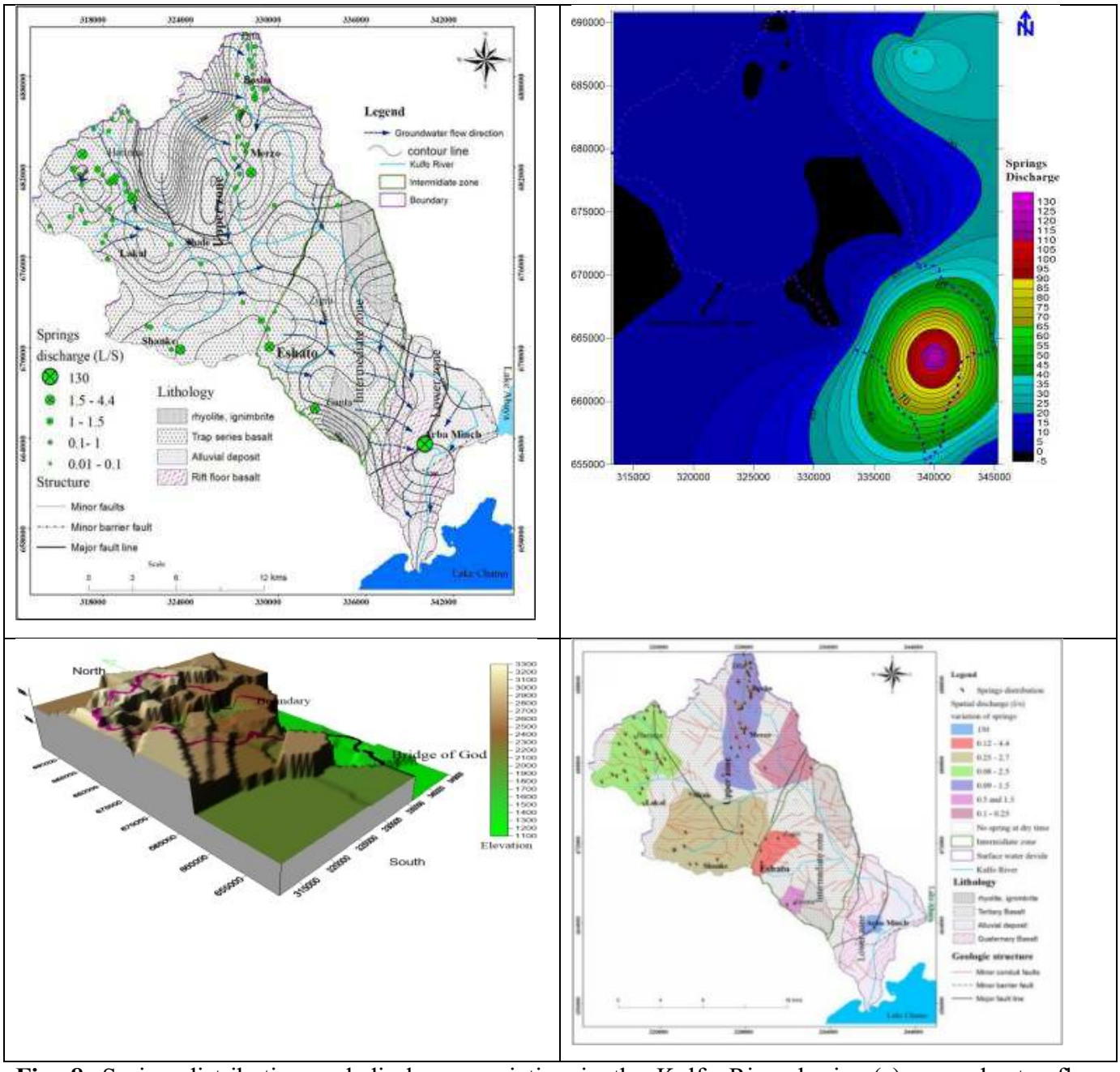


Fig. 8. Spring distribution and discharge variation in the Kulfo River basin: (a) groundwater flow direction and spring-discharge classes, (b) interpolated spring-discharge variation, (c) 3D physiographic surface model, and (d) spring distribution in relation to lithology, drainage, and faults.

Spatial statistical analysis of spring distribution and discharge

The spatial statistical analysis provides quantitative evidence for the observed non-uniform distribution of springs and spring discharge in the Kulfo River basin. While the previous section shows that spring yield varies from 0.01 l/s to 130 l/s and that spring density is higher in the upper part of the basin but discharge is higher in the lower part, the spatial statistical results confirm that this pattern is not random. Instead, the occurrence and discharge of springs are spatially organized by localized hydrogeological conditions, especially structural connectivity, fault-controlled permeability, drainage convergence, and lithological variation. The summary of the spatial statistical results is presented in Table 4.

The spatial relationship between springs and structural-density factors is shown in Figure 8. The fault-density map indicates that many springs are located in areas of moderate to high fault density, suggesting that fault-controlled fracture permeability strongly influences groundwater emergence. In contrast, the lineament-density map shows a more dispersed pattern, and springs do not uniformly coincide with all lineament-density zones. This indicates that the presence of lineaments alone does not necessarily produce spring discharge; rather, groundwater emergence depends on the hydraulic activity, openness, depth, and connectivity of faults and fractures. Fig. 9. Shows the spatial relationship of spring locations with surface environmental factors: (a) rainfall distribution map and (b) NDVI map.

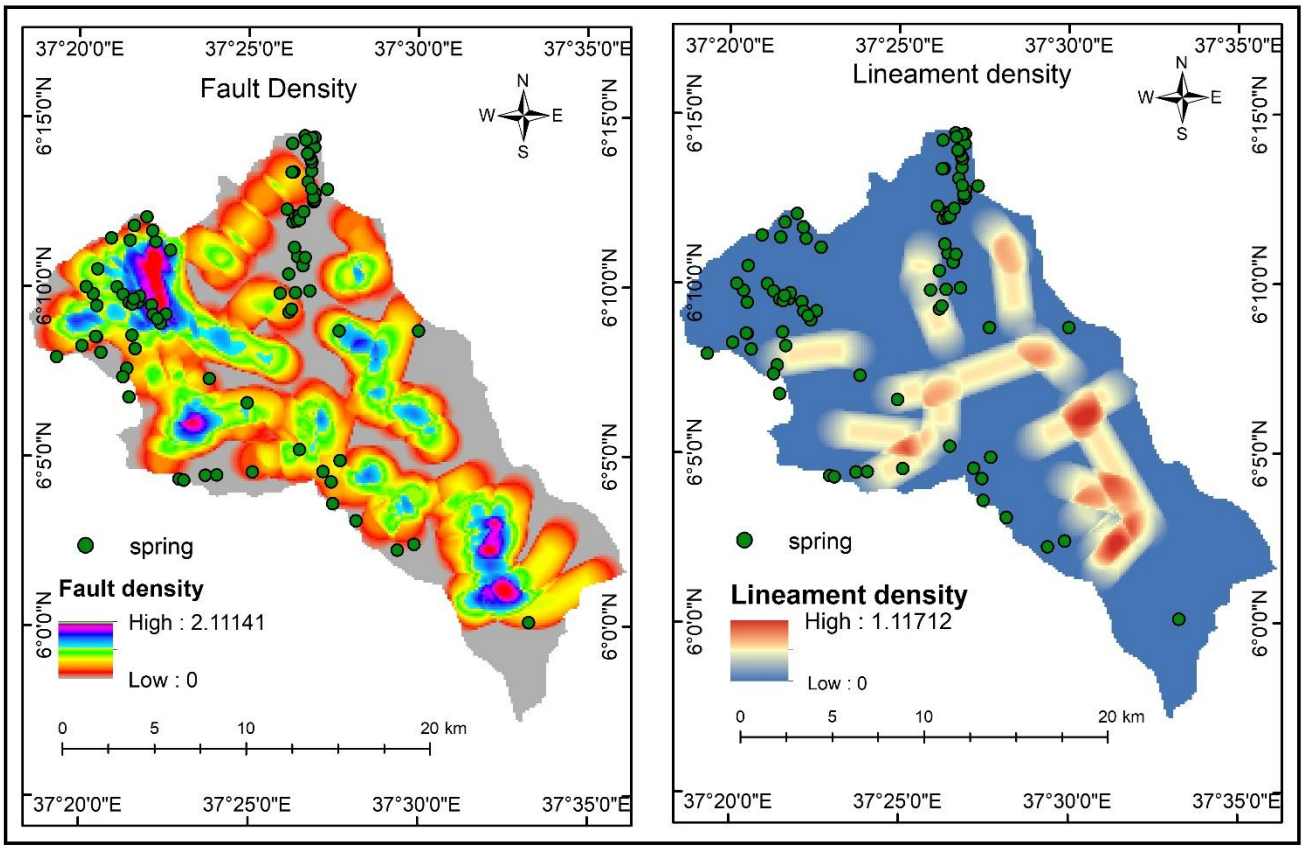


Fig. 9. Spatial relationship between spring locations and structural controlling factors in the Kulfo River basin: (a) fault-density map and (b) lineament-density map

