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Determination of Potential Aquifer Recharge Zones Using Geospatial Techniques for Proxy Data of Gilgel Gibe Catchment, Ethiopia

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Abstract: The lack of valuable baseline information about groundwater availability hinders the robust decision-making process of water management in humid, arid, and semi-arid climate regions of the world. In sustainable groundwater management, identifying the spatiotemporal and extrapolative monitoring of potential zone is crucial. Thus, the present study focused on determining potential aquifer recharge zones using geospatial techniques for proxy data of the Gilgel Gibe catchment, Ethiopia. Proxy data are site information derived from satellite imageries or conventional sources that are operated as a layer attribute in the geographical information system (GIS) to identify groundwater occurrence. First, GIS and analytical hierarchy process (AHP) were applied to analyze ten groundwater recharge controlling factors: slope, lithology, topographic position index lineament density, rainfall, soil, elevation, land use/cover, topographic wetness index, and drainage density. Each layer was given relative rank priority depending on the predictive implication of groundwater potentiality. Next, the normalized weight of thematic layers was evaluated using a multi-criteria decision analysis AHP algorithm with a pairwise comparison matrix based on aquifer infiltration relative significance. Lithology, rainfall, and land use/cover were dominant factors covering a weight of 50%. The computed consistency ratio (CR = 0.092, less than 10%) and consistency index (CI = 0.1371) revealed the reliability of input proxy layers' in the analysis. Then, a GIS-based weighted overlay analysis was performed to delineate very high, high, moderate, low, and very low potential aquifer zones. The delineated map ensures very high (29%), high (25%), moderate (28%), low (13%), and very low (5%) of the total area. According to validation, most of the inventory wells are located in very high (57%), high (32), and moderate (12%) zones. The validation results realized that the method affords substantial results supportive of sustainable development and groundwater exploitation. Therefore, this study could be a vigorous input to enhance development programs to alleviate water scarcity in the study area.

Keywords: aquifer recharge; groundwater resources; GIS and remote sensing; GIS-based AHP; groundwater potential mapping; proxy data sources

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1. Introduction

Assessing the continuous availability of freshwater in all climatic regions with low development costs is crucial to withstand the water-food security issues [1,2]. Nowadays, freshwater demand has become a global issue due to natural and anthropogenic influences [3–6]. Groundwater is a renewable resource that provides areas with limited access to surface water [7,8]. Groundwater is essential to improve socio-economic development in the rapidly increasing demand of rural and urban populations [9,10]. Africa has a substantial amount of groundwater storage that has not been adequately utilized and managed yet [11]. In Africa and most developing countries, such as Ethiopia, subsurface water is the leading source of crop production and drinking water supply [11–13]. Despite this, most people suffer water scarcity due to poor knowledge in identifying and utilizing water resource potentials to the limit [5,14,15]. However, most groundwater aquifers do not afford sufficient scientific evidence to assess groundwater flow for setting long-term utilization and national development goals [13,16].

The variability of groundwater recharge affects freshwater availability [17]. The spatiotemporal assessment of groundwater recharge is becoming a critical concern due to data scarcity in different climatic regions [18]. Recharging becomes effective if the infiltration is concentrated at a given time and space [19]. Groundwater recharge requires detailed assessments of scientific principles governing groundwater flow processes [20]. Delineating potential aquifer recharge zones (PARZ) in the areas of interest is vital in determining water demand and supply under hydrologic extremes [21,22]. However, several factors hinder water sector development from attaining sustainable and appropriate mitigating strategies [23–25]. The physical, hydrological, and climate variables are the key factors that govern the subsurface flow of the aquifer system [26]. Determining the governing controlling factors leads to reasonable design input and decision-making processes for complex systems. Identifying potential groundwater sites remains challenging as its exploration relies on precise analysis of hydrogeological data [27]. Recently, geospatial techniques have become essential tools in spatiotemporal predictions of groundwater [28–30].

Geospatial techniques have been used in many recharge studies to avoid dilemmas of methods that rely on groundwater flow [31,32], field surveys [13,32], and geophysical technologies [33], which are both costly and complex. The robust application of Geographic Information Systems (GIS) and Remote Sensing (RS) can manage the amount of spatially correlated governing parameters [34–37]. In addition, GIS increases the accuracy of results, minimizing bias [38]. The development of these technologies with Multi-Criteria Decision Analysis (MCDA) provided a new scientific inquiry in recent groundwater studies [39–42]. GIS and RS are effective tools that offer a fast and systematic spatiotemporal depiction of productive areas [2,14,29,43–45]. MCDA technique has been accepted worldwide for solving decision problems in driving groundwater controlling parameters [46–49]. The Analytical Hierarchy Process (AHP), advanced by Saaty [50], is the extensively used MCDA technique for complex decision-making in groundwater studies worldwide. The AHP provides a formalized approach for creating better resolutions of varied domains of highly dynamic, uncertain, and unpredictable complex decision-making problems [51,52]. Many authors comprehensively used different groundwater flow controlling parameters to delineate potential zones with GIS-based MCDA [25,30,53,54]. Various controlling factors were applied in other research conducted worldwide though the results vary from site [27]. Hence, accurate predictions of groundwater recharge zones challenged scientists as factors that control infiltration have remained unsolved [19,55].

In the Gilgel Gibe catchment, there is an alarming expansion of many satellite cities with unregulated population growth and increasing freshwater demand. Groundwater will remain the critical source of freshwater as most streams are drying up due to natural and anthropogenic activities. Groundwater has immense advantages of drought resilience [13], less treatment cost, and slow response to climate variability [56]. The area is mainly rain-fed agriculture despite the high potential for irrigable land. As rainfall is erratic, rainfall-dependent agriculture does not support sustainable crop production, resulting in food insecurity issues. Therefore, exploration of groundwater aquifers and identifying potential zones is desirable for sustainable groundwater management and selection of productive aquifers. Exploring PARZ is one of the best approaches for emerging viable water utilization for domestic, irrigation, and industrial developments [15]. PARZ can be determined from proxy data sources and has substantial advantages under data-scarce conditions [36,57–59]. Proxy data are site information produced from satellite imageries or conventional sources prepared as a geospatial layer attribute in the GIS environment. Satellite imagery affords tremendous insights into hydrologic characteristics [27,60]. However, robust application of proxy data has not been exclusively applied in the study area, which causes overexploitation and an unreliable decision-making process. Hence, the present study aims to determine potential aquifer recharge zones from proxy data sources of Gilgel Gibe catchment using geospatial techniques based on MCDA and AHP. This study used ten thematic layers to reinforce the data analysis and interpretation process. The present study will become significant baseline information to enhance aquifer management and engineering judgments.

