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Article

Application of GIS, Multi-Criteria Decision-Making Techniques for Mapping Groundwater Potential Zones: A Case Study of Thalawa Division, Sri Lanka

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Abstract: Groundwater resources are depleting due to phenomena such as significant climate change and overexploitation. Therefore, it is essential to estimate water production and identify potential groundwater zones. An integrated conceptual framework comprising GIS and the analytical hierarchy process (AHP) has been applied for the present study to identify groundwater potential areas in the Thalawa division of Sri Lanka. The criteria, including rainfall, soil types, slope, stream density, lineament density, geology, geomorphology, and land use, were taken into account as the most contributing factors when identifying the groundwater zones. Weights were allocated proportionally to the eight thematic layers according to their importance. Hierarchical ranking and final normalized weighting of these determinants were performed using the pairwise comparison matrix (PCM) available in AHP. Based on the results obtained, the groundwater potential zone (GWPZ) was classified into three regions: low potentiality (33.4%), moderate potentiality (55.8%), and high potentiality (10.6%). Finally, the zoning map was compared to find consistency with field data on groundwater discharge and depth taken from 18 wells in the division. The results revealed that the GIS-multi-criteria decision-making (MCDM) approach brings about noticeably better results, which can support groundwater resource planning and sustainable use in the research area.

Keywords: analytical hierarchy process (AHP); dry zone; geographic information system (GIS); groundwater potential zones; multi-criteria decision making (MCDM); SDG-6

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1. Introduction

Water is an essential resource for every organism to maintain its life. Water that stays below the earth's surface is called groundwater. Also, the term refers to all water found beneath the surface of the ground as groundwater [1,2]. The total volume of water resources and water on earth is estimated at 1386 trillion liters, of which 97% is saltwater, 3% is freshwater, and only 0.6% is available as groundwater [3]. It is crucial for ecology, food security, and human health [4]. Due to the scarcity of surface water, the significance of subsurface water reduction is highlighted, notably in dry areas [5]. With climate change and increased use of groundwater, many groundwater sources are experiencing water depletion. Groundwater availability depends on several factors, such as porousness, permeability, storage capacity, and transmissivity. The term "Groundwater potential" can be defined as the potential for groundwater to exist in an area [6,7].

The main indicator of groundwater storage reduction is the decrease in groundwater heads in wells. Groundwater in the Sri Lankan dry zone is mainly fed by rainfall. It should also be mentioned that, due to changes in rainfall patterns and excess water withdrawal for domestic and agricultural activities, the amount of water that reaches the ground is gradually decreasing. It is proven that 72% of Sri Lanka's rural population and 22% of its urban residents use groundwater for drinking and domestic purposes [7]. The importance of a proper assessment of groundwater potential is indicated by studies on water scarcity and drought [8–11]. The potential for groundwater in Sri Lanka is lower compared to surface water resources [12]. According to the hydrogeological conditions, about 90% of the land area of the country consists of hard rocks with low potential for groundwater, and the rest of the land consists of sedimentary rocks with high groundwater potential [13]. Sedimentary rock is limited to the north, northwest, and northeast regions of Sri Lanka [13]. There is a significant need to use groundwater in a sustainable manner in the dry zone due to reduced rainfall and an increased population [14,15]. Thalawa is one of the most important agricultural regions in the dry zone that belongs to irrigated farming. In the study area, groundwater is currently obtained from shallow and very deep wells. Sustainable development of groundwater resources as the best option to support dry zone people can contribute to improving their well-being by increasing agricultural productivity without depleting groundwater resources.

We must make decisions in our daily lives; some may be complex, while others are simple. Multi-criteria decision analysis (MCDA) ranks potential actions or alternatives in order of priority. To make the best choice feasible, MCDA is used to assess and contrast several factors, which are frequently at odds with one another [16]. Multi-criteria approaches are referred to in the academic community in a variety of ways, including multiple-criteria decision aiding (MCDA), multi-criteria decision making (MCDM), multi-objective decision making (MODM), and multi-attribute decision making (MADM) [16–18]. Different MCDA techniques are available, including the analytical hierarchy process (AHP), TOPSIS, PROMETHEE, ELECTRE, SWARA, WASPAS, etc. However, the AHP, TOPSIS, and VIKOR approaches were the most popular techniques that have been used in previous research works during the last four decades [16,19]. The spatial dimension of the assessment criteria, decision substitutes, and geographic data models are all factors that MCDA takes into account while assessing the criteria [20,21]. Researchers frequently use AHP to support decision making in the processes of environmental planning and natural resource management because of its capacity to recognize and balance the significance of complex aspects [22–25]. Different approaches have been used in recent years to delineate groundwater potential zones globally. Many researchers have found in their studies that AHP and MCDA methods are effective tools for identifying groundwater potential. In the case of Sri Lanka, only a limited set of studies have been carried out to identify groundwater potential areas based on the geographic information system (GIS) [3,12,14,26,27]. Groundwater research has reached a turning point with the use of remote sensing (RS) and GIS in resource discovery, which has significantly aided in groundwater resource analysis, monitoring, and protection [28,29]. Abijita et al. [30] attempted to delineate potential groundwater zones in the Ponnaniyar Basin, Tamil Nadu, using AHP and the multi-influence factor (MIF). Detection of potential groundwater zones through an appropriate modeling approach was essential in solving water problems in the drought-prone Kilinochchi district [12,14]. Kumar et al. [31] have tried to identify groundwater potential zones in the Chennai river basin using GIS and AHP in their study. Rajasekhar et al. [32] identified groundwater potential areas in the Jiledubanderu River catchment, India, using GIS, AHP, and combined fuzzy-AHP techniques. A study was undertaken by Doke et al. [33] using a systematic and scientific GIS-based AHP to prepare a groundwater potential map for the Ulhas Basin, India. The concept of using the latest techniques, such as RS and GIS, for groundwater management research is relatively new [34–37]. As time- and cost-effective methods, combined GIS and AHP demonstrate it is a useful method for defining probable groundwater zones [38–41]. Hence, based on the literature, the GIS-MCDA integrated method has been used for the present study.

In the Anuradhapura district, there is not sufficient water to meet the required volume, and the potential of groundwater needs to be explored. No related studies have been carried out in this area previously. Therefore, the study has been conducted to fill the existing research gap in the study area. The resulting groundwater potential map will provide better insights into sustainable water resource management. The current study is primarily focused on using GIS MCDA methodologies to map the potential groundwater zones using eight different criteria. The research was structured into the five sections listed below. Section 1 is devoted to explaining the research background and previous literature, and Section 2 describes the study area, materials, and methods. The results are thoroughly explained in Section 3, along with the model validation. In the discussion section, the similarities and differences of the key findings are compared with other similar research works. Section 5 gives the conclusions.