Table 4. Summary of spatial statistical results for spring distribution and controlling factors

Analysis	Result	Interpretation
Nearest Neighbor Analysis	R = 0.526	Strong clustering of springs
Moran's I	I = 0.096, p = 0.013	Weak but significant spatial autocorrelation
Faults/lineaments	R = 1.452	Dispersed structural network
NDVI	CV = 0.195	Weak direct control on spring occurrence

Nearest Neighbor Analysis of Spring Distribution

Nearest Neighbor Analysis was used to determine whether the spatial distribution of springs is clustered, random, or dispersed. The result yielded a Nearest Neighbor Ratio (R) of 0.526, indicating a strongly clustered distribution of springs. Since an R-value less than 1 indicates clustering, the result confirms that spring locations in the Kulfo River basin are not randomly distributed across the landscape. Rather, they are spatially concentrated in favorable hydrogeological zones. This clustered

distribution is consistent with the field and geological observations presented in the manuscript. Many springs occur along fault zones, escarpment margins, fractured volcanic rocks, river valleys, and lithological contact zones. The upper part of the basin contains a large number of springs, but most have relatively low discharge, while the lower part contains fewer springs with significantly higher discharge, including the Arba Minch spring system. This indicates that distinct yet related hydrogeological factors control the number of springs and the discharge volume. Spring occurrence is favored by local fracture openings and shallow litho-structural conditions, whereas high discharge is associated with deeper, better-connected fault systems and regional groundwater flow paths. The clustered spring pattern, therefore, supports the interpretation that groundwater discharge is controlled by localized structural and geomorphic conditions rather than by uniform regional factors. In particular, clustered spring occurrence may reflect zones where faults, fractures, joints, river incision, lithological boundaries, and slope breaks intersect to create preferential groundwater emergence points. This result strengthens the existing interpretation that groundwater occurrence in the Kulfo River basin is mainly controlled by faults, fractures, and fractured volcanic aquifers.

Spatial pattern of faults and lineaments

In contrast to the clustered distribution of springs, the Nearest Neighbor Ratio for structural features, including faults and lineaments, is R = 1.452, indicating a dispersed structural network. This means that faults and lineaments are widely distributed across the basin rather than being concentrated only around spring zones. This result is important because it shows that the mere presence of faults and lineaments does not automatically produce spring discharge. Instead, springs are likely controlled by specific structural configurations, especially where faults and lineaments intersect, where fracture apertures are open, where fault zones connect recharge areas with discharge areas, or where barrier faults force groundwater toward the surface. Therefore, the structural control on groundwater occurrence is selective and localized rather than uniform. The dispersed pattern of faults and lineaments also explains why some structurally affected areas lack major springs. Some faults may act as groundwater conduits, while others may act as barriers or exhibit limited hydraulic connectivity due to clay filling, mineral sealing, narrow fracture apertures, or unfavorable orientation. This supports the conceptual model already described in the manuscript, in which faults are interpreted as conduits, barriers, and storage zones depending on their hydrogeological conditions.

Moran's I spatial autocorrelation of spring yield

Global Moran's I was used to assess whether similar spring yields occur near each other. The analysis

produced a Moran's I value of 0.096 with a statistically significant p-value of 0.013. This result indicates weak but statistically significant positive spatial autocorrelation of spring yield. Although the Moran's I value is low, its statistical significance shows that spring yield is not spatially random. Similar discharge values tend to occur near each other more than would be expected by chance. This suggests that the groundwater system is spatially heterogeneous: some zones favor high-yield discharge, while low-yield springs or no dry-season spring occurrence dominates others. The weak magnitude of Moran's I is hydro geologically meaningful. It indicates that a single continuous regional factor does not control spring yield. Instead, discharge varies according to local controls, including fracture size, fault connectivity, lithological permeability, and hydraulic gradient, recharge concentration, and proximity to regional discharge zones. This supports the observed basin-scale pattern in which many low-discharge springs occur in the upper catchment, while fewer but higher-yielding springs occur in the lower rift-floor area. Therefore, Moran's I indicates a non-random, yet spatially diffuse groundwater distribution system. The result supports the interpretation that groundwater discharge in the Kulfo River basin is governed by localized hydrogeological controls rather than uniform basin-wide conditions.

Getis-Ord Gi* hotspot and cold spot analysis

Getis-Ord Gi* hotspot analysis was applied to identify statistically significant clusters of high and low spring yield. The result distinguishes groundwater discharge hotspots and cold spots within the basin. Hotspot zones, represented by positive Gi* Z-scores greater than 1.96, indicate statistically significant concentrations of high spring yield. Cold spot zones, represented by Gi* Z-scores less than -1.96, indicate statistically significant concentrations of low spring yield. The hotspot zones represent areas where groundwater discharge is concentrated and where aquifer conditions are favorable for sustained spring flow. These zones are likely associated with major fault systems, fault intersections, lineament crossings, highly fractured volcanic rocks, river-valley convergence, and localized recharge accumulation. In the lower part of the basin, the presence of high-yield springs, especially the Arba Minch spring system, indicates strong subsurface hydraulic connectivity between upland recharge zones and lower-discharge areas. Cold spot zones represent areas with low spring yield or weak groundwater emergence. These areas are likely associated with massive or less fractured lithological units, poor fracture connectivity, limited permeability, reduced recharge concentration, or weak hydraulic connection to regional groundwater flow paths. Cold spots may also occur where faults behave as barriers rather than conduits, preventing groundwater from reaching the surface. The hotspot

and cold spot pattern therefore refines the interpretation of groundwater potential zones. It shows that groundwater occurrence is not simply controlled by lithology or structure alone, but by the spatial combination of structural permeability, hydraulic gradient, lithological storage capacity, and groundwater-flow convergence. The hotspot map should therefore be used as a supporting map for the hydrogeological classification and groundwater-potential interpretation.

NDVI and land-surface variability

The NDVI results show relatively low spatial variability, with a mean of 0.586, a standard deviation of 0.114, and a coefficient of variation of 0.195. This indicates moderate and relatively uniform vegetation cover across the analyzed spring environment. The low coefficient of variation suggests that vegetation condition alone has a limited direct influence on spring occurrence and discharge. Although vegetation may be denser around spring emergence zones, fault-controlled depressions, moist valley floors, and groundwater-fed areas, the NDVI result indicates that land-cover variation is not the dominant control on spring distribution. Instead, vegetation is better interpreted as a secondary surface expression of subsurface moisture availability. This finding is consistent with the manuscript's interpretation that geology, faults, fractures, and physiographic conditions primarily control spring occurrence. Vegetation may help identify moisture-rich areas, but it should not be treated as an independent controlling factor for groundwater discharge in the basin.

Elevation clustering and topographic control

Elevation clustering identified four distinct terrain zones, indicating that topography contributes to the spatial organization of spring occurrence and discharge. The topographic variation of the basin is important because elevation influences recharge, hydraulic gradient, groundwater-flow direction, spring emergence level, and the relationship between recharge and discharge zones. The upper catchment, located at a higher elevation, acts mainly as a recharge zone and contains many low-yield springs associated with fractured and weathered volcanic rocks. The intermediate zone functions as a transition area where groundwater movement is influenced by slope, river incision, and structural openings. The lower rift-floor zone acts as a major discharge area, where regional groundwater flow is expressed through high-yield springs. However, the statistical results indicate that topography alone does not fully explain spring yield. Elevation, slope, and other surface factors exert a weaker influence than fault density and structural connectivity. Therefore, topography should be interpreted as a secondary control that guides groundwater movement, while faults and fractures provide the main hydraulic pathways for groundwater discharge.

Regression analysis and controlling factors of spring yield

Ordinary Least Squares regression was used to evaluate the relationship between spring yield and selected environmental variables, including elevation, slope, NDVI, rainfall, lineament density, and fault density. The regression model was based on 83 observations after excluding records with missing raster values, No Data cells, or invalid predictor values. This should be clearly stated, as the manuscript reports 92 perennial springs, whereas the regression analysis uses 83 valid observations. The OLS model explained 13.4% of the variability in spring yield, with an R^2 value of 0.134 and an adjusted R^2 value of 0.065. The low R^2 value indicates that linear surface variables alone have limited capacity to explain spring-yield variation in the Kulfo River basin. This is expected in fractured volcanic aquifer systems, where groundwater discharge is controlled by complex subsurface conditions that may not be fully represented by surface variables. The model produced an F-statistic of 1.957 with a probability value of 0.0823, indicating that the overall model is weak at conventional statistical significance levels. The overall model performance and diagnostic statistics are summarized in Table 5.