2. Materials and Methods

2.1. Description of Study Area

The Gilgel Gibe catchment (GGC) is situated in Eastern Africa in the Omo-Gibe river basin of Southwestern Ethiopia. The watershed geographically (Figure 1) lies between (226126.133, 304388.193) North Latitudes and (811017.916, 883266.897) East Longitudes. Numerous intermittent rivers also characterize the catchment. The primary water source for the rivers is precipitation from the mountainous areas. The weather in Ethiopia is primarily managed through topography and seasonal variations in the Inter-Tropical Convergence Zone [61]. Ethiopia has a two-season tropical climate. The magnitude of rainfall varies with topography, location, and elevation. The catchment falls within the humid tropical class with a monomodal rainfall distribution. A semi-arid and humid subtropical weather is typically GGC. The cyclic wave of the intertropical convergence area and numerous panoramas mainly affect the climate conditions in Ethiopia. The GGC has an average annual rainfall and air temperature of 1405.8 mm and 18.5 °C, respectively. There is a dry winter weather season between October and April and a wet season (the summer season) between May and September. The geography of the catchment is typically rugged topography with varied mountains, hills, and plains, with upper plateaus divided by deep V-shaped valleys into the flanks and flat river terraces around the main river.

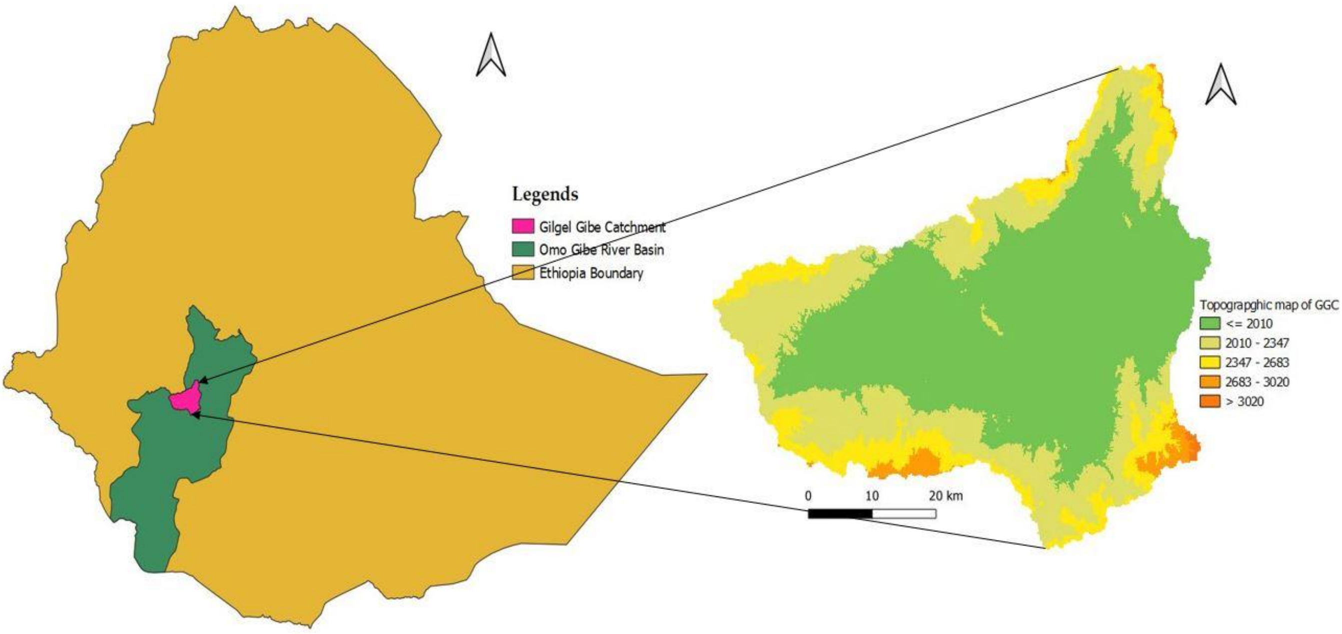


Figure 1. Location map of the study area.

2.2. Aquifers Recharge Controlling Parameters

Geospatial techniques, a synergistic effect of RS, GIS, and AHP, were employed to combine ten significant proxy data sets which affect groundwater potential and recharge rates. The proxy information was produced from satellite images using a digital image-processing algorithm. The generated proxy layers were prepared with a GIS environment to reclassify and adjust for further interpretation and spatial manipulation. Finally, a set of weights for their features were decided based on personal judgment and experts' opinion considering their relative significance for aquifer recharging potentiality in the area of interest. The comprehensive workflow approach for this study to delineate the final PARZ is shown in Figure 2.

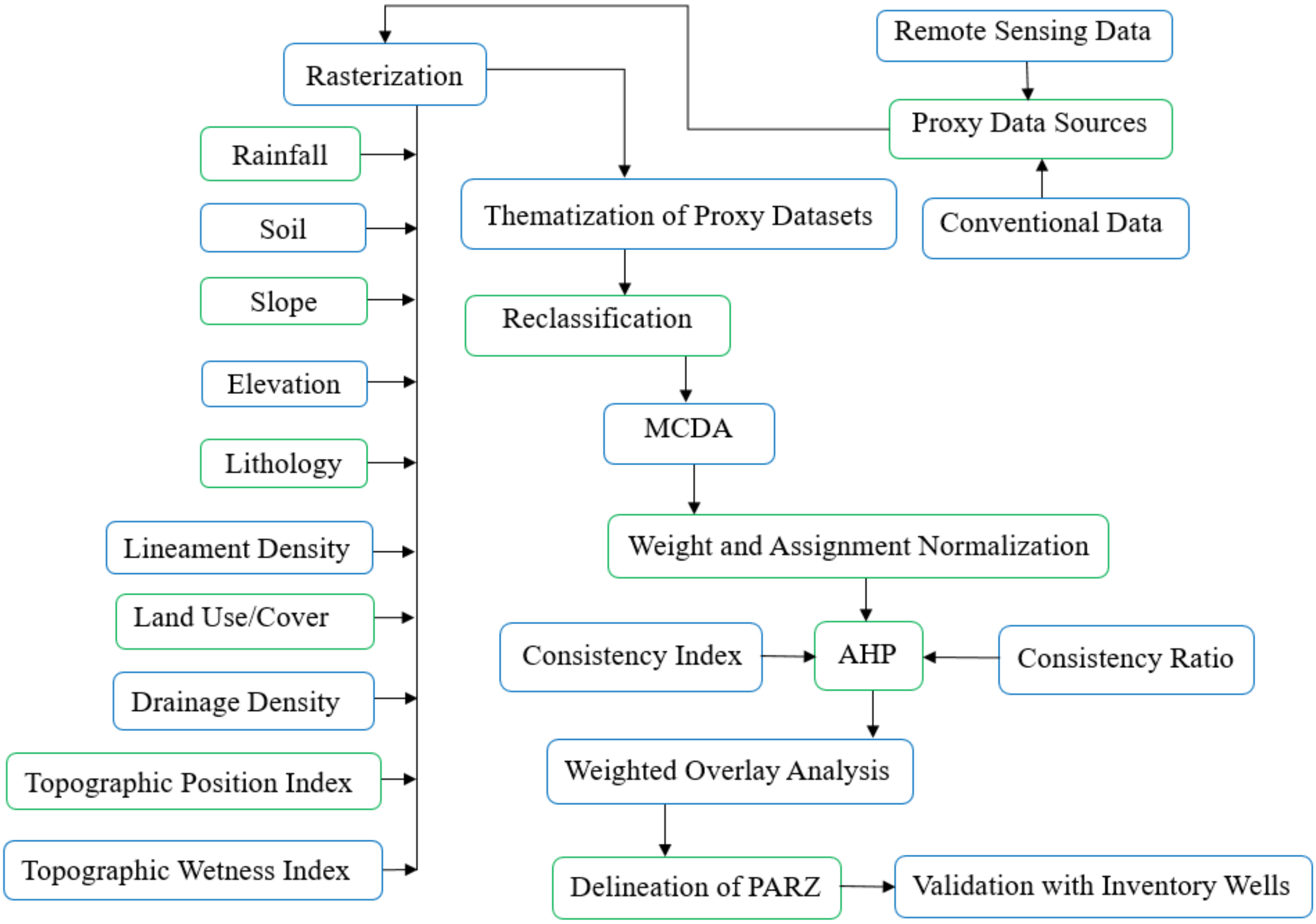


Figure 2. General flowchart of study methodology.