2. Materials and Methods

2.1. Study Area

This study was carried out in the Thalawa Divisional Secretariat Division (DSD), located in the Anuradhapura district of the North Central Province of Sri Lanka, covering a 218.45 km^2 area and having 39 Grama Niladhari Divisions (GNDs). It lies between 8°10′63″ N and 80°36′72″ E (Figure 1). The study area belongs to the dry zone; the average annual rainfall in the study area is around 1300 mm, with a mean annual temperature of 21 to 32 °C. There is 3182 ha of agricultural land in the Thalawa DSD under the agrarian service division of Thalawa, Eppawala, and Katiyawa [42]. The primary source of income in the study region is agriculture, with paddy being the predominant crop [43]. The area is part of the Mahaweli H zone, where irrigation water is used to support agriculture. All agricultural zones in the region are covered by the irrigation canal system. The northeast monsoon, which lasts from December to February, contributes significantly to the region's annual rainfall. Based on the annual rainfall pattern, agriculture is carried out in two seasons: '*Yala*' from March to September and '*Maha*' from October to February. The tank cascades spread over the area are linked to agriculture; a substantial portion of the entire area's topography is made up of very flat terrain with heights of less than 150 feet. The area has unique climatic characteristics, and except for a few months of the year, the other months are dry. There are a variety of plants adapted to dry climates. Reddish-brown earth soils, which are commonly found in the dry zone, are also available in the Talawa area. The lithological formation in the region is an important factor in the groundwater composition, quality, and formation of aquifers.

2.2. Selecting Criteria and Data Preparation

The selection of criteria for ranking is an important step in the suitability assessment process in any area for potential groundwater zones. Table 1 illustrates the criteria considered in earlier research when analyzing suitability for potential groundwater zones. Necessary data were obtained from various institutes, and then the steps required for ground-water potential zoning were followed by GIS MCDA [44].

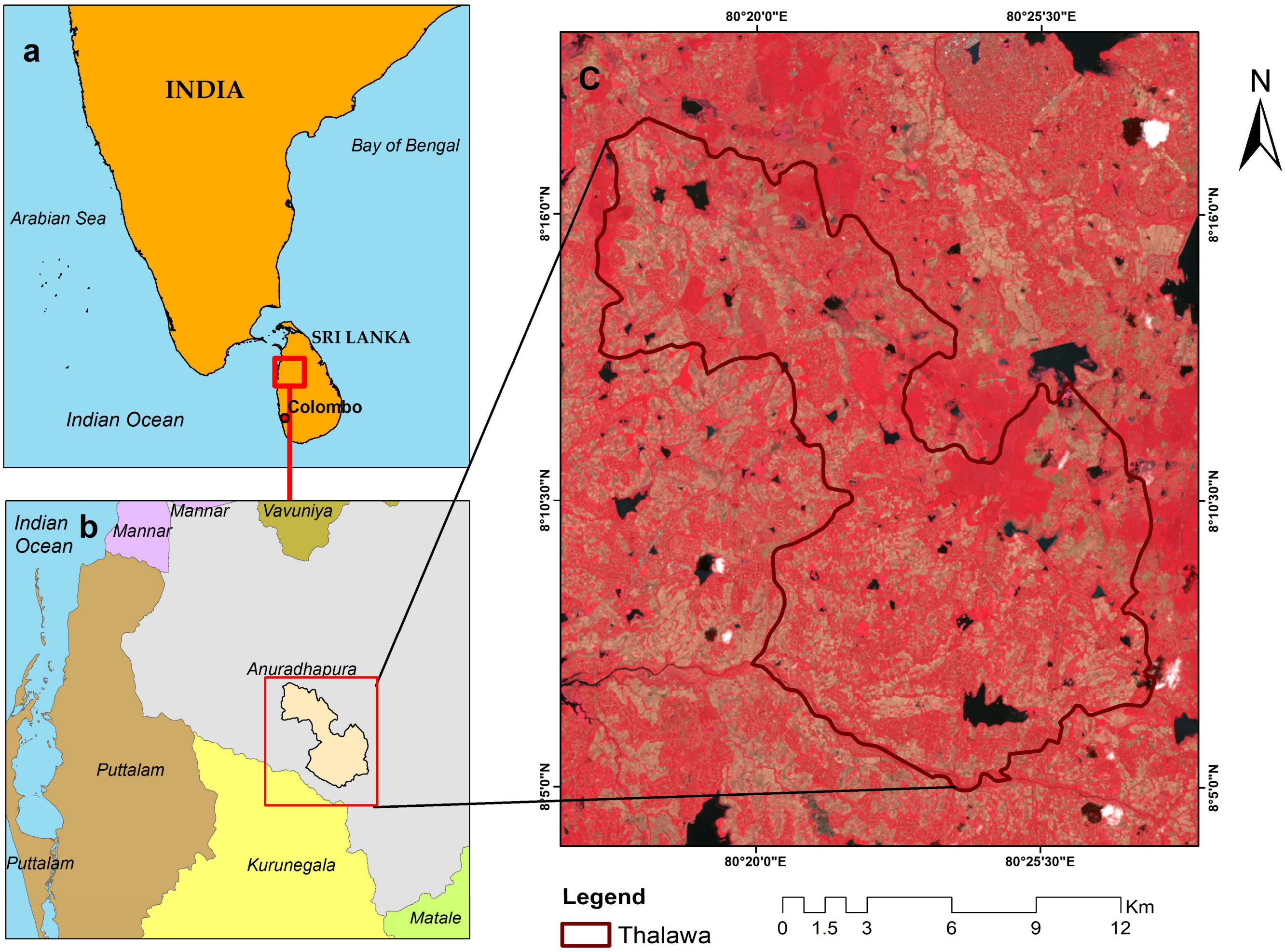

Figure 1. Geographical location of the study area: (**a**) Location of Sri Lanka in the Indian Ocean; (**b**) Location of Thalawa DSD; (**c**) Thalawa DSD in Landsat 8 false color (5,4,3) composite.

Table 1. Criteria used in previous studies to determine the potentiality of groundwater.