Table 5. OLS regression model summary for spring yield

Statistic	Value
Dependent variable	Yield
Number of observations	83
R-squared	0.134
Adjusted R-squared	0.065
F-statistic	1.957
Prob. F-statistic	0.0823
Log-likelihood	-73.448
AIC	160.9
BIC	177.8
Durbin-Watson	2.320
Jarque-Bera	1301.541
Prob. JB	2.37E-283
Skewness	3.494
Kurtosis	21.098
Condition number	5.26E+04

However, individual predictor results provide important hydrogeological insight. Among all variables, fault density is the only statistically significant predictor of spring yield, with a coefficient of 0.4252, t-value of 2.649, and p-value of 0.010. The positive coefficient indicates that spring yield tends to increase with increasing fault density.

This result provides strong quantitative support for the manuscript's main geological interpretation:

faults are the dominant structural control on groundwater occurrence and discharge. In particular, the positive and significant relationship between fault density and spring yield suggests that fault zones enhance groundwater movement, concentrate flow paths, and facilitate spring emergence. This is especially important in the lower part of the basin, where high-yield springs are associated with regional fault-controlled discharge zones. Other variables were not statistically significant in the OLS model. Elevation has a coefficient of 0.0001 and p-value of 0.736; slope has a coefficient of 0.0025 and p-value of 0.668; NDVI has a coefficient of 0.1263 and p-value of 0.865; rainfall has a coefficient of -0.0016 and p-value of 0.152; and lineament density has a coefficient of -0.3888 and p-value of 0.596. These results suggest that surface topographic, climatic, vegetation, and lineament-density variables exhibit weaker direct linear relationships with spring yield than fault density.

Although lineaments are important indicators of structural discontinuities, the negative and statistically insignificant coefficient suggests that lineament density alone does not guarantee high spring yield. This supports the interpretation that groundwater discharge is not controlled solely by lineament abundance, but by the hydraulic quality, depth, openness, orientation, and connectivity of structural features. The model has a high condition number of 5.26E+04, indicating possible multicollinearity among predictors. This means that some explanatory variables, such as elevation, slope, rainfall, lithology, drainage, fault density, and lineament density, may be interrelated. For example, fault zones may influence slope breaks, drainage alignment, lithological boundaries, and spring emergence zones simultaneously. Therefore, the regression coefficients should be interpreted as supporting evidence rather than as complete independent causal effects. The regression coefficients show that fault density is the only statistically significant predictor of spring yield, as shown in Table 6.

Table 6. OLS regression coefficients for spring yield

Variable	Coefficient	Std. Error	t-value	p-value	95% CI Lower	95% CI Upper	Significance
Constant	2.5189	1.036	2.432	0.017	0.456	4.582	Significant
Elevation	0.0001	0.000	0.339	0.736	-0.001	0.001	Not significant
Slope	0.0025	0.006	0.431	0.668	-0.009	0.014	Not significant
NDVI	0.1263	0.742	0.170	0.865	-1.352	1.604	Not significant
Rainfall	-0.0016	0.001	-1.448	0.152	-0.004	0.001	Not significant
	-		-				Not

Lineament density	0.3888	0.730	0.533	0.596	-1.843	1.065	significant
Fault density	0.4252	0.161	2.649	0.010	0.106	0.745	Significant

Variable importance of hydrogeological controlling factors

Variable-importance analysis ranked the relative contribution of controlling factors to spring-yield variation. The result showed that stream density has the highest importance value, with a score of 0.460038, followed by fault density at 0.154796, rainfall at 0.135146, slope at 0.071621, elevation at 0.063429, lithology at 0.055521, NDVI at 0.031333, land use/land cover at 0.025310, and lineament density at 0.002805. The high importance of stream density indicates a strong spatial association between spring occurrence and drainage networks. This is hydro geologically reasonable because many springs emerge along valley sides, stream heads, slope breaks, and drainage-convergence zones where groundwater intersects the land surface. Stream density may therefore represent both surface-water organization and the expression of groundwater discharge. Fault density is the second most important variable and the only statistically significant predictor in the OLS regression model. This combination of results suggests that fault density is the most reliable direct structural control on spring yield, while stream density may represent the geomorphic expression of groundwater discharge and catchment drainage convergence. Therefore, stream density should be considered an important associated factor, whereas fault density should be considered the strongest statistically supported controlling factor.

Rainfall, slope, elevation, and lithology show moderate importance, indicating that they influence groundwater recharge, hydraulic gradient, aquifer storage, and flow direction. However, their effects are likely indirect and spatially variable. NDVI and land use/land cover have relatively low importance values, suggesting that vegetation and surface cover are secondary factors in controlling spring discharge. Lineament density has the lowest importance score, reinforcing the interpretation that not all mapped lineaments are hydraulically active or connected to productive groundwater flow paths. The relative importance of the hydrogeological controlling factors is summarized in Table 7.

Table 7. Relative importance of hydrogeological controlling factors

Rank	Variable	Importance
1	Stream density	0.460038
2	Fault density	0.154796
3	Rainfall	0.135146
4	Slope	0.071621
5	Elevation	0.063429
6	Lithology	0.055521

7	NDVI	0.031333
8	Land use/land cover	0.025310
9	Lineament density	0.002805

Hydrogeological classification

The hydrogeological classification of different lithological units is based on the hydrogeological and hydraulic properties of the aquifers that facilitate groundwater flow through natural and well pumpage. The hydrogeologic units in the study area are classified as aquifer of fractured rift floor basalt, fractured trap series basalt, highly weathered and fractured trap series basalt, ignimbrite, and rhyolite) aquifer and alluvium aquifer (Table. 8). The boreholes penetrated alluvial deposits are AMT# BH1 at a depth of 112m, AMU-BH6 at a depth of 68 m, AMU-BH7 at a depth of 86m, AMU-BH8 at a depth of 42 m, and AMU-BH9 at 60 m. Based on BH yields, transmissivity in the lower part, spring discharge variation and distribution, and water-bearing formations (aquifers), the formations are classified as high, medium to high, and low productive. Based on the BH well log, the thickness of the alluvial deposit varies from 42 to 112 m. Fig. 10. Shows the hydrogeology map of the Kulfo River basin.

Table 8. Hydrolithologic unit for the manifestation of aquifer classification

Hydrogeological units	Borehole yield(l/s)	Minimum springs yield (l/s)	Transmissivity (m2/day)	Distribution of perennial springs (No)	Aquifer classification
Fractured rift floor basaltic unit	-	130	unknown	40	High productive
Fractured trap series basaltic unit	-	0.1 – 4.4	unknown	72 – 90	Medium - high productive
Mixed trap series	-	< 0.08	unknown	4 – 12	Low productive
Quaternary alluvial deposits	3 to 52	No spring	30 - 525	-	Medium - high productive