2.2.1. Rainfall

Rainfall is the primary basis for infiltration and recharge. Groundwater flow and storage capacity depend on the percolation rate in the aquifer [42,62,63]. The rainfall records of GGC and surrounding areas were collected from the National Meteorological Agency. Rainfall maps evolved from the historic rainfall information (1988–2018) measured from meteorological stations inside the study area's buffer zone. The rainfall map was produced using the soil and water assessment tool (SWAT) in the QGIS environment using the inverse distance weight (IDW) interpolation technique. The rainfall depth plays a significant role in infiltration; consequently, the weight rainfall classes were assigned (Figure 3a). The rainfall classes have been reclassified and ranked into five classes, mainly based on their effect on the flow and storage of groundwater.

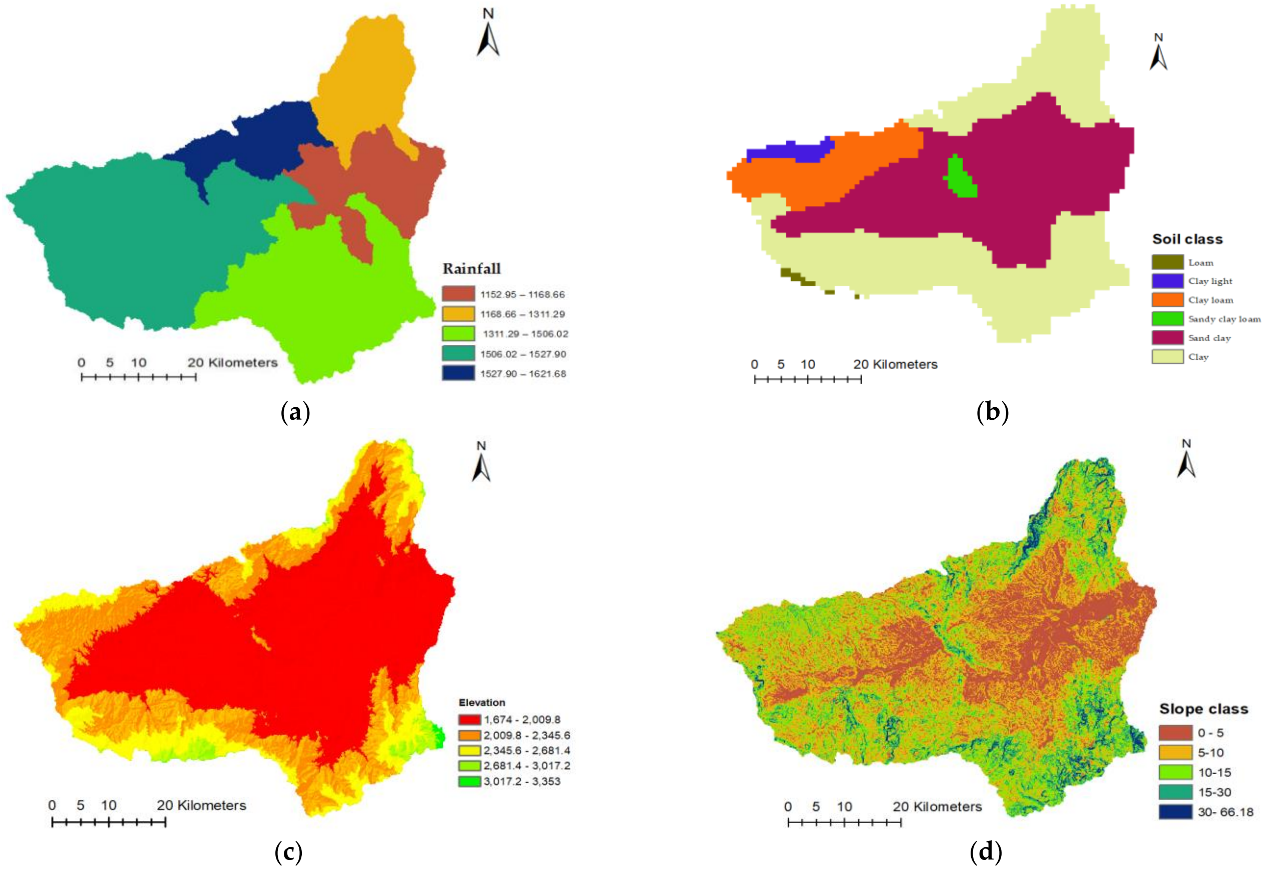


Figure 3. Thematic map of (**a**) Rainfall, (**b**) Soil, (**c**) Elevation, (**d**) Slope.

2.2.2. Elevation and Slope

The Digital Elevation Model (DEM) is a quantitative demonstration of landscape significant for science, hydrological applications, geologic analyses, and agricultural land management [64]. The required spatial data sets were projected to Adindan UTM Zone 37, the transverse Mercator projection parameter for Ethiopia. For the present study, 30-m grid resolution DEM was used and retrieved from freely available open-source product United States Geological Survey (USGS), Shuttle Radar Topography Mission (SRTM). The slope changes elevation between two locations and directly influences groundwater recharge and infiltration [65]. The water flow energy is driven by the slope [66,67]. Thus, slope and infiltration rate are inversely correlated factors [35,68,69]. This study generated the slope from SRTM DEM (Figure 3c), using the spatial analysis tool in the GIS environment. The slope was then reclassified and ranked into five classes flat, gentle, moderate, high, and steep slopes reliant on aquifers recharging potentiality, as indicated in (Figure 3d).