References	RF	GM	GL	SL	SP	LU	DS	LD	AS	GL	TWI
Ibrahim-Bathis and Ahmed [1]	×	×			×	×	×	×			
Pathmanandakumar et al. [12]	×	×	×	×	×	×	×	×			
Aslan & Celik [39]	×	×	×	×	×	×	×	×			
Kumar et al. [31]	×	×	×	×	×	×	×	×	×	×	
Sarwar et al. [44]	×	×	×	×	×	×	×	×			
Pal et al. [45]	×		×		×	×				×	×
Verma & Patel [46]	×	×	×	×	×	×	×	×			
Senthilkumar et al. [47]			×		×	×	×			×	
Arulbalaji et al. [48]	×	×	×	×	×	×	×	×			×
Arefin [49]	×	×	×	×		×	×				
Yıldırım [50]	×	×	×	×	×	×	×	×			×
Jhariya et al. [51]	×	×	×	×	×	×	×	×			
Benjmel et al. [52]			×			×	×	×			×

Table 1. *Cont.*

References	RF	GM	GL	SL	SP	LU	DS	LD	AS	GL	TWI
Singh et al. [53]			×	×	×	×	×				
Tiwari et al. [54]	×	×	×	×	×	×	×	×			
Pradhan et al. [55]	×				×	×	×				×

Notes: RF: Rainfall, GM: Geomorphology, GL: Geology, SL: Soil, SP: Slope, LU: Land Use, DS: Drainage Density, LD: Lineament Density, AS: Aspect, GL: Groundwater Level, TWI: Topographic Wetness Index (TWI).

The preparation of thematic layers (criteria) included RS data extraction, digitization of existing maps, and the collection of institutional data. Using preliminary investigation as a basis, the eight thematic layers were developed as follows: rainfall, geology, geomorphology, land use, soil type, stream density, lineament density, and slope [12,14,16,23,36]. Thematic layers were created once all the data were prepared, and these layers were then converted into raster datasets [35]. Finally, utilizing GIS-MCDA-integrated approaches, potential groundwater zones have been identified. The summary of the data sources is described in Table 2.

Table 2. Data sources used for mapping groundwater potential mapping.

Variables	Data	Resolution	Source Locations
Rainfall	Rainfall Data		Department of Meteorology [56]
Geology	Geological map	1:100,000	Geological Survey and Mines Bureau [57,58]
Geomorphology	Geomorphological map	1:100,000	Shuttle Radar Topography Mission [58]
Soil type	Soil map	1:100,000	Irrigation Department [59]
Land use	Land use Data		Survey Department of Sri Lanka [60]
Slope	Shuttle Radar Topography Mission (SRTM)	30 m	United States Geological Survey [61]
Stream Density	Shuttle Radar Topography Mission (SRTM)	30 m	United States Geological Survey [61]
Lineament Density	Shuttle Radar Topography Mission (SRTM)	30 m	United States Geological Survey [61]

The methodological flowchart for the groundwater potential zones is illustrated in Figure 2. To map groundwater potentiality, the control factors for groundwater movement, storage, and occurrence may be investigated [62,63]. A rainfall map was produced using the inverse distance weighted (IDW) interpolation technique using point data sources employing Arc GIS 10.8 software. GNU Octave 7.3 software was used to calculate the criteria and factors for AHP weight using an algorithm developed by Mathew, 2020 (https://mathewmanoj.wordpress.com/mul (20 July 2023). Because the point data were scattered and sparse, IDW methods were selected instead of distance thresholding. The dependable IDW model is utilized in this work to interpolate geographical information based on the idea of weighting distance [12]. The geological and geomorphological layers of the study area were prepared using an existing map of the geological survey and mines bureau (GSMB) under the scale of 1:100,000. The soil map was created by digitizing the resource map with the help of the Irrigation Department. Shuttle radar topography mission (SRTM)—digital elevation model (DEM) was used to create the slope, stream, and lineament density layers of the area. Land use information was collected from the Survey Department of Sri Lanka. Finally, these thematic layers underwent raster data conversion and weighted overlay analysis in the Arc GIS environment.