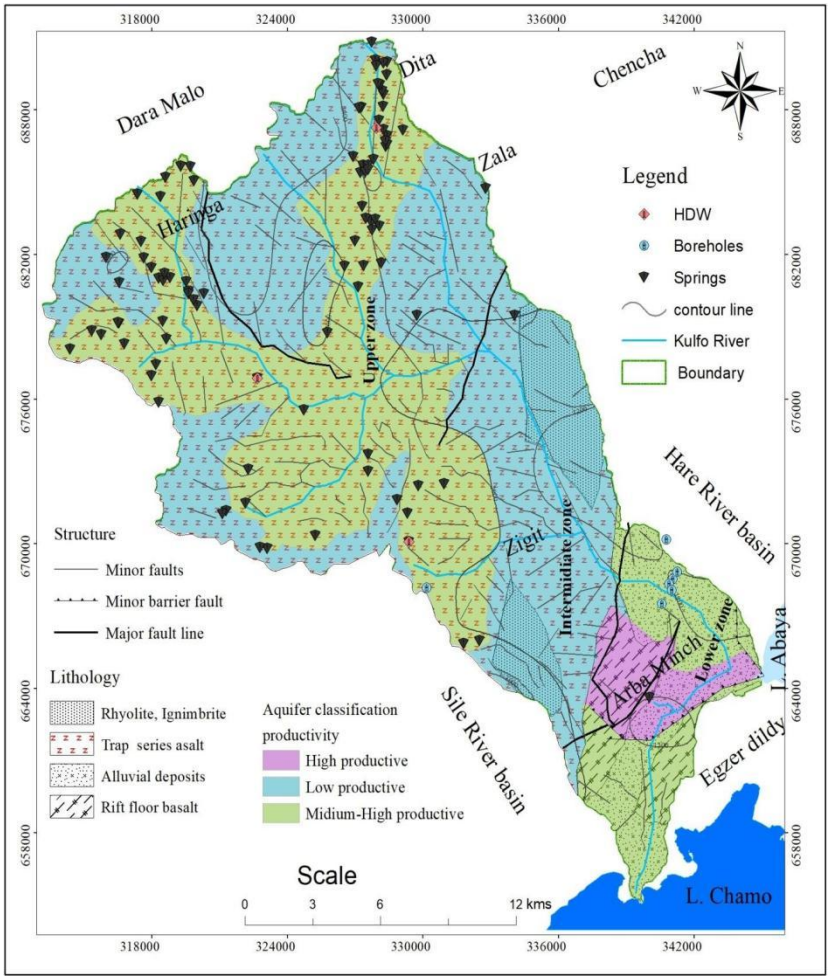


Fig. 10. Hydrogeology map of the Kulfo River basin

Groundwater flow

Groundwater flow does not follow a single lateral or vertical line below the earth's surface toward a lower catchment. This is due to tectonism, which causes crustal breaks that form faults and joints underground. The important parameters used to detect groundwater flow direction are the static water levels of existing boreholes and the elevation of a perennial spring well. Just as surface water, groundwater tends to move down gradient from higher water table elevations to lower elevations (Niven Kresic, 2010). In this case, groundwater flow in the river basin commonly depends on water head, which decreases in the flow direction (fig. 11). In this figure, the groundwater flow pattern is oriented downstream toward forty springs and an alluvial aquifer. Groundwater flow direction points out that the river basin is highly fractured and dynamically connected at depth.

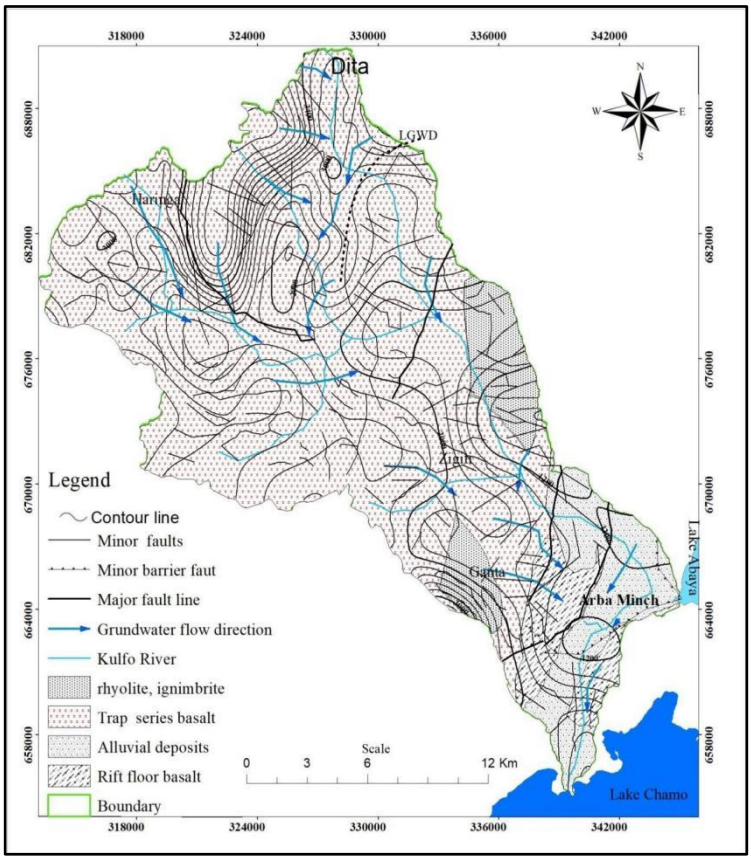


Fig. 11. Groundwater flow direction map

Faults, spring discharge, and variation

As a result of geotectonic activity (Davis SN., et al., 1960), the morphologic system in the study area is characterized by step-up and step-down features with sharp fault escarpments. As a result of a downthrown block, a young, deeply penetrating fault is associated with the rift floor and some of the upper zone. Faults are major geologic and geomorphologic structures that control the discharge of spring water through conduits and barriers beneath the Earth's surface. Faults themselves play one of the following three roles: conduit for groundwater flow, storage of groundwater, and barrier to groundwater. Figure 12a shows that springs in the upper and middle parts of the Kulfo River basin mainly emerge from fractured tertiary basalt along slope breaks, escarpments, and local fault or fracture zones. Springs such as Gum'ee, Bosha Kashe, Merzo, and Eshato are controlled by fracture-guided groundwater flow. The arrows indicate that groundwater moves through fissures and joints from higher elevations toward lower discharge points. This supports the interpretation that many upper-basin springs are local groundwater outlets with relatively low to moderate discharge because they are mainly

supplied by shallow fractured volcanic aquifers.

Figure 12b illustrates the hydrogeological condition of the lower basin around the Arba Minch or Forty Springs system. In this area, groundwater flow is controlled by a major fault plane, fissured Quaternary basalt, and overlying alluvial deposits. The water table slopes toward the fault-controlled discharge zone, where groundwater is forced upward and emerges as high-yield springs. This explains why the lower basin contains fewer springs but much higher discharge than the upper basin.

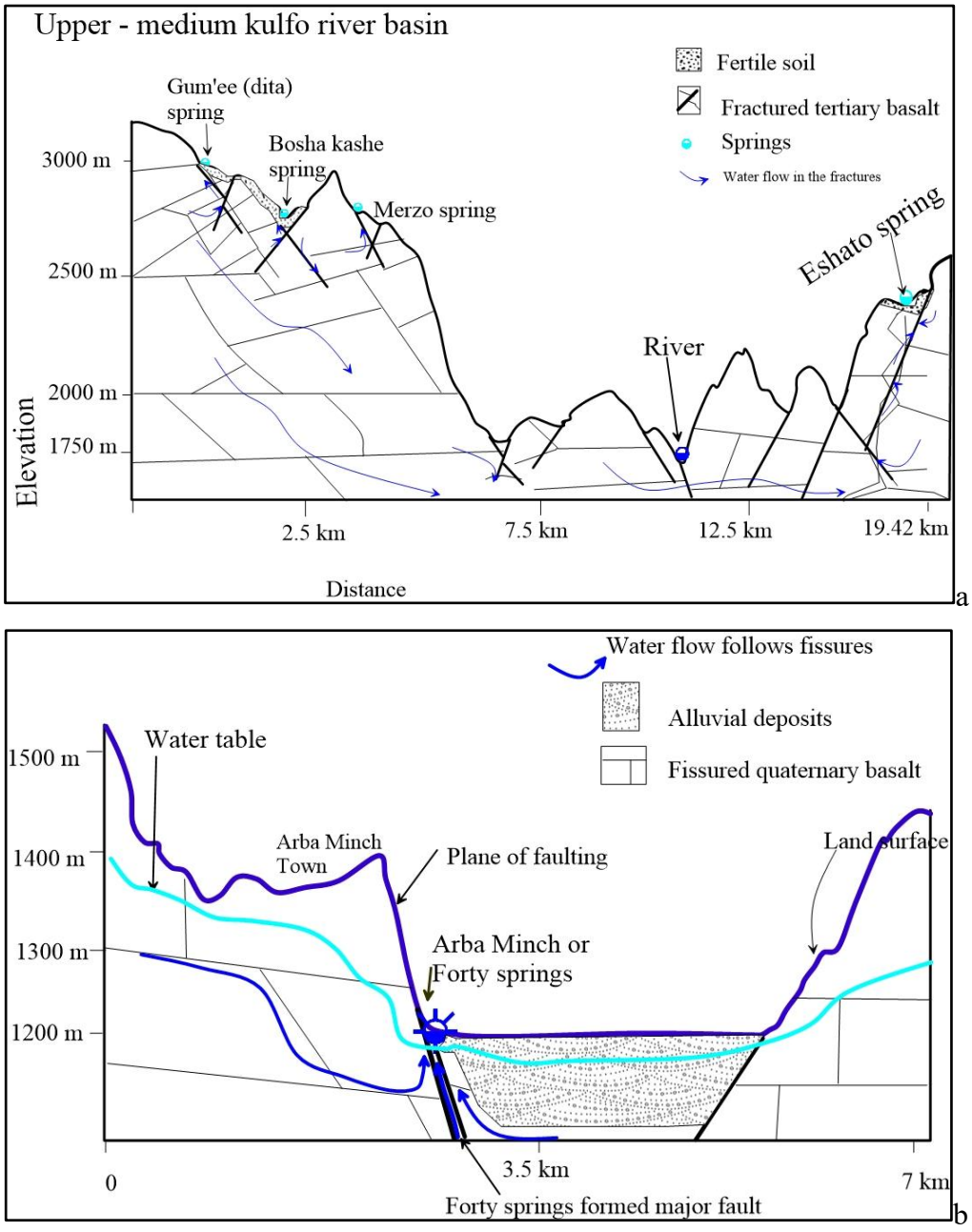


Fig. 12. Conceptualized map overview of fault control on groundwater flow. a. in the upper and middle parts of the Kulfo River basin. b. lower basin around the Arba Minch or Forty Springs system