2.2.3. Land Use/Cover and Soil Map

The land use/cover (LULC) happens mainly due to population increase, urbanization, and anthropogenic activities [70,71], affecting infiltration, runoff, evapotranspiration rates, groundwater quantity, and recharge process [72,73]. LULC data were retrieved from World's First Global Land Cover Datasets at a 30 m Resolution, GlobeLand30 [74–76]. The LULC has been classified into inland water bodies, agricultural land, grassland, forest-mixed, range and shrubland, and settlement and urban. Groundwater recharge is subjective with LULC of the study area [35,70,77,78]. LULC is classified (Figure 4a) according to infiltration capacity suitable for aquifer potential. Soil influences groundwater recharging potential by controlling runoff and infiltration rates [36]. The catchment soil information was acquired from FAO Harmonized World Soil Database (HWSD) [79], a freely accessible open-source/www.fao.org/geonetwork/website (accessed on 23 April 2021). HWSD viewer v 1.21 was used to generate a code for soil properties. First, six dominant soil textures were distinguished, sandy clay loam, loam, clay loam, clay light, clay, and clay-heavy. Then the soil map linked to the soil database intended to hold data for all of the world's soils. Finally, the soil textures that are suitable for groundwater recharge were analyzed based on FAO classification on infiltration and water holding capacity.

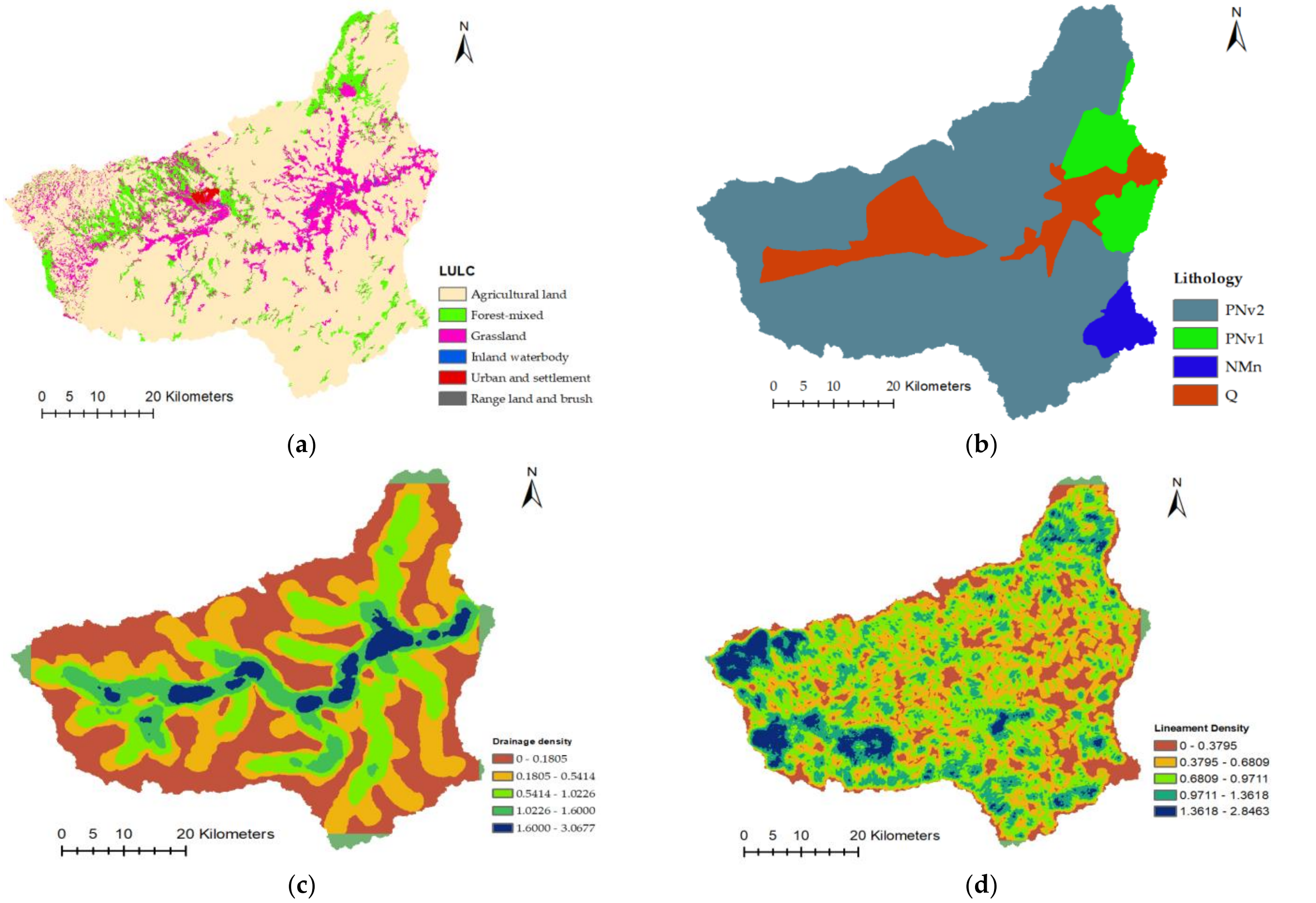


Figure 4. Thematic map of (**a**) LULC, (**b**) Lithology, (**c**) Drainage density, (**d**) Lineament density.

2.2.4. Drainage Density

Drainage density (DD) is the typical flow structure to a pooled point. DD refers to the closeness of stream networks and the total length of channel segment per unit area [69], as indicated in Equation (1). It indicates surface and subsurface formation, soil permeability, infiltration, and runoff. High DD values have high excess surface flow signifying a probability of low groundwater availability [59,80–82]. This implies that DD and permeability have an inverse correlation in determining potential aquifer sites [44,83]. In this study, DD was prepared using SRTM DEM by line density tool of the GIS environment and reclassified (Figure 4c) as appropriate for groundwater potential and recharging effects.

$$\mathrm{DD} = \sum_{\mathrm{i}}^{\mathrm{n}} \frac{\mathrm{D_i}}{\mathrm{A_i}} \tag{1}$$

where Di is the stream's total length (km), and A is the watershed unit area (km^2).

2.2.5. Lineament Density

Lineaments are physical discontinuity of the Earth's surface and linear plan landscapes critical for infiltration [42,84,85]. They are linear features in a terrain that demonstrates a fundamental geological structure such as folds, faults, joints, or fractures as secondary porosity [68,86,87]. Lineaments characterize the weak zones which disturb groundwater flow, increasing infiltration to the subsurface [88]. The thematic layer of LD (km/km^2) is defined as the total length of all verified lineaments divided by the unit area of grid cells [68], as given in Equation (2). The lineaments increase groundwater recharging potential implicitly if linked to an aquifer [68]. The lineaments were converted to an LD map using the Line Density Tool in the Spatial Analysis Tool inverse distance to a power function of the GIS environment. The LD was interpolated with Geospatial Data Abstraction Library (GDAL) toolbox with Inverse distance weighted (IDW). Each unit was then given weights on the suitability of infiltration contributions to groundwater, as indicated in (Figure 4d). Thus, high LD areas are suitable for groundwater recharge, and low LD is ideal for groundwater recharge and discharges [81,88,89].

$$\mathrm{LD} = \sum_{\mathrm{i}}^{\mathrm{n}} \frac{\mathrm{L_i}}{\mathrm{A_i}} \tag{2}$$