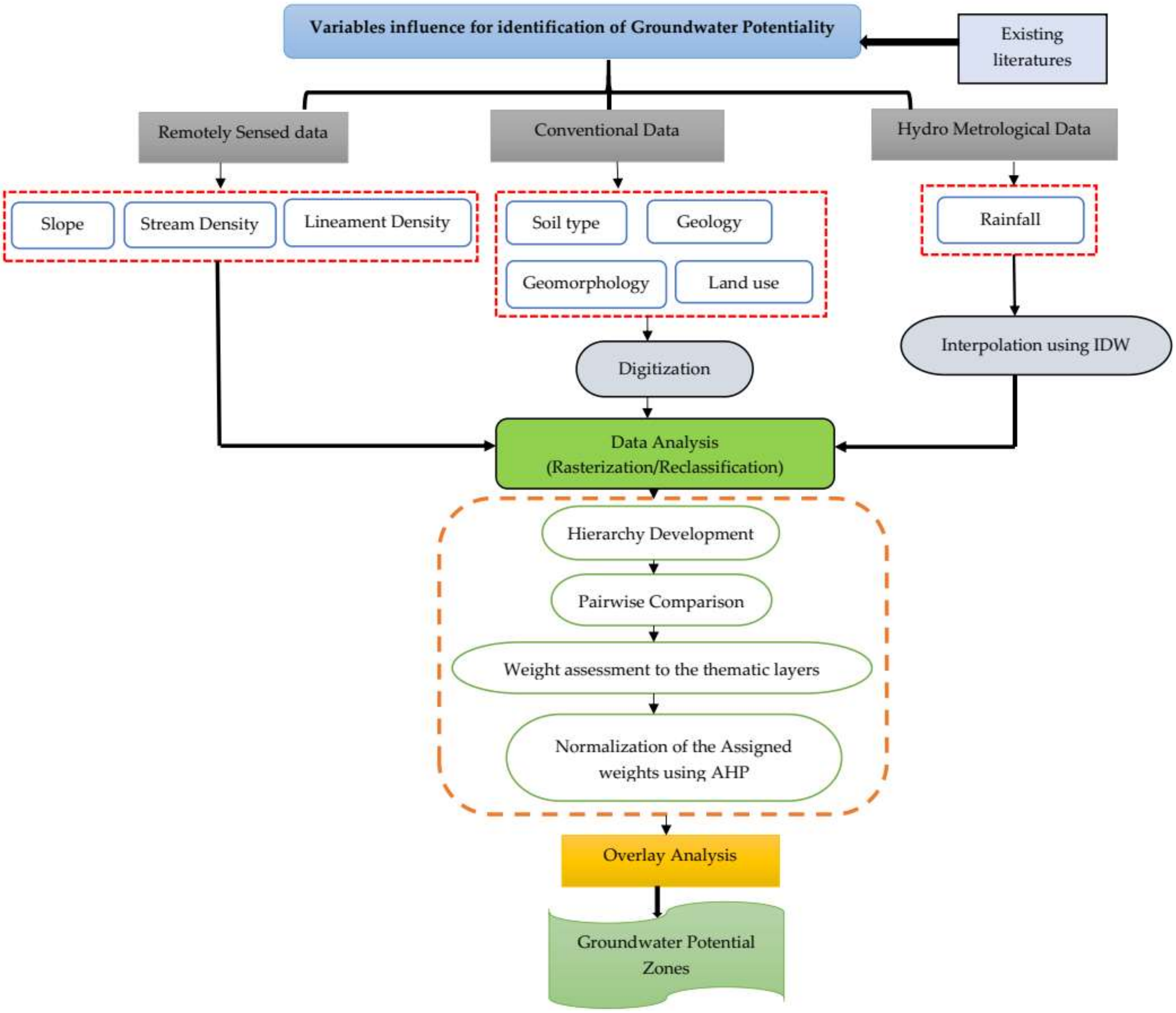

Figure 2. Methodological flowchart for delineating groundwater potential zones.

2.3. Assignment of Weights and Criteria Normalization

In integrated analysis, the weight assignment of each feature class is most important since the weight assignment depends on the output. The AHP proposed by Saaty [63,64] was applied to allocate weight to each of the criteria used in the study. The AHP is a multi-criteria decision-making technique widely used in the field of groundwater studies as well as in environmental and other geospatial contexts [57]. Multi-criteria decision analysis can be identified as a commonly accepted and important technique for solving complicated problems [12]. Saaty's scale was used in allocating standard weights [65]. Establishing weights for each criterion was the next stage. The weight computation determined the relative weights of the various criteria [66]. The AHP has the benefit of reducing pairwise comparisons of complicated judgments and aiding in determining the weight of the criterion [67,68].

For the chosen theme levels, a pairwise comparison matrix (PCM) was initially created to assess the scale weight of the relevant layers in relation to their contribution to groundwater potentiality. After that, a pairwise comparison matrix (M) was prepared, as in Equation (1). If n is the number of criteria, the size of M is $n \times n$ [61].

$$M = \begin{bmatrix} 1 & p & q \\ 1/p & 1 & r \\ 1/q & 1/r & 1 \end{bmatrix} \tag{1}$$

Here, each component of M uses a number ranging from 1 to 9 (Table 3) to represent the relative weight of the two criteria [69]. Typically, the ratings range from 1 (equal importance) to 9 (extreme importance).

Table 3. AHP Scale.

Scale	1	2	3	4	5	6	7	8	9
Importance	Equally	Weak	Moderately	Moderate Plus	Strong	Strong plus	Very Strong	Very very Strong	Extreme

Based on earlier research and expert opinions obtained by referring a semi-structured questionnaire to six experts from different fields, the Saaty scale was used to assign weights to the selected criteria and determine their relationship with characteristics and influence on groundwater potential. Three GIS experts (University academics), one hydrologist, one geologist, and a land use planning director participated in the semi-structured questionnaire survey within their busy schedules and the limited pool of GIS and hydrology experts in the Sri Lankan context. The proportion of influence of the thematic layers and the categorization of the constraints were computed using the PCM, the relative weight matrix, and the normalized primary eigenvalue (Table 4).

Table 4. Normalized pairwise comparison matrix analysis for the AHP Process.

Criteria	Slope	Rainfall	Geomorphology	Soil	Geology	Stream Density	Land Use	Lineament Density
Slope	**1.00**	0.333	0.2	0.333	0.2	3.00	3.00	3.00
Rainfall	3.00	**1.00**	5.00	3.00	5.00	5.00	3.00	5.00
Geomorphology	5.00	0.2	**1.00**	5.00	3.00	5.00	5.00	5.00
Soil	3.00	0.333	0.2	**1.00**	0.2	5.00	5.00	5.00
Geology	5.00	0.2	0.333	5.00	**1.00**	5.00	3.00	5.00
Stream Density	0.333	0.2	0.2	0.2	0.2	**1.00**	3.00	1.00
Land use	0.333	0.333	0.2	0.2	0.333	0.333	**1.00**	5.00
Lineament Density	0.333	0.2	0.2	0.2	0.2	1.00	0.2	**1.00**

The order of layer incentive on groundwater potential is expressed by the eigenvector [70]. The criteria of high groundwater potential are given more weight, whereas the criteria of low groundwater potential are given less weight. The column elements should be divided by the sum of the elements of the same column to normalize M and determine the weight of each criterion. The necessary relative test weights are provided by averaging the rows of the new matrix. Hence, all data are prepared as thematic layers and weighted overlay analysis using spatial analyst tools.

2.4. Normalized Weights and Identification Groundwater Potentiality

The relationship between the layers and their relative importance for the generation of the 8×8 pairwise matrix and the groundwater potential preparation determine how the eight thematic layers were integrated. They are displayed as, slope (SP), rainfall (RF), geomorphology (GM), soil (SL), geology (GL), stream density (SD), land use (LU), and lineament density (LD). Consequently, the result is a continuous mapping of suitability to produce a composite suitability map. The overlay tool creates raster layers using a common measurement range and weights each one based on its significance, which gives the final layer values ranges of 1–5 [12,34,71]. The last step was to prepare the composite map for groundwater potential. Weighted criteria are integrated to produce the potential map. This combination was performed by the weighted linear combination (WLC) method. The ability to achieve the relationship between the eight thematic maps using AHP with different classes is remarkable. Based on the PCM, the relative weight matrix and normalized weights were assigned to estimate the importance of the thematic layers on groundwater potential (Table 5).

Table 5. Normalized pairwise comparison matrix and weights were obtained for each criterion.