Discussion

Interpretation of spring-discharge variation

The spatial variation in spring discharge across the Kulfo River basin indicates that groundwater occurrence is heterogeneous and controlled by the combined effects of lithology, structural connectivity, physiographic position, and drainage convergence. The basin contains many perennial springs in the upper catchment, but most of them have low dry-season discharge, commonly between 0.01 and 2.7 l/s. In the intermediate zone, measured dry-season discharge generally ranges from 0.1 to 4.4 l/s, whereas the lower rift-floor zone contains fewer but much higher-yielding springs, especially the Arba Minch spring system with a minimum dry-season discharge of about 130 l/s and a reported maximum discharge of about 250 l/s. This contrast shows that the number of springs and the magnitude of discharge are controlled by different hydrogeological conditions. Numerous low-yield springs in the upper catchment indicate shallow, local groundwater circulation within weathered and fractured volcanic rocks, while high-yield springs in the lower basin indicate more integrated groundwater flow paths connected to deeper and regionally extensive structures. The persistence of spring flow during the dry season is a strong indication of groundwater storage and hydraulic connectivity in the aquifer system. Springs are surface expressions of groundwater flow, and their discharge commonly reflects aquifer permeability, hydraulic gradient, recharge-discharge relationships, and the degree of connection between fractures and storage zones (Tóth et al., 2022; Mostowik et al., 2021; Kouassi et al., 2024). Therefore, the observed dry-season spring discharge in the Kulfo River basin should not be interpreted only as local seepage. Instead, it represents the visible outlet of a structurally guided groundwater system. This interpretation is consistent with studies showing that springs are useful indicators for characterizing groundwater systems where direct borehole information is limited (Nishimura et al., 2022; Seelig et al., 2024).

Structural control on groundwater occurrence

The results strongly indicate that faults and fracture networks are the dominant controls on groundwater emergence in the basin. Field observations, geological cross-sections, and the groundwater-flow map show that many springs occur along escarpment margins, river valleys, lithological contacts, and fault-controlled depressions. The lower-basin high-yield springs are particularly associated with major regional faults, including the Arba Minch fault system and related rift-floor structures. These faults likely act as conduits that transmit groundwater from upland recharge areas toward the lower discharge

zone. In some locations, faults may also behave as barriers that impede lateral flow and force groundwater upward to the surface.

This conduit-barrier interpretation agrees with previous hydrogeological studies showing that faults can transmit, store, or obstruct groundwater depending on their aperture, filling material, orientation, connectivity, and relationship with host-rock permeability (Scibek et al., 2016; Keegan-Treloar et al., 2022). In volcanic terrains, groundwater flow commonly depends on secondary porosity produced by fractures, joints, weathering, and tectonic deformation rather than on primary matrix porosity alone (Ayenew et al., 2008; Mengistu et al., 2021; Mihret & Wuletaw, 2025). The Kulfo River basin follows this pattern: spring discharge is not uniformly distributed across all volcanic units, but is concentrated where fractured basaltic aquifers are intersected by hydraulically active structures.

The Nearest Neighbor Analysis supports this interpretation quantitatively. Spring locations show a strongly clustered spatial pattern, with a Nearest Neighbor Ratio of R = 0.526. Because R-values below 1 indicate clustering, the result confirms that springs are not randomly distributed across the basin. Instead, they are concentrated in favorable hydrogeological zones. By contrast, faults and lineaments show a dispersed pattern, with R = 1.452. This difference is important because it shows that the mere presence of faults and lineaments does not automatically generate springs. Productive springs occur where specific structural conditions are met, particularly where faults, fractures, river incision, lithological contacts, and slope breaks intersect. Similar spatial-statistical approaches have been used to identify structural and terrain controls on spring and groundwater potential in other hydrogeological settings (Iván et al., 2020; Ahmad et al., 2021; Nhu et al., 2020).

Spatial dependence and localized groundwater discharge

Moran's I analysis produced a weak but statistically significant positive spatial autocorrelation of spring yield (I = 0.096, p = 0.013). The low magnitude of Moran's I indicates that spring discharge is not controlled by one uniform regional factor. However, the statistically significant p-value indicates that discharge values are more similar than would be expected by chance. This means that groundwater discharge in the Kulfo River basin is spatially organized but locally heterogeneous. High-yield springs are concentrated in structurally favorable zones, whereas low-yield springs dominate areas where groundwater circulation is shallow, fracture connectivity is limited, or permeability is low.

The Getis-Ord Gi* hotspot results further support this interpretation by distinguishing zones of high and low spring yield. Hotspot areas represent groundwater-discharge zones where structural permeability, hydraulic gradient, lithological storage capacity, and flow convergence combine to produce relatively

high spring discharge. These zones are most likely associated with major faults, fault intersections, fractured rift-floor basalt, and drainage-convergence areas. Coldspot areas represent low-discharge zones where rocks are less fractured, fracture apertures are narrow or sealed, or the hydraulic connection with regional groundwater flow paths is weak. Such spatial clustering and hotspot analysis are valuable because they move the interpretation beyond visual map comparison and provide quantitative evidence for groundwater-potential zoning (Ahmad et al., 2023; Islam et al., 2021; Li et al., 2020).

Lithological and hydrogeological implications

Lithology exerts an important secondary control on spring occurrence and discharge because it determines the storage and transmission properties of the aquifer units. The fractured rift-floor basaltic unit is interpreted as highly productive because it hosts the Arba Minch spring system and is associated with the highest measured spring discharge. The fractured trap-series basaltic unit is classified as medium to highly productive because it contains many perennial springs, although most have lower discharge than the lower-basin springs. Mixed trap-series volcanic units, including less fractured or less permeable units, are interpreted as low productive where spring yields are small. Quaternary alluvial deposits in the lower basin are also medium to highly productive based on borehole yields of about 3 to 52 l/s and transmissivity values reported in the manuscript.

This lithological pattern agrees with regional hydrogeological knowledge of Ethiopian volcanic aquifers, where fractured basalts, weathered volcanic rocks, and alluvial deposits commonly form productive aquifers, whereas massive or poorly fractured volcanic units have lower groundwater potential (Ayenew et al., 2008; Bonetto et al., 2021; Hulluka et al., 2023). However, the Kulfo results indicate that lithology alone is insufficient to explain spring discharge variation. The same broad volcanic terrain contains both numerous low-yield springs and fewer high-yield springs. Therefore, lithology provides the aquifer framework, while faults and fractures determine the hydraulic connectivity and discharge points. This explains why spring discharge generally increases from the upper fractured trap-series terrain toward the lower rift-floor basalt and alluvial aquifer system.

Role of topography, drainage, and land-surface factors

Topography and drainage also influence the spatial pattern of springs by controlling recharge elevation, hydraulic gradient, valley incision, and the point where groundwater intersects the land surface. The upper catchment, with high elevation and rugged terrain, functions mainly as a recharge and local discharge zone. The intermediate zone acts as a transition area where groundwater moves along slope-controlled and structurally controlled pathways. The lower rift-floor zone serves as a major discharge

area, where regional groundwater emerges through high-yield springs. This pattern is consistent with basin-scale groundwater-flow concepts in which groundwater moves from higher hydraulic head zones toward lower discharge areas (Tóth et al., 2022).

Variable-importance analysis showed that stream density had the highest importance value (0.460038), followed by fault density (0.154796), rainfall (0.135146), slope (0.071621), elevation (0.063429), lithology (0.055521), NDVI (0.031333), land use/land cover (0.025310), and lineament density (0.002805). The high importance of stream density is hydrogeologically meaningful because many springs occur near streamheads, valley margins, slope breaks, and drainage-convergence zones. Stream density may therefore represent both surface-water organization and the geomorphic expression of groundwater discharge. However, stream density should not be interpreted as the primary cause of spring yield. Rather, it reflects locations where groundwater pathways, valley incision, and surface drainage networks intersect.