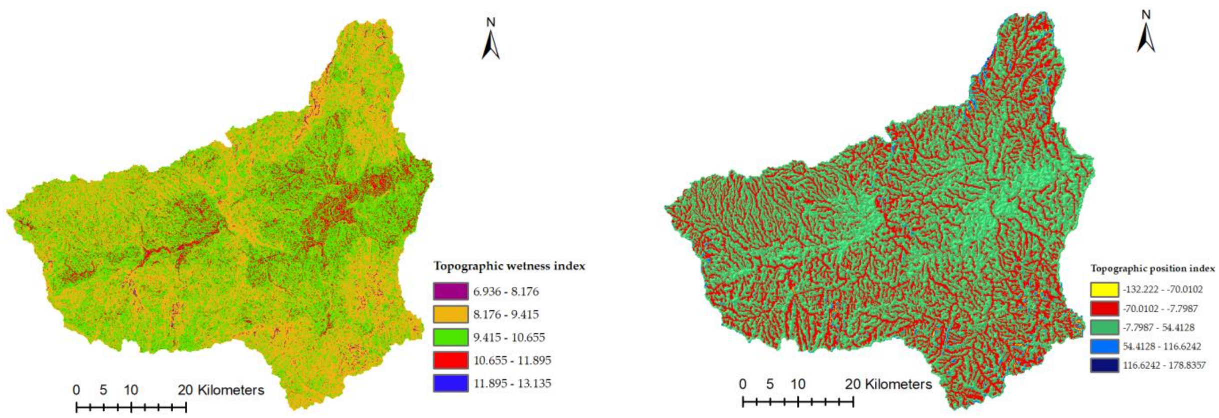
where $\mathrm{L_i}$ indicates lineaments' total length (km), A represents the unit area (km^2)

2.2.6. Lithology

Lithology governs the quantity and quality of groundwater occurrence and permeability of aquifer rocks [49,90]. It is a governing factor for empathetic recharge and infiltration processes [39,91,92]. Therefore, lithological characteristics should be examined to define PARZ accurately. The dominant geological materials are volcanic rocks, intercalated basalt flows with quaternary volcanic, lacustrine deposits, and alluvial sediments exposure [93]. The catchment consists of volcanic rocks (37–11 Ma) [94], the alluvial and lacustrine (sandy silt, clay, diatomite, limestone, and beach sand), Eocene and Paleocene-Pleistocene undivided lacustrine and fluvial sediments, sand, silt gravel conglomerate (Omo group), agglomerates, and basalts [20,93]. The spatial occurrence of the different geological materials is very complex and heterogeneous and not known in detail. Each lithology unit has a different impact on groundwater permeability. Hence, it was ranked as the aquifer's recharging and permeability feature (Figure 4b).

2.2.7. Topographic Position Index

The topographic position index (TPI) is an algorithm extensively applied to quantify topographic positions and systematize land surface categorizations [95]. TPI is a terrain classification method where each data point's altitude is evaluated against its neighbors [96]. In addition, it is correlated with various physical processes in the given aquifer system [97]. First, a TPI map was produced using the GDAL raster analysis tool of the QGIS environment. Then, the reclassification and ranking were conducted based on each unit's recharging suitability, as shown (Figure 5a).



(a) (b)

Figure 5. Thematic map of (**a**) Topographic position index, (**b**) Topographic wetness index.

2.2.8. Topographic Wetness Index

The topographic wetness index (TWI) measures terrain-driven variation in soil moisture, the subsurface lateral transmissivity, and blends the upslope catchment area of the aquifer system [98–100] and downslope drainage for each cell in a DEM [82]. TWI is used to evaluate the landscape influence on hydrological processes of infiltration. TWI was prepared using the TOPMODEL toolbox [101] in the QGIS. This model simulates hydrologic fluxes of water throughout the watershed [82], SAGA terrain analysis tool. Then, reclassified and ranked (Figure 5b) depending on the groundwater recharging capabilities [81].

2.3. Multi-Criteria Decision Analysis

Multi-criteria decision analysis (MCDA) is a technique used for configuring numerous problems and a principle of measurement by pairwise comparison and governed by experts' decisions [42]. Data normalization is widely used in GIS-based MCDA and diminishes all decision criteria to a standard measurement scale [39,41,57,88]. In this study, MCDA was used to configure numerous pairwise comparisons matrices' (PCM) to derive priority scales for proxy data layers. The AHP is a powerful tool introduced and developed by Saaty [50] to tackle different decision-making questions providing an MCDA for measuring one unique alternative. Saaty's AHP was used to normalize hierarchical orders for the comparative effectiveness of various proxy data layers. Then, it creates a PCM based on expert opinions or judgment between the standards chosen. Saaty's [50] importance scale of intensity relative importance (Table 1) compared the thematic maps classification criteria. The weights were normalized by averaging the values in each row to the corresponding ranking, which gives the normalized weights of each parameter.

The normalized principal eigenvector was computed to find the relative importance of parameters per PCM to find a consistency ratio (CR). The influence of each factor was decided by experts' knowledge [23,35] and personal judgment. Finally, the PCM of the assigned weights to different thematic layers using [102,103] were normalized using the eigenvector approach [50,104]. The CR, which indicates the suitability of a PCM, was computed to inspect the normalized implications as presented in [50,104,105]. CR is a measurement of the consistency of the PCM and calculated using Equation (3). The comparison of the random consistency index shows how essential a layer is [50]. The consistency index (CI) designates the tolerability of the reciprocal matrix, which is computed with the mean Eigenvalue of the PCM (λmax), random consistency index (RI), and the number of applied parameters (N) [50,106] as in Equations (3) and (4). The CR of the matrix is significant if less than 10% unless the matrix should be re-evaluated based on the (CI) measure tabulated in (Table 2) [104].

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{3}$$

$$\mathrm{CI} = \frac{\lambda\mathrm{max} - \mathrm{N}}{\mathrm{N} - 1} \tag{4}$$

Table 1. Saaty's 1–9 scale of relative importance [104].

Scale	Importance
1	Equal importance
2	Weak importance
3	Moderate importance
4	Moderate plus
5	Strong plus
6	Strong importance
7	Very strong importance
8	Very very strong importance
9	Extreme importance

Table 2. Tabulated standards of N for Saaty's ratio index.

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.89	1.12	1.24	1.32	1.41	1.45	1.49

2.4. Estimating Spatial Distribution of Recharge Zones

The PCM of the given weight for proxy data classes was constructed and normalized using AHP and the eigenvector approach. Next, a comparative rank for each raster was given depending on the extrapolative implication of groundwater potentiality. Next, the thematic raster layers were overlaid based on weighted overlay analysis (WOA) in the GIS environment. Finally, after the thematic maps were integrated, an output raster map was obtained to classify and quantify the potential aquifer recharge zones.

3. Results and Discussion

3.1. Assessing the Effects of Groundwater Controlling Parameters

Numerous parameters of measurable infiltration rates mainly control the potential aquifer recharge zone map development. Hence, the groundwater movement and occurrence controlling proxy data layers were presented and discussed in the following section according to the degree of infiltration to the subsurface for the potentiality of the aquifer system.