Criteria	SP	RF	GM	SL	GL	SD	LU	LD	Normalized Weight	%
Slope (SP)	0.06	0.12	0.03	0.02	0.02	0.12	0.13	0.10	0.0732	7.33%
Rainfall (RF)	0.17	0.36	0.68	0.20	0.49	0.20	0.13	0.17	0.3109	31.09%
Geomorphology (GM)	0.28	0.07	0.14	0.33	0.30	0.20	0.22	0.17	0.2231	22.31%
Soil (SL)	0.17	0.12	0.03	0.07	0.02	0.20	0.22	0.17	0.1061	10.61%
Geology (GL)	0.28	0.07	0.05	0.33	0.10	0.20	0.13	0.17	0.1650	16.51%
Stream Density (SD)	0.02	0.07	0.03	0.01	0.02	0.04	0.13	0.03	0.0495	4.9%
Land use (LU)	0.02	0.12	0.03	0.01	0.03	0.01	0.04	0.17	0.0352	3.53%
Lineament Density (LD)	0.02	0.07	0.03	0.01	0.02	0.04	0.01	0.03	0.0369	3.7%

The groundwater potential map was created by superimposing all of the criterion maps and utilizing the WLC technique with Arc GIS software 10.8 [71]. To calculate the groundwater potential index (GWPI), groundwater potential areas were produced using eight layers inserted into the GIS. The following formula describes the WLC process [72–74].

$$\text{GWPI} = \sum_{w=1}^{m} \sum_{1}^{n} \left(W_j \times X_i\right) \tag{2}$$

Here, GWPI is the groundwater potential index, Wj is the normalized weight of the j-th thematic layer, X_i refers to the weight of the I class of the criteria, m represents the number of criteria, and n denotes the total number of classes. Table 6 illustrates the weights and ranks for each of the eight impact factors.

Table 6. Weight and ranking for different criteria.

Criteria	Weight	Feature	Rank (r_i)	Potentiality Level
Slope (Degrees)	7	0.018–1.5	5	Very High
		1.6–3.9	4	High
		4–8.3	3	Moderate
		8.4–15	2	Low
		16–22	1	Very Low
Rainfall (mm per month)	31	88.9–94.4	2	Low
		94.5–99.9	2	Low
		100–105	3	Moderate
		106–111	4	High
		112–116	5	Very High

Table 6. *Cont.*

Criteria	Weight	Feature	Rank (r_i)	Potentiality Level
Geomorphology	22	Lower Levels of Intermediate Plantation Surfaces	4	High
		Lower Plant Surfaces, Inselbergs, and thin Soil (Dry zone)	3	Moderate
Soil Types	10	Alluvial Soils	5	Very High
		Low Humic Gley Soils	4	High
		Red-Yellow Podzoilc Soils	3	Moderate
		Redish-Brown Earth Soils	2	Low
Geology	16	Biotite Gneiss/Hornblende	1	Very Low
		Calciphyre/Minor Marble	4	High
		Carbonatite	1	Very Low
		Charnockitic Gneiss	2	Low
		Granitic Gneiss with Pinkish Microcline	3	Moderate
		Quartzite/Quartz Schist	2	Low
Stream Density (km^2)	4	0–0.735	5	Very High
		0.736–1.47	4	High
		1.48–2.21	3	Moderate
		2.22–2.94	2	Low
		2.95–3.68	1	Very Low
Lineament Density (km^2)	3	0–0.386	1	Very Low
		0.387–0.772	2	Low
		0.773–1.16	3	Moderate
		1.17–1.54	4	High
		1.55–1.93	5	Very High
Land use	3	Paddy	3	Moderate
		Homestead	3	Moderate
		Water Bodies	4	High
		Forest	3	High
		Road Network	1	Very Low
		Scrubs	2	Low

The relative weight (W*i*) of the slope is 0.0732, and the ranking was fifth among all criteria. As the Thalawa area is on a flat surface belonging to the dry zone, very high rough, slope (deep) features cannot be identified. Rainfall became the most important criterion, gaining a high relative weight of 0.3109. Geomorphology was the second most important criterion in groundwater potential zoning, derived at 0.2231 relative weight. According to its significance, the soil criterion gained 0.1061 relative weight and became the fourth important factor. Geology was the third most important factor in groundwater potential zoning and derived 0.1650 relative weight from AHP. The land use criterion is the least important among all others according to the relative weight assigned by AHP derived from 0.0352. Stream density gained 0.0495 relative weight (sixth most important criterion) according to the AHP results. Lineament density gained a 0.0369 relative weight and was reported as the seventh most important factor in groundwater potential zoning. To perform GIS overlay analysis, each criterion was assigned a ranking order that ranges from 1–5 (1—very low, 2—low, 3—moderate, 4—high, 5—very high). These ranks were allocated based on the ranking orders collected from experts' opinions using the questionnaire survey.

3. Results

3.1. Groundwater Potentiality for Major Criteria

The outputs of the AHP estimation of eight criteria and sub-criteria used in the research and standardized rating values (r_i) are shown in Tables 5 and 6. As well as the thematic layers that are produced through the reclassification of main criteria using r_i values are shown in Figure 3. Details of all these criteria and their spatial distribution are described below.