NDVI showed relatively low spatial variability, with a mean of 0.586, a standard deviation of 0.114, and a coefficient of variation of 0.195. This suggests that vegetation condition alone has limited direct control on spring occurrence and discharge. Vegetation may be denser around spring outlets, moist valley floors, and fault-controlled depressions, but it is better interpreted as a surface expression of shallow moisture or groundwater emergence rather than as an independent controlling factor. Similarly, elevation and slope contribute to groundwater movement by influencing recharge and hydraulic gradient, but their direct statistical relationship with spring yield is weaker than that of fault density.

Regression evidence for fault-dominated control

The OLS regression model provides important quantitative support for the structural interpretation. The model used 83 valid observations after excluding records affected by missing or invalid raster values. It explained 13.4% of the variability in spring yield (R^2 = 0.134; adjusted R^2 = 0.065), indicating that linear surface variables alone have limited predictive capacity in this fractured volcanic aquifer system. This low explanatory power is expected because spring yield is controlled by subsurface fracture aperture, depth of fault penetration, degree of fracture interconnection, aquifer storage, and hydraulic boundary conditions, which are not fully represented by surface raster variables.

Among all predictor variables, only fault density showed a statistically significant positive relationship with spring yield (coefficient = 0.4252, t = 2.649, p = 0.010). This confirms that spring discharge tends to increase with higher fault density and supports the field-based interpretation that faults provide the main pathways for groundwater movement and emergence. Elevation, slope, NDVI, rainfall, and

lineament density were not statistically significant in the OLS model. The insignificant lineament-density coefficient is particularly important: it indicates that mapped lineament abundance alone is not equivalent to hydraulic activity. Only lineaments or faults with open apertures, sufficient depth, favorable orientation, and connection to recharge and discharge zones are likely to produce high spring yields. This result is consistent with studies emphasizing that geological structures influence groundwater occurrence only when they are hydraulically connected and sufficiently permeable (Idris et al., 2018; Embaby et al., 2024; Mihret & Wuletaw, 2025).

The model condition number (5.26E+04) suggests possible multicollinearity among explanatory variables. This is reasonable in the Kulfo River basin because faults simultaneously influence slope breaks, drainage alignment, lithological boundaries, valley development, and spring-emergence zones. Therefore, the regression coefficients should be interpreted as supporting evidence rather than as completely independent causal effects. Even with this limitation, the significant fault density result is consistent with the geological mapping, cross-sections, spring distribution pattern, and hydrogeological classification.

Groundwater occurrence and distribution model

The combined evidence supports a conceptual model in which groundwater is recharged mainly in the upper catchment at higher elevation and flows downward through fractured and weathered volcanic rocks. In the upper catchment, shallow fractures, joints, lithological contacts, and local slope breaks produce many low-discharge perennial springs (Keegan-Treloar et al., 2022; Medici et al., 2023). These springs indicate groundwater presence but generally reflect local aquifer storage and limited fracture connectivity. In the intermediate zone, groundwater flow becomes more structurally guided, and springs with moderate discharge occur where local faults and valley incision intersect. In the lower rift-floor zone, regional groundwater flow converges toward major faults and fractured rift-floor basalt, producing high-discharge springs such as the Arba Minch spring system (Keegan-Treloar et al., 2022; Medici et al., 2023).

This model explains why the basin contains both dense spring occurrence in the upper part and high-yield discharge in the lower part. Spring density reflects the frequency of local emergence points, whereas spring yield reflects the scale and connectivity of the groundwater-flow system feeding each outlet. The high discharge of the Arba Minch spring system, therefore, indicates a regional groundwater-discharge zone connected to deeper fault-controlled pathways. In contrast, the low-yield upper springs represent smaller local flow systems within fractured trap-series basalt and weathered volcanic units.

Similar relationships between spring discharge, structural permeability, and aquifer connectivity have been reported in fault-controlled and fractured aquifer systems elsewhere (Keegan-Treloar et al., 2022; Medici et al., 2023; Briški et al., 2020; Sapkota et al., 2024).

Implications for groundwater exploration and management

The results have direct implications for groundwater development in the Kulfo River basin. Groundwater exploration should prioritize zones where high fault density, stream convergence, fractured basaltic units, slope breaks, and lower-basin discharge conditions overlap. However, the dispersed distribution of faults and lineaments indicates that structural mapping alone is insufficient. Productive groundwater zones should be identified by integrating field observations, spring discharge data, fault and fracture mapping, lithological classification, drainage analysis, and spatial statistics. This integrated approach is consistent with recent groundwater-potential mapping studies in Ethiopia and other regions, which show that combining hydrogeological and geospatial variables improves groundwater assessment in data-limited basins (Abrar et al., 2021; Temesgen et al., 2023; Oyda et al., 2025; Ahmad et al., 2021).

Because perennial springs are important water-supply sources, especially during dry seasons, protection of recharge areas, spring outlets, fault-controlled discharge zones, and riparian corridors should be a management priority. The lower-basin high-yield spring system is especially important because it likely integrates groundwater flow from a larger recharge area. Land-use changes, contamination near spring outlets, excessive abstraction from connected aquifers, and degradation of recharge zones could reduce spring discharge or water quality. Sustainable use, therefore, requires monitoring spring discharge, groundwater levels, and water quality throughout the seasonal cycle. Such monitoring is also important because spring yield can respond to climate variability, changes in recharge, and aquifer storage conditions (Lamacová et al., 2024; Maria et al., 2024; Mukherjee et al., 2024).

Overall, the spatial variation in spring discharge in the Kulfo River basin indicates that groundwater occurrence is structurally controlled, lithologically conditioned, and topographically guided. The strongest evidence comes from the clustered distribution of springs, the significant spatial autocorrelation of spring yield, the hotspot distribution of high-yield discharge, and the statistically significant positive relationship between fault density and spring yield. The study therefore confirms that perennial springs provide reliable field evidence for identifying groundwater occurrence and distribution in structurally complex volcanic basins, particularly where borehole data are sparse.

The study has the following limitations: first, the spring discharge data used in this study were mainly based on dry-season measurements, and continuous seasonal monitoring was not available for all

springs. Therefore, the analysis may not fully capture temporal variations in spring discharge driven by seasonal recharge, rainfall variability, evapotranspiration, and short-term changes in groundwater storage. Although dry-season discharge is useful for identifying sustained groundwater occurrence, future monitoring during both wet and dry seasons would improve understanding of aquifer response and long-term spring sustainability. Second, the statistical and spatial analyses were primarily based on surface and near-surface factors, including elevation, slope, rainfall, NDVI, stream density, lineament density, fault density, lithology, and land use/land cover. However, groundwater occurrence in fractured volcanic terrains is strongly influenced by subsurface conditions, including fracture aperture, depth of fault penetration, aquifer thickness, hydraulic conductivity, fault filling material, and connectivity between recharge and discharge zones. Since these subsurface properties were not fully quantified, the regression model explained only part of the spring-yield variation. Therefore, the results should be interpreted together with detailed field mapping, geophysical surveys, borehole data, and hydro geochemical investigations. The findings of this study have important implications for SDG-oriented groundwater planning. The identification of fault-controlled high-yield spring zones supports SDG 6 by providing scientific evidence for sustainable groundwater exploration, spring protection, and improved water supply planning. The clustered distribution of springs and the strong influence of fault density indicate that groundwater development should not be conducted randomly, but should focus on structurally favorable and hydro geologically productive zones. This can reduce unsuccessful drilling, improve water-use efficiency, and support long-term groundwater sustainability. In addition, the recognition of dry-season spring discharge zones contributes to SDG 13 by helping communities and planners identify resilient groundwater sources during seasonal water stress and climate variability.

Conclusion

This study concludes that spatial variation in spring discharge is a reliable indicator of groundwater occurrence and distribution in the Kulfo River basin. The results show that springs are strongly clustered rather than randomly distributed, with many low-discharge springs in the upper catchment and fewer but high-yield springs in the lower rift-floor area, especially around the Arba Minch spring system. Spatial statistical analysis, including Nearest Neighbor Analysis, Moran's I, Getis-Ord Gi* hotspot analysis, and OLS regression, confirms that groundwater occurrence is mainly controlled by localized hydrogeological conditions. Among the evaluated factors, fault density is the only statistically significant predictor of spring yield, indicating that faults, fractures, and structurally connected volcanic aquifers play the dominant role in groundwater movement, storage, and discharge. Therefore, the

fractured rift-floor basalt, fractured trap-series basalt, and Quaternary alluvial deposits represent the most important groundwater-bearing units in the basin.