3.1.1. Rainfall and Soil Textures

The annual catchment rainfall ranges from 1152.95–1621.68 mm. The areal rainfall distribution is classified into five as 1152.95–1168.66, 1168.66–1311.29, 1311.29–1506.02, 1506.02–1527.90, and 1527.90–1621.68 mm very low, low, moderate, high, and very high, respectively (Figure 3a). Low rainfall shows low recharge indicating low groundwater potential zones, while the excessive rainfall quantities suggest the chance of high recharge, the potentiality of high groundwater zones. The catchment zones that obtained high rainfall have a chance of getting more percolated water than with low rainfall. In contrast, the high rainfall class is given high ranks as of its significance for groundwater recharge potentiality of the aquifer system. Rainfall infiltrates if the soil has sufficient permeability or goes away as overland flow based on the aquifer's nature. Therefore, it is reasonable to account for precipitation to determine its influence on groundwater recharge. Similar studies confirmed that rainfall is a critical parameter governing the groundwater potential recharge [23,25,41,53,57].

Soil texture controls the infiltration rate into the subsurface and influences groundwater recharge. The high hydraulic conductivity of the soil allows more infiltration and limits evaporation [29,45,107,108]. Therefore, the study area soil was reclassified and comprised of six soil types (Figure 3b). The soil was characterized by very low to very high infiltration capacity. Therefore, ranks were assigned as sandy clay loam (high), loam (high), clay loam (moderate), clay light (poor), clay (poor), and clay-heavy (very poor) based on infiltration and water holding capacity as suitable for groundwater. The groundwater potential is higher in a coarse-grained structure and very low in a fine-grained structured soil type. The least weight was assigned for clayey soil because clay horizons considerably restrict percolation and have low permeability.

3.1.2. Elevation and Slope

The elevation of the study area varies from 3353 m (highest) to 1674 m (lowest). In elevated areas, runoff conditions are high, and low infiltration indicates water delays over the land surface for percolation [68]. The elevation was reclassified and ranked as suitable for groundwater recharging potential 1674–2009.8 m (very high), 2009.8–2345.6 m (high), 2345.6–2681.4 m (moderate), 2681.4–3017.2 m (low), 3017.2–3353 m (very low) as shown in (Figure 3c). The lower elevation areas were more favorable for groundwater recharge predictions than higher elevations. However, soil texture is the leading cause of percolation in highly elevated areas. Potential groundwater is high at lower elevations with sandy loam soil. The percolation rate varies from low to very low at low elevations with clay soil. Similar studies confirmed that elevation was a good decision and robust parameter for delineating PARZ [59,88,109]. The slope affects groundwater percolation during the overland and base flow [110]. The landscape slope is classified into five classes based on suitability of recharging potential and infiltration rate, then assigned weights to each slope class. The classified slope (in degrees) was 0–5 (Flat), 5–10 (gentle), 10–15 (moderate), 15–30 (hill), and 30–66.18 (steep) with very high, high, moderate, low, and very low, respectively, of recharging suitability (Figure 3d). The slope classes with flat, gentle, moderate, hilly, and steep are 15.41%, 15.61%, 16.53%, 40.77%, and 11.68%, respectively. As steepness increases, the percolation rate decreases due to the high speed of overland flow. Therefore, flat and gentle slopes indicate the presence of high groundwater recharging potentials.

3.1.3. Land Use/Cover and Lithology

The LULC substantially influences infiltration rates [71–73,111]. This study ranked LULC classes based on the capacity to infiltrate water into the ground and water holding capacity. Inland water bodies, agricultural land, grassland, forest-mixed, range and shrubland, and settlement and urban (Figure 4a) were weighted and ranked as very high, high, moderate, slightly moderate, low, and very low, respectively, as suitable for recharging potentiality. The LULC classes of GGC constitute about 77.52% (agriculture), 12.08% (grassland), 9.84% (forest-mixed), and others for water bodies, settlement and urban, and range and shrubland. Agricultural land has high groundwater potential with more porosity increasing soil water percolation [48]. An intense agricultural activity changes the hydrologic cycle by causing soil moisture conditions and recharge [70,77]. Waterbodies are the most fundamental and permanent source of groundwater recharge. Forest-mixed sites have lower groundwater recharge rates than grassland increases groundwater recharge [84] and reduce the runoff process by increasing infiltration rates, thereby augmenting groundwater recharge. On the other hand, built areas generate runoff having poor groundwater recharging potential. Other studies have agreed that land use covers are essential in delineating potential groundwater zones [30,47,59,68,86].

Infiltration is predominantly good in plateaus covered by thick alluvial sediments [20]. The dominant lithology is divided into four aquifer subclasses based on permeability and productivity potentials. The study area Lithological unit groundwater prospect classification is adapted from [20], as shown in (Figure 4b). These are very highly permeable-volcanic sand (NMn), lower felsic, volcanic, and sedimentary formation (PNv1), sandy pyroclastic sediments of the Pleistocene-Holocene volcanic group (Qv1), upper felsic volcanic (PNv2). The quaternary sediments are alluvium, river gravels, fans, and travertine [20,112]. The quaternary alluvial has good potential for deposits and structures with higher permeability and productivity [20,112]. If fractured, quaternary volcanic have to yield considerable groundwater flow [113]. Numerous studies confirmed the importance of lithological features in PARZ map development [33,49,57,59,85].

3.1.4. Drainage Density and Lineament Density

Drainage density (DD) influences the distribution of runoff and infiltration [30]. Low DD is associated with widely spaced streams due to less resistant surface materials or high infiltration. Low DD leads to a coarse texture, while high DD is favorable with a high infiltration rate [23,114]. DD (km/km^2) values are categorized into five classes as 0–0.18045 (very high), 0.18045–0.54136 (high), 0.54136–1.02256 (moderate), 1.0226–1.6000 (low), and 1.6000–3.0677 (very low) as suitable for groundwater recharge rate rankings, respectively, as revealed in (Figure 4c). High DD values indicate low groundwater availability assigned with low rank having high runoff. The lowest DD values were given the highest level for decreasing runoff in the area, as low DD is related to higher recharge and higher groundwater potentials. High DD indicates impermeable sub-surface and mountainous relief. On the other hand, the low DD of the watershed reveals that it is composed of permeable subsurface, good land cover, and more infiltration capacity. Similar studies confirmed the applicability of DD in mapping potential groundwater zone [23,25,30,47,89]. Lineament density (LD) is directly relational to the groundwater perspective [85,89]. The LD (km/km^2) was determined and reclassified into five categories, 0–0.3795 (very low), 0.3795–0.6809 (low), 0.6809–0.9711 (moderate), 0.9711–1.3618 (high), and 1.3618–2.8463 (very high) as per prospects of groundwater suitability as shown in (Figure 4d). In a very high LD, there is a high infiltration rate to the subsurface, whereas, in low LD, the rate of infiltration is low [23,25,30,47,114].