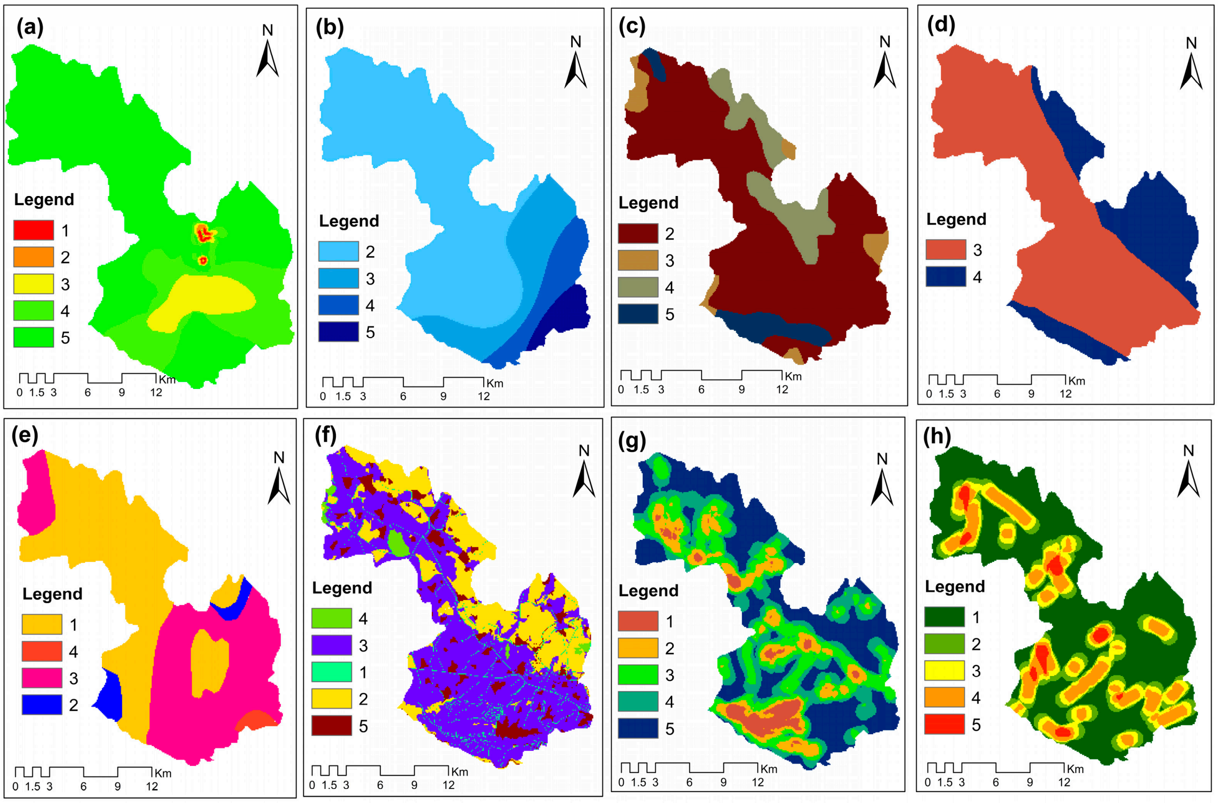

Figure 3. Distribution of rating values for eight criteria in groundwater potential zones in Thalawa: (**a**) Slope; (**b**) Rainfall; (**c**) Soil; (**d**) Geomorphology; (**e**) Geology; (**f**) Land use; (**g**) Stream density; (**h**) Lineament density.

3.1.1. Slope

The flat terrain (Figure 3a) of the study area may reveal the possibility of high groundwater potential. The slope of the area was categorized into five groups very high (0.018–1.5), high (1.6–3.9), moderate (4–8.3), low (8.4–15), and very low (16–22). Towards the center of the area, there is a slightly steeper slope. Due to the flat terrain and high infiltration rate, the research area with a slope of 0.018–1.5 is classified as having "very high" groundwater storage. The slope gradient between 16 and 22 has considered the groundwater storage as 'very low'. While the very high-potential areas comprised 69% the high-potential areas were covered by 19.4%. Moderate, low, and very low were covered by 0.20%, 0.28%, and 7.9%, respectively.

3.1.2. Rainfall

Rainfall has a dominant effect on the hydrological cycle of the area and is directly related to the groundwater capacity. As a result of the dry climate of the study area, there are constant variations in the groundwater potential. The area receives rainfall with the activation of the northeast monsoon from September to December. The annual rainfall of the area has been classified into five classes (Figure 3b). The maximum and minimum rainfall in the area are 116 mm and 88 mm, respectively. Compared with the northern portion of the area, a higher trend of rainfall intensity can be detected in the southeast quarter. Rainfall distribution and slope gradient greatly influence surface water runoff, which also contributes to the determination of groundwater potential. As per the reclassification results, 67.6% of the area is of low potential, while moderate, high, and very high potential areas are covered by 18%, 9.5, and 4.7%, respectively.

3.1.3. Geomorphology

In the study area, two prominent landforms, namely, lower intermediate plantation surfaces and lower plant surfaces, have been observed. Conspicuous landforms were reclassified into two classes (Figure 3c). Porous and permeable zones are well explained in geomorphology and can be considered an essential phenomenon in groundwater recharge. High weight was allocated to the lower intermediate plantation surfaces, and low weight was assigned to the low plantation surfaces geomorphological unit that has moderate groundwater potential zones. 71.3% of the total area is in the moderate potential zone, while 28.7% is in the high potential zone.

3.1.4. Soil Types

Analysis of soil types revealed that the study area is mainly covered by four major soil types. Namely, alluvial, low-humic gley, red-yellow podzolic, and reddish-brown earth. This reddish-brown soil, which is typical of the dry zone, is spread over a large area. The brown texture and drainage of this soil are also widespread. The majority of the study area consists of reddish-brown earth soils (165 km^2). Alluvial soils are covered in the south and northwest areas, and low-humic gley soils can be identified towards the center of the area. Red-yellow podzolic soils are spread over an area of 11.5 km^2. In determining the influence of soil types on the occurrence of groundwater potential in the area, it can be identified that alluvial soils and low-humic gley soil contribute to being considered "very high" and "high", respectively. Red-yellow podzolic soil was assigned a moderate weight because it was generally more conducive to stabilizing groundwater potential than reddish-brown soil. In depicting the groundwater potential, reddish-brown soil was assigned low weight due to its fine surface nature. When 74.1% of the area is in a low potential zone, high, very high, and moderate potential zones are covered at 13.7%, 6.7%, and 5.2%, respectively.

3.1.5. Geology

In the study area, the geological features are formed in relation to three types of rocks, and the determination of groundwater potential varies according to the geological types. Biotite Gneiss/Hornblende, Calciphyre/Minor Marble, Carbonatite, Charnockitic Gneiss, Granitic Gneiss with Pinkish Microcline, and Quartzite/Quartz Schist are the seven geological forms found in the area of study. Biotite Gneiss/Hornblende represents 47.5% and covers mainly the Northern and southwest parts, while other formations such as Granitic Gneiss with Pinkish Microcline, Quartz Schist, Carbonatite, and Calciphyre/Minor Marble are mostly identified in the Eastern portion of the area. Charnockitic Gneiss also represents 2.3% of the study area. The geology of the area indicates that the possible high groundwater holding formation is only Calciphyre/Minor Marble. Also, Calciphyre/Minor Marble is formed under the metamorphic rocks, which greatly influence the consistent groundwater capacity of the area. Calciphyre/minor marble is assigned high weights, while biotite gneiss/hornblende, carbonatite, charnokitic gneiss, and quartzite are given low weights, respectively. Granitic gneiss with pinkish Microcline, the second most widespread geological type in the area, has been found to have moderate suitability for groundwater potential. According to the thematic rating map (Figure 3e), only 1.4% of the area is in the high potential zone, while 42.9% and 51.6% are in the moderate and very low potential zones, respectively.

3.1.6. Land Use

Prominent land use/land covers include, paddy, homesteads, water bodies, forests, roads, and scrubs. Around 40% of the total area is rice paddy land. There is a tendency for water to infiltrate more in the vicinity of agricultural lands and forest areas. This is because a vegetated area has the ability to retain water and also allows for proper drainage. In the study, the water bodies and the forest cover have been identified as land covers that have a high groundwater potential. As the drainage system of the area is mainly connected with tanks and canals, water percolation occurs regularly. Therefore, it has been suggested in the study to give a higher weight to those land uses. Both homestead and paddy land uses have moderate suitability for groundwater potential (Figure 3f). The road network and scrubs are categorized as very low and low, respectively, for groundwater potential. After the rating assignment, 58.6% of the area was identified as having moderate potential, while 8.9% represented very high potential. Low and very low potential areas represented 26.4% and 4.1%, respectively.