Based on these findings, groundwater development should prioritize fault-controlled zones, fractured basaltic aquifers, spring-discharge hotspots, valley-bottom areas, and structurally connected lower basin aquifers. Major springs, particularly the Arba Minch spring system, should be protected from contamination, overuse, and uncontrolled land-use change through the establishment of spring protection zones and regular monitoring. Future research should focus on seasonal spring discharge monitoring, hydrochemical and isotope analysis, geophysical investigations, groundwater flow modeling, and water-quality assessment to better understand recharge sources, flow paths, aquifer connectivity, and sustainable abstraction limits. Further studies should also evaluate the impacts of climate variability and land-use change on spring discharge and groundwater availability in the Kulfo River basin.

Overall, this study supports the implementation of SDG 6: Clean Water and Sanitation by improving understanding of groundwater occurrence, spring distribution, and groundwater potential zones in the Kulfo River basin. The results provide practical information for sustainable groundwater development, spring protection, and water-resource management. The study also contributes to SDG 13: Climate Action by identifying groundwater discharge zones that may serve as important water sources during dry periods and under future climate variability. Therefore, integrating spring-discharge analysis with geological, structural, and spatial statistical methods can strengthen sustainable water planning in the basin.

Statements and Declarations

Competing interests: The authors declare that they have no competing interests.

Clinical trial declaration: not applicable.

Ethical approval: Not Applicable.

Consent to participate: Not Applicable.

Consent to publish: Not Applicable.

Competing interests: The authors declare no competing interests.

Funding: The Arba Minch University Research and Dissemination Office AMU/RDO/2022 funded this study.

Data availability: Data related to this paper will be made available upon reasonable request from the corresponding author.

Acknowledgments

The authors would like to express their gratitude to the Arba Minch University for their financial support of this study. And our gratitude extends Gamo people who encouraged us during field work.

Author Contributions Statement:

Tekle Bangu: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization, Writing – reviewing and editing. Tariku Degife: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization, Writing – reviewing and editing. Dejene Getnet: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization, Writing – reviewing and editing. Teklehaimanot Teklearegay: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization, Writing – reviewing and editing. Muralitharan Jothimani: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization, Writing – reviewing and editing.

References

Abrar, H., Kura, A., Dube, E., & Beyene, D. (2021). AHP based analysis of groundwater potential in the western escarpment of the Ethiopian rift valley. Geology, Ecology, and Landscapes, 7, 175 - 188. https://doi.org/10.1080/24749508.2021.1952761.

Ahmad, I., Dar, M., Fenta, A., Halefom, A., Nega, H., Andualem, T., & Teshome, A. (2021). Spatial configuration of groundwater potential zones using OLS regression method. Journal of African Earth Sciences, 177, 104147. https://doi.org/10.1016/j.jafrearsci.2021.104147.

Ahmad, I., Zeleňáková, M., Fenta, A., Dar, M., Teka, A., Berhan, M., Damtie, M., & Nurye, M. (2023). Configuring the groundwater potential zone spatially using optimized hotspot analysis. Environmental Earth Sciences, 82. https://doi.org/10.1007/s12665-023-11160-2.

Aragaw, T., & Gnanachandrasamy, G. (2021). Evaluation of groundwater quality for drinking and irrigation purposes using GIS-based water quality index in urban area of Abaya-Chemo sub-basin of Great Rift Valley, Ethiopia. Applied Water Science, 11. https://doi.org/10.1007/s13201-021-01482-6.

Ayana, M., Bizuneh, Y., Koshuma, A., Workneh, A., Ali, B., & Lohani, T. (2022). Developing a DEM and Elucidating through SWAT to Conserve Soil in Kulfo Watershed of Rift Valley Basin, Ethiopia. Applied and Environmental Soil Science.

https://doi.org/10.1155/2022/7702739.

Ayenew, T., Demlie, M., & Wohnlich, S. (2008). Hydrogeological framework and occurrence of groundwater in the Ethiopian aquifers. Journal of African Earth Sciences, 52, 97-113. https://doi.org/10.1016/j.jafrearsci.2008.06.006.

Bonetto, S., Caselle, C., De Luca, D., & Lasagna, M. (2021). Groundwater Resources in the Main Ethiopian Rift Valley: An Overview for a Sustainable Development. Sustainability. https://doi.org/10.3390/su13031347.

Briški, M., Stroj, A., Kosovic, I., & Borović, S. (2020). Characterization of Aquifers in Metamorphic Rocks by Combined Use of Electrical Resistivity Tomography and Monitoring of Spring Hydrodynamics. Geosciences. https://doi.org/10.3390/geosciences10040137.

Burkhard, M., Atteia, O., Sommaruga, A., Gogniat, S., Evard, D. (1998). Tectonics and hydrogeology of the Neuchatel Jura. Eclogae Geologicae Helvetiae 91 (**1**), 177–183.

Charles R. Fitts (2002). Groundwater sciences, (Book). New York

Church TM. 1996. An underground route for the water cycle. *Nature* 380:579–80

Elshall, A., Arik, A., El-Kadi, A., Pierce, S., Ye, M., Burnett, K., Wada, C., Bremer, L., & Chun, G. (2020). Groundwater sustainability: a review of the interactions between science and policy. Environmental Research Letters, 15. https://doi.org/10.1088/1748-9326/ab8e8c.

Embaby, A., Youssef, Y., & El-Magd, S. (2024). Delineation of lineaments for groundwater prospecting in hard rocks: inferences from remote sensing and geophysical data. Environmental Earth Sciences, 83, 1-28. https://doi.org/10.1007/s12665-023-11389-x.

Frappart, F., & Merwade, V. (2022). Editorial: Groundwater systems worldwide. https://doi.org/10.3389/feart.2022.1097789.

Gebru, H., Gebreyohannes, T., Hagos, E., & Perilli, N. (2025). Hydrogeological Assessment and Steady-State Groundwater Flow Modeling for Groundwater Management in the Golina River Sub-Basin, Northern Ethiopia, Using MODFLOW 6. Water. https://doi.org/10.3390/w17070949.

Graaf, I., Graaf, I., Graaf, I., Gleeson, T., Beek, L., Sutanudjaja, E., & Bierkens, M. (2019). Environmental flow limits to global groundwater pumping. Nature, 574, 90 - 94.

https://doi.org/10.1038/s41586-019-1594-4.

Hulluka, T., Balcha, S., Yohannes, B., Bantider, A., & Negatu, A. (2023). Review: Groundwater research in the Ethiopian Rift Valley Lakes region. https://doi.org/10.3389/frwa.2023.819568.

Idris, M., Garba, M., Kasim, S., Madabo, I., & Dandago, K. (2018). The role of geological structures on groundwater occurrence and flow in crystalline basement aquifers: a status review. Bayero Journal of Pure and Applied Sciences. https://doi.org/10.4314/bajopas.v11i1.27.

Islam, Z., Ranganathan, M., Bagyaraj, M., Singh, S., & Gautam, S. (2021). Multi-decadal groundwater variability analysis using geostatistical method for groundwater sustainability. Environment, Development and Sustainability, 24, 3146 - 3164. https://doi.org/10.1007/s10668-021-01563-1.

Iván, V., Stevenazzi, S., Pollicino, L., Masetti, M., & Mádl-Szőnyi, J. (2020). An Enhanced Approach to the Spatial and Statistical Analysis of Factors Influencing Spring Distribution on a Transboundary Karst Aquifer. Water. https://doi.org/10.3390/w12082133.

Jothimani, M., Getahun, E., & Abebe, A. (2022). Remote sensing, GIS, and RUSLE in soil loss estimation in the Kulfo river catchment, Rift valley, Southern Ethiopia. Journal of Degraded and Mining Lands Management. https://doi.org/10.15243/jdmlm.2022.092.3307.

Keegan-Treloar, R., Irvine, D., Solórzano-Rivas, S., Werner, A., Banks, E., & Currell, M. (2022). Fault-controlled springs: A review. Earth-Science Reviews. https://doi.org/10.1016/j.earscirev.2022.104058.

Keegan-Treloar, R., Irvine, D., Solórzano-Rivas, S., Werner, A., Banks, E., & Currell, M. (2022). Fault-controlled springs: A review. Earth-Science Reviews. https://doi.org/10.1016/j.earscirev.2022.104058.

Kevin, M. Hiscock (2005). Hydrogeology, School of Environmental Sciences University of East Anglia: United Kingdom, Blackwell Publishing

Kouassi, K., Lachassagne, P., Mangoua, O., Sombo, A., & Dibi, B. (2024). Identifying the origin of springs in weathered-fractured crystalline aquifers using a hydrogeophysical approach. Scientific Reports, 14. https://doi.org/10.1038/s41598-024-63748-8.

Lachassagne, P., Dewandel, B., & Wyns, R. (2021). Review: Hydrogeology of weathered crystalline/hard-rock aquifers—guidelines for the operational survey and management of their groundwater resources. Hydrogeology Journal, 29, 2561 - 2594. https://doi.org/10.1007/s10040-021-02339-7.