3.1.5. Topographic Positioning Index and Topographic Wetness Index

The topographic position index (TPI) is used in figuring out the landscape's upper, middle, and lower components [97]. High TPI values are located close to the ends of hills, while small TPI is close to valley bottoms [47]. The highest rating is given for low TPI due to the potentiality of groundwater prospects. Accordingly, the TPI of this study was reclassified and ranked (Figure 5a) as −133.22 to −70.0102 (very high), −70.0102 to −7.7987 (high), −7.7987 to 54.4128 (moderate), 54.4128 to 116.6242 (low), and 116.6242 to 178.8357 (very low). These studies confirmed TPI as a vigorous groundwater flow controlling parameter in delineating PARZ [47,115]. The topographic wetness index (TWI) was applied to quantify topographic control of groundwater infiltration capability due to topographical effects [84,116]. The lowest rank was given to the lowest TWI and vice versa. Then, TWI were reclassified into five categories (Figure 5b) 6.936–8.176 (very low), 8.176–9.415 (low), 9.415–10.655 (moderate), 10.655–11.895 (high), and 11.895–13.135 (very high) as suitability for infiltration of soil water into the subsurface. This indicates that TWI considerably influences runoff concentration at the soil surface. Likewise, various studies used TWI as a robust parameter in determining PARZ [47,86,117].

3.2. Multi-Criteria Decision Analysis and Weight Normalization

In this study, the AHP was developed hierarchically, based on expert opinions, weighing the criteria were used to normalize principal eigenvector values depending on MCDA. The MCDA has been widely used in many studies to predict potential groundwater zones [25,40,44,45,67,84]. The weights were normalized and considered by averaging values to find the normalized weights of respective parameters. According to interpretation, the normalized weights of each feature of proxy data layers for groundwater potentiality are indicated in Table 3. In the PCM, the consistency ratio value was less than 0.1, indicating that all experts' weightings are consistent and suitable for implementation. The calculated normalized principal Eigenvector value (λmax = 11.371). A PCM is consistent only if λmax is equal to or more than the examined thematic layers; otherwise, a new matrix must be created. In the present study, λmax is 11.371 and has ten thematic layers, confirming that there is no need to develop a matrix of new data layers. Hence, the principal eigenvalue (λmax) exemplifies a purpose for the matrix divergence [106]. The λmax was computed depending on the consistency ratio from the PCM of ten parameters. The consistency index was calculated to overcome the consistency ratio formula, which results in CI = 0.1371. Then, taking the RI value as 1.49 from Table 2, the computed consistency ratio (CR = 0.0920), less than 10%, and the given weights were valid for further analysis. The CI and CR were evaluated, and a PCM of ten groundwater-controlling factors was generated in the AHP process. The consistency evaluation indicates that the PARZ s map developed using MCDA is reasonably accurate.

Table 3. Normalized weights for proxy layers as suitable for groundwater recharge.

Thematic Layers	Normalized Weight (%)	Category	Ranks	Similar Efforts
Rainfall	14.5	1152.95–1168.66 1168.66–1311.29 1311.29–1506.02 1506.02–1527.90 1527.90–1621.68	Very low Low Moderate High Very high	[23,25,30,41,53,57,59]
Lithology	20.2	NMn PNv1 Qv1 PNv2	High Moderately Moderately Poor	[33,49,57,59,85]
Land use/cover	15.3	WATR AGRC RNGE FRST RNGB URBN	Very high High Moderate Slightly moderate Low Very low	[25,30,59,68,80,88,89]
Drainage density	7.2	0–0.18045 0.18045–0.54136 0.54136–1.02256 1.0226–1.6000 1.6000–3.0677	Very high High Moderate Low Very low	[23,25,30,47,89]
Elevation	5.1	1674–2009.8 m 2009.8–2345.6 m 2345.6–2681.4 m 2681.4–3017.2 m 3017.2–3353 m	Very high High Moderate Low Very low	[43,59,88,109]
Slope	5.4	0–5 5–10 10–15 15–30 30–66.18	Flat Gentle Moderate Hill Steep	[23,25,28,43,53,57,114]
Lineament density	8.8	0–0.3795 0.3795–0.6809 0.6809–0.9711 0.9711–1.3618 1.3618–2.8463	Very low Low Moderate High Very high	[23,25,30,47,114]
Soil	8.8	Sandy loam Loam Clay loam Clay light Clay Clay-heavy	High High Moderate Poor Poor very poor	[23,25,30,36,53,57,59]
Topographic position index	7.5	−133.22 to −70.0102 −70.0102 to −7.7987 −7.7987 to 54.4128 54.4128 to 116.6242 116.6242 to 178.8357	Very high High Moderate Low Very low	[47,84,115]
Topographic wetness index	7.3	6.936–8.176 8.176–9.415 9.415–10.655 10.655–11.895 11.895–13.135	Very low Low Moderate High Very high	[47,84,86,116,117]

3.3. Evaluating the Spatial Distribution of Potential Recharge Zones

In the present study, the importance of factors is assigned based on experts' opinions and personal judgment as there is no standard scale for a simple WOA. The thematic layer's relative weight is defined using a PCM based on the expert judgment of other similar studies [24,30,59,68,69]. These criteria were weighted based on the recharging potentiality by constructing pairwise assessments in MCDA. The maps were reclassified into five classes based on aquifer recharging potentiality to examine the areas with different stages of aquifer recharging potential. The weighted index map of the study area was developed using ten thematic layers with WOA in the GIS environment. The raster layers and their corresponding weights have been assigned to account for relative significance from a recharging perspective. The computed scale importance weighted normalization showed the value of 20.2% for lithology, 15.3% for LULC, 7.3% for topographic wetness index, 8.8% for lineament density, 5.4% for slope, 5.1% for elevation, 8.8% for soil, 14.5% for rainfall, 7.2% for drainage density, and 7.5% for topographic position index. The dominant factors governing the aquifer recharging potential were lithology, rainfall, and LULC, covering about 50% of the total weight. The catchment is delineated into five PARZ zones: very high, high, moderate, low, and very low, combining all reclassified raster layers. The developed map covers very high (29%), high (25%), moderate (28%), low (13%), and very low (5%) of the total area. The developed PARZ map with high potential zones predominantly exists in the Eastern part (Figure 6). Accordingly, most of the southwestern and northeast parts of the catchment are categorized under high and very high groundwater potentiality. As revealed from the consistency index criteria, the selected groundwater controlling factors were reliable.