3.1.7. Stream Density

The stream density has been categorized into five categories, and it varies in the range of <0.7 to >3.68 km^2. A higher weight is given to regions with low stream density, and a lower weight is given to areas with very high stream density. In the study area, it is not possible to identify many regions with significantly high stream densities, and the stream density is more concentrated in the Southern part of the research area. Areas with low stream density have high levels of infiltration from rainfall. Hence, permeability works inversely and plays an important role in stream density for flow distribution and infiltration rates. Accordingly, 36.8% of the area (Figure 3g) is in the very high potential zone, while 22.9% is in the high potential zone. 5.2% and 12.1% of the area are in the very low and low potential zones, while the moderate potential zone is covered by 22.8%.

3.1.8. Lineament Density

The lineament map of the study area was derived from SRTM DEM using USGS. The lineament density of the study area varies from 0.7 km^2 to 3.6 km^2. In the study area, there is no specific place where the density of lines is high and the lines are distributed in a spreading manner. The linear features were classified into five groups, namely: 0–0.7 km^2, 0.7–1.4 km^2, 1.4–2.2 km^2, 2.2–2.9 km^2, and 2.9–3.6 km^2. Based on the rating assignment for the thematic layer, 56.9% of the area was covered by a very low potential zone, while very high and high potential zones covered 17% together (Figure 3h).

3.2. Distribution of the Groundwater Potential Zones in Thlawa

In the study, every main criterion was individually rated and multiplied by AHP weights. Knowledge-based rating and weighting of various classes for each thematic layer have been assigned through the weighted overlay analysis process based on experts' judgment. The weighted linear combination (WLC) output map displays three distinct groups, including low, moderate, and high potential for groundwater (Figure 4). High (23.34 km^2), moderate (122.04 km^2), and low (73.07 km^2) groundwater potential zones cover about 10.6%, 55.8%, and 33.4% of the area, respectively. The factors of rainfall and geology have directly contributed to the presence of high groundwater potential conditions in the east, southeast, and south regions.

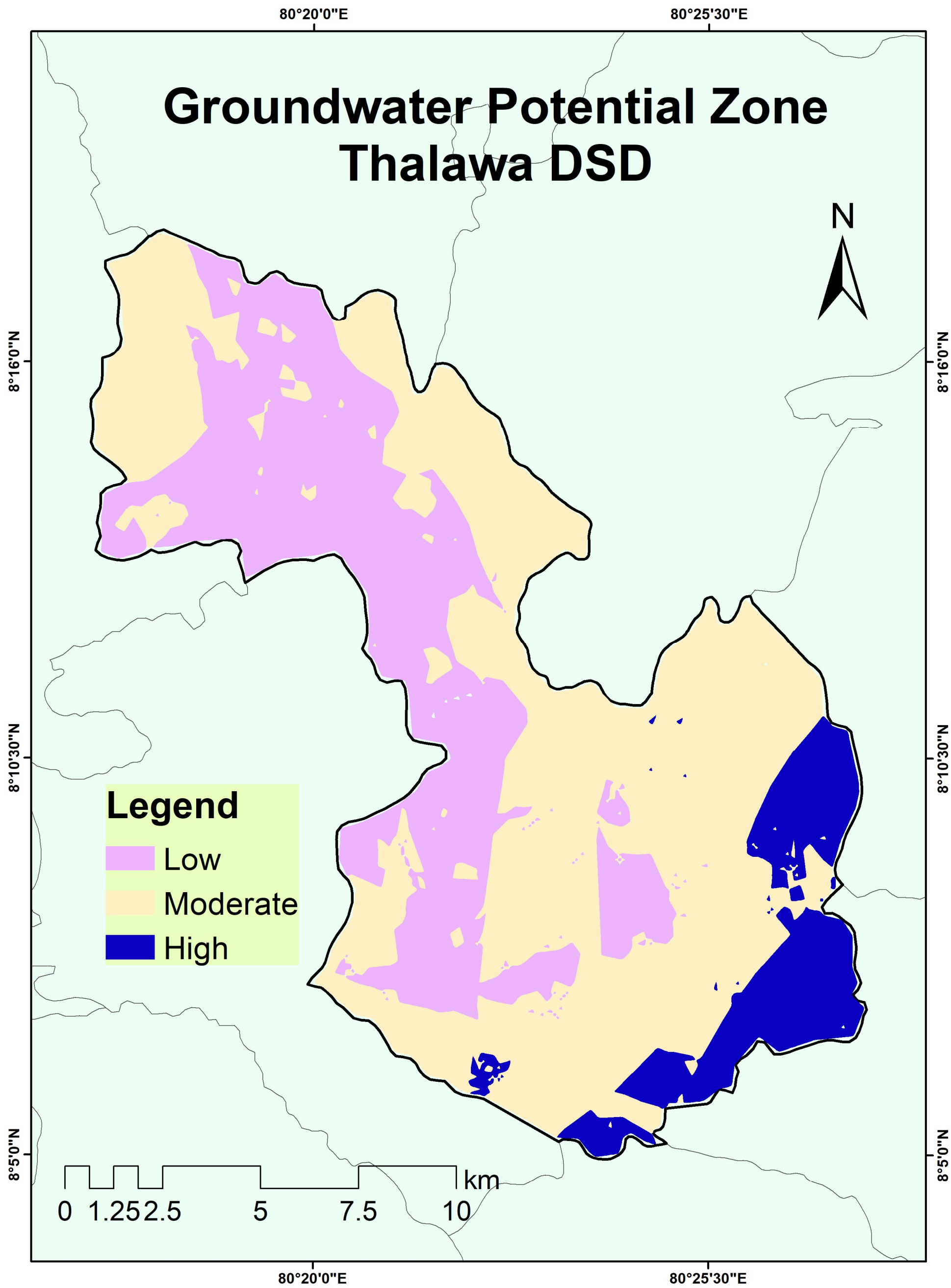

Figure 4. Groundwater potential zones of the study area.