Lamacová, A., Ledvinka, O., Bohdálková, L., Oulehle, F., Kreisinger, J., & Vlnas, R. (2024). Response of spring yield dynamics to climate change across altitude gradient and varied hydrogeological conditions.. The Science of the total environment, 171082 . https://doi.org/10.1016/j.scitotenv.2024.171082.

Li, Y., Tsangaratos, P., Shahabi, H., Ilia, I., Xue, W., & Bian, H. (2020). Groundwater Spring Potential Mapping Using Artificial Intelligence Approach Based on Kernel Logistic Regression, Random Forest, and Alternating Decision Tree Models. Applied Sciences. https://doi.org/10.3390/app10020425.

Maria, F., Stefano, S., Enrico, D., Michele, F., Christine, S., Gianluca, V., Tommaso, C., Beatrice, T., & Alessandro, G. (2024). Hydrogeological assessment of a major spring discharging from a calcarenitic aquifer with implications on resilience to climate change.. The Science of the total environment, 169770 . https://doi.org/10.1016/j.scitotenv.2023.169770.

Maria, F., Stefano, S., Enrico, D., Michele, F., Christine, S., Gianluca, V., Tommaso, C., Beatrice, T., & Alessandro, G. (2024). Hydrogeological assessment of a major spring discharging from a calcarenitic aquifer with implications on resilience to climate change.. The Science of the total environment, 169770 . https://doi.org/10.1016/j.scitotenv.2023.169770.

Masaoka, N., Kosugi, K., Yamakawa, Y., & Tsutsumi, D. (2016). Processes of bedrock groundwater seepage and their effects on soil water fluxes in a foot slope area.. Journal of Hydrology, 535, 160-172. https://doi.org/10.1016/j.jhydrol.2016.01.081.

Medici, G., Lorenzi, V., Sbarbati, C., Manetta, M., & Petitta, M. (2023). Structural Classification, Discharge Statistics, and Recession Analysis from the Springs of the Gran Sasso (Italy) Carbonate Aquifer; Comparison with Selected Analogues Worldwide. Sustainability. https://doi.org/10.3390/su151310125.

Meinzer, O.E. (1923). The occurrence of groundwater in the United States with a discussion of principles. U.S. Geological Survey, Water-Supply Paper 489, Washington, DC

Mengistu, T., Chung, I., Chang, S., Yifru, B., Kim, M., Lee, J., Ware, H., & Kim, I. (2021). Challenges and Prospects of Advancing Groundwater Research in Ethiopian Aquifers: A Review. Sustainability. https://doi.org/10.3390/su132011500.

Mihret, B., & Wuletaw, A. (2025). The impact of geological structures on groundwater potential assessment in volcanic rocks in the Borena Sayint district, northwestern Ethiopian Plateau: a review. Hydrology and Earth System Sciences. https://doi.org/10.5194/hess-29-2951-2025.

Ministry of water and energy (MoWE), 2012. The study on groundwater resources assessment in the rift valley lake basin in the Federal Democratic Republic of Ethiopia. Final report

Mostowik, K., Krzyczman, D., Płaczkowska, E., Rzonca, B., Siwek, J., & Wacławczyk, P. (2021). Spring recharge and groundwater flow patterns in flysch aquifer in the Połonina Wetlińska Massif in the Carpathian Mountains. Journal of Mountain Science, 18, 819 - 833. https://doi.org/10.1007/s11629-020-6524-2.

Mukherjee, A., Jha, M., Kim, K., & Pacheco, F. (2024). Groundwater resources: challenges and future opportunities. Scientific Reports, 14. https://doi.org/10.1038/s41598-024-79936-5.

NEH, Amend. (2012). The springs and Wells. Journal of National Resources Conservation Service, National Engineering Handbook.

Neven K. and Zoran S., (2010). Groundwater Hydrology of springs. (Book) ISBN: 978-1-85617-502-9,

Nhu, V., Rahmati, O., Falah, F., Shojaei, S., Al-Ansari, N., Shahabi, H., Shirzadi, A., Górski, K., Nguyen, H., & Ahmad, B. (2020). Mapping of Groundwater Spring Potential in Karst Aquifer System Using Novel Ensemble Bivariate and Multivariate Models. Water. https://doi.org/10.3390/w12040985.

Nhu, V., Rahmati, O., Falah, F., Shojaei, S., Al-Ansari, N., Shahabi, H., Shirzadi, A., Górski, K., Nguyen, H., & Ahmad, B. (2020). Mapping of Groundwater Spring Potential in Karst Aquifer System Using Novel Ensemble Bivariate and Multivariate Models. Water. https://doi.org/10.3390/w12040985.

Nigate, F., Van Camp, M., Yenehun, A., Belay, A., & Walraevens, K. (2020). Recharge–Discharge Relations of Groundwater in Volcanic Terrain of Semi-Humid Tropical Highlands of Ethiopia: The Case of Infranz Springs, in the Upper Blue Nile. Water.

https://doi.org/10.3390/w12030853.

Nishimura, R., Jones, N., Williams, G., Ames, D., Mamane, B., & Begou, J. (2022). Methods for Characterizing Groundwater Resources with Sparse In Situ Data. Hydrology. https://doi.org/10.3390/hydrology9080134.

Ojoawo, A., & Adagunodo, T. (2023). Groundwater occurrence and flow in varying geological formations. IOP Conference Series: Earth and Environmental Science, 1197. https://doi.org/10.1088/1755-1315/1197/1/012009.

Oyda, Y., Hatiye, S., & Jothimani, M. (2025). Identification of groundwater potential zones using geospatial analysis and frequency ratio model: the case of Kulfo-Hamassa watershed, Rift Valley, Ethiopia. Discover Applied Sciences, 7. https://doi.org/10.1007/s42452-025-07092-0.

RALPH C. HEATH (1983). Basic groundwater hydrology. U.S. Geological Survey Water-Supply Paper 22 -20, 86 p

Sapkota, A., Lamsal, S., & Paudyal, K. (2024). Mountain hydrogeology and influence of active fault: A study of the Bhimgethi-Devisthan section in Western Nepal. Journal of Nepal Hydrogeological Association. https://doi.org/10.3126/jnha.v1i1.78218.

Scibek, J., Gleeson, T., & McKenzie, J. (2016). The biases and trends in fault zone hydrogeology conceptual models: global compilation and categorical data analysis. Geofluids, 16, 782-798. https://doi.org/10.1111/gfl.12188.

Seelig, M., Seelig, S., Vremec, M., Wagner, T., Brielmann, H., Eybl, J., & Winkler, G. (2024). Quantitative Classification of Spring Discharge Patterns: A Cluster Analysis Approach. Hydrological Processes, 38. https://doi.org/10.1002/hyp.15326.

Setiawan, T., Alam, Y., & Haryono, E. (2023). Spatio-temporal variation of karst spring parameters for characterizing of the aquifer system of Watuputih Area, Indonesia. Journal of Water and Land Development. https://doi.org/10.24425/jwld.2020.133056.

Steiakakis, E., Vavadakis, D., & Mourkakou, O. (2023). Groundwater Vulnerability and Delineation of Protection Zones in the Discharge Area of a Karstic Aquifer—Application in Agyia's Karst System (Crete, Greece). Water. https://doi.org/10.3390/w15020231.

Tamiru Alemayehu, (2006). Ground water occurrence in Ethiopia (BSC, MSc, PHD) thesis, Addis

Ababa University Ethiopia

Temesgen, E., Goshime, D., & Akili, D. (2023). Determination of groundwater potential distribution in Kulfo-Hare watershed through integration of GIS, remote sensing, and AHP in Southern Ethiopia. Journal of Groundwater Science and Engineering. https://doi.org/10.26599/jgse.2023.9280021.

Tóth, Á., Kovács, S., Kovács, J., & Mádl-Szőnyi, J. (2022). Springs regarded as hydraulic features and interpreted in the context of basin-scale groundwater flow. Journal of Hydrology. https://doi.org/10.1016/j.jhydrol.2022.127907.

UNESCO, (1972). Groundwat er Studies. An International Guide for Research and Practice. (Book): Paris

Yisehak, B., Adhena, K., Shiferaw, H., Hagos, H., Abrha, H., & Bezabh, T. (2020). Characteristics of hydrological extremes in Kulfo River of Southern Ethiopian Rift Valley Basin. SN Applied Sciences, 2. https://doi.org/10.1007/s42452-020-3097-1.

Zanettin, B. (1978). The evaluation of Chencha Escarpment and Ganjuli Graben (Lake Abaya) in the Southern Ethiopia rift, N. jb. Geol. Palaont. Mh., pp. 473 -490