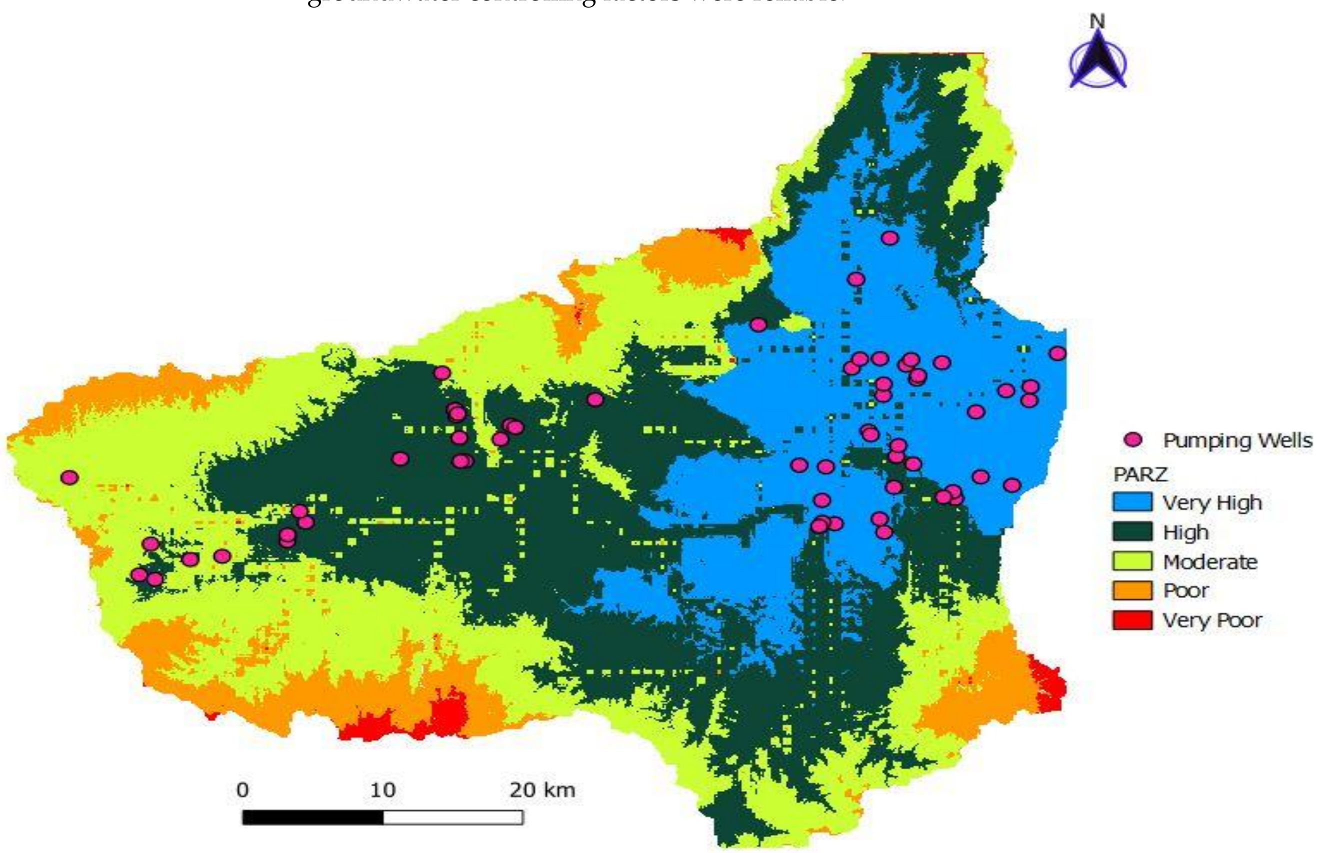


Figure 6. Spatial distribution of potential aquifer recharge zones of the study area.

The very high groundwater potential comprises quaternary alluvium deposits and quaternary volcanics and sediments. In addition, most of the tertiary volcanics and sediments, undivided quaternary alluvium, eluvium, and lacustrine sediments, have high to moderate potential zones. The very high aquifer recharging potential is found in the flat plains of the catchment with high rainfall distribution, which has a very high infiltration potential to the subsurface flow. The high potential zone is due to high lineament density with gentle slope, alluvial plains, and valleys. As a result, quaternary lacustrine sediment controls dominate low drainage density, flatter slopes, and agricultural land distribution. Loamy soil, high lineament density, and low drainage density promote groundwater aquifers' high infiltration rate. The moderate PARZ is mainly agrarian land flatter to gentle slope, with high lineament density and low drainage density. The high elevation and impermeable rock formations increase runoff resulting in low groundwater recharging. Steep slopes and the hilly regions, clay soil, and very high drainage density are the main reasons for low infiltration potential and low groundwater storage capacity.

3.4. Validation of Developed Map

The probability of aquifer recharge zone defined by geospatial techniques is usually validated by matching existing inventory data [67]. The validity of the potential aquifer recharge map was performed by overlaying the point data of inventory wells with the generated PARZ map. In addition, the result has been validated using the available inventory data or pumping wells information in the catchment (Figure 6). The validation points of the PARZ indicated that most of the production wells are located in very high (57%), high (32), and moderate (12%) delineated recharge zones with a productivity rate range of 0.35—21.6 L/s. This supports an agreement between the groundwater inventory data and PARZ defined using geospatial techniques. Based on the distribution of wells and the corresponding yield values, the developed PARZ map was complimented as a proxy for the aquifer productivity of existing pumping wells. Depending on their productivity, most African aquifers [118,119] are classified as very high (>20), high (5–20), moderate (2–5), low-moderate (0.5–2), low (0.1–0.5), very low (<0.1) in liters/second. However, from total inventory wells in the Gilgel Gibe catchment, according to the aquifer productivity classification of most African aquifers [118,119], there exists very high (25%), high (22%), moderate (28%), and low (25%) production wells. Therefore, the developed aquifer recharge map and the production wells are mismatched at some locations. This study verifies that the applicability of proxy data sources to delineate is trustworthy in groundwater development and management. This confirms that the significance of the weighted influencing parameter threshold values through GIS-based overlay analysis as credible support for delineating potential recharge zones is valuable for stakeholders to augment groundwater management and reduce the uncertainty of the decision-making process and resources allocation.

4. Conclusions

In the present study, the integrated application of GIS, RS, and MCDA were applied to identify potential aquifer recharge zones for the proxy data of the Gilgel Gibe catchment, Ethiopia. The study has proven that geospatial techniques can afford suitable proxy data analysis for viable groundwater assessments. An attempt was made to analyze ten governing data layers using GIS and AHP, and the corresponding weights of thematic layers have been assigned considering the relative implication of recharging. Each layer has no equal importance in controlling groundwater flow within the aquifer system. Accordingly, the most significant factors with a weighted value of lithology (20.2%), lineament density (8.8%), slope (5.4%), elevation (5.1%), soil (8.8%), LULC (15.3%), rainfall (14.5%), drainage density (7.2%), topographic position index (7.5%), and topographic wetness index (7.3%), respectively. Accordingly, the assessment revealed that lithology, rainfall, and LULC are dominant factors covering 50% of the controlling groundwater flow in the study area.

The computed consistency ratio (CR = 0.0920), less than 10%, verified that the established results are reasonably accurate and given valid weights. The developed map was classified into five classes: very high, high, moderate, low, and very low groundwater potentiality using weighted overlay analysis with GIS-based AHP analysis. The developed map with high potential predominantly exists in the central, western, and eastern parts. Areas with poor potential contribute to high runoff and relatively low infiltration. Therefore, a very high zone indicates the most appropriate place for productive wells allocations in practical applications. The validation indicated that most of the inventory wells are located in very high (57%), high (32), and moderate (12%) zones. The study is the first attempt to develop potential aquifer recharge zones in the Gilgel Gibe catchment. Hence, the findings are essential in providing insights to reduce complexity in decision-making processes for proper groundwater aquifer management. Furthermore, the study confirms that the applied techniques are helpful for groundwater exploration in varied climates and remote regions. The present study recommends that assessing the amount of exploitable and vulnerable groundwater in the catchment is indispensable for sustainable utilization and ecosystem management.

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