3.3. Validation of Groundwater Potential Zones in Thalawa

Any suitability assessment must be cross-checked with actual ground-truth information to maintain the reliability of the results. The delineated groundwater potential zone map was validated using secondary data and well-discharge statistics gathered during the field survey. To validate the resulting groundwater potential zone map, water discharge and depth data were integrated. Below-ground level (bgl) data were collected from the water resource board and Mahaweli Authority, Sri Lanka. Accordingly, the data was collected from 18 groundwater wells in three different potential zones (Table 7). Water discharge from ground wells ranges from 0.9 Ls^{-1} to 92 Ls^{-1}. Also, the depth of the water level is between 0–77 m.

Table 7. The data of verified sample wells in the Thalawa division.

ID of Well	X and Y Coordinates (WGS 84)		Depth of GW (m bgl)	Water Discharge (Ls^{-1})	GW Potential Zone
	X	Y			
GW1	324,502	164,541	4.2	74.4	High
GW2	323,444	164,224	2.8	92	High
GW3	322,809	162,213	1.6	43.6	High
GW4	321,327	160,831	0.7	12	High
GW5	323,126	157,345	28.5	64.2	Moderate
GW6	324,396	159,885	24.6	73	Moderate
GW7	325,349	161,895	29	58.3	Moderate
GW8	328,841	163,800	21	34	Moderate
GW9	330,217	164,435	19	54.7	Moderate
GW10	331,381	164,012	0.7	28.6	Moderate
GW11	331,910	162,530	16	14	Moderate
GW12	338,366	155,969	14.3	29.5	Moderate
GW13	340,012	147,185	4.8	36.2	Moderate
GW14	329,370	155,228	72.8	48.6	Low
GW15	331,805	154,805	64.5	77	Low
GW16	331,180	153,958	77	64.5	Low
GW17	335,297	152,900	37	37	Low
GW18	335,297	150,571	46	54.6	Low

According to the validation results, four groundwater wells are located in the high potential area, while nine and five wells are located in moderate and low groundwater potential zones, respectively. The water discharge of the wells in the high potential zones is between 12 Ls^{-1} and 92 Ls^{-1} with a mean of 26 Ls^{-1} and the depth of groundwater ranges from 0.7 m to 4.2 m with a mean of 2.1 m. The mean water discharge of the wells in moderate potential zones is 44, with 14 Ls^{-1} minimum and 73 Ls^{-1} maximum. The mean groundwater depth of the wells in moderate zones is 21.2 m (min: 0.7 m max: 32 m). The water discharge of the wells in low potential zones ranges from 0.7 Ls^{-1} to 0.3 Ls^{-1} with a 0.92 Ls^{-1} mean. The mean water depth is 68 m (min: 37 m, and max: 77 m). The groundwater potential zone produced from the AHP approach demonstrated satisfactory levels of results when predicting the groundwater potential zone in Thalawa DS, Anuradhapura district, according to the verification results. The outcomes further demonstrated that groundwater potential zones might be identified using the methods presented here. Since the research area is essentially an agricultural-dominant DS, this will be more beneficial as a time-cost-efficient approach to choosing and finding groundswells for agricultural uses. This will reduce overexploitation and help conserve the area's scarce groundwater resources. But for this purpose, spatial data at a finer spatial scale may increase the accuracy of the results. The study has limitations since we did not analyze the relationship between groundwater potential and well yield data.

4. Discussion

4.1. The Potentiality of Groundwater, Water Depth, and Discharge

The study area was divided into three distinct groundwater potential zones, namely high, moderate, and low. These zones encompassed 10.6%, 55.8%, and 33.4% of the total area, respectively. The Southern portion of the division is predominantly occupied by high-potential areas, while moderate-potential areas are scattered along the Eastern portion. Low-potential areas, on the other hand, are found in the Western and Northern parts of the division, as depicted in Figure 4. The acceptability of the derived groundwater potential map, generated using GIS-MCDA, was determined based on the groundwater depth and discharge data obtained from a set of representative ground wells. These data were utilized for validation. The existing body of research indicates a considerable correlation between groundwater potential zones and the discharge and water yield seen in the wells within the study locations [75–77].

4.2. The Impact of Slope, Rainfall, and Elevation on Groundwater Potential

The slope is a significant topographic element that influences the process of surface runoff. The impact of slope on groundwater recharge in aquifers is significant [78]. The relationship between slope gradient and surface water percolation is a significant factor in the delineation of groundwater potential zones [79,80]. Previous research has also indicated that flat terrain exhibits significant potential for groundwater accumulation as a result of the extended duration required for water to percolate [75,81–83].

The precipitation patterns exert a significant influence on the hydrological processes within the region and exhibit a direct correlation with the groundwater storage capacity [67,78]. The study area exhibits a maximum rainfall of 116 mm and a minimum rainfall of 88 mm. Several previous studies have demonstrated a strong positive association between rainfall and groundwater [75,84,85]. A study conducted on the Beshilo River watershed in Ethiopia revealed that precipitation had a positive impact on groundwater storage capacity. However, it was observed that the soil structure exhibited variations throughout the catchment area. In regions characterized by the presence of clay deposits, reduced rates of infiltration were found to correspond with decreased groundwater potential. In the context of sandy loam soil, it is observed that regions exhibit rapid absorption and subsequent contribution to the groundwater reservoir. In contrast to higher elevations, lower altitudes exhibited a higher likelihood of groundwater occurrence [86].

4.3. Effect of Geological Factors on Groundwater Potentiality

The utilization of geomorphology as a factor in various studies pertaining to the assessment of groundwater potentiality is of great significance. This is due to its ability to depict the landform and topography of a specific geographical region. Drought, classified as a natural calamity, manifests in regions characterized by arid climatic conditions, leading to the proliferation of vegetation patterns that have evolved to withstand such environmental constraints. The study area is characterized by low plantation surfaces, inselbergs, and a thin soil cover. The eroded relics observed in this context are identified as the oldest plain composed of Vijayan gneiss and quartzite [12]. The moderate and high potentiality of the bulk of the area can be attributed to the high permeability of water on low-level and intermediate plantation surfaces. Prior research has also demonstrated that areas characterized by rocks and sediments exhibiting a high degree of permeability experience rapid infiltration of water into the underlying soil [75,87].

Approximately 40% of the overall land surface consists of rice paddy fields, characterized by a higher degree of porosity that facilitates enhanced water percolation. Consequently, a significant portion of the land falls within the high and moderate potential classifications. Previous research has indicated a positive correlation between arable and agricultural land with moderate and high groundwater potential [75,88,89].

The stream density in a particular area governs the permeability and the percolation rate of precipitation. In the study area, the identification of locations with notably high stream densities that have had a discernible positive impact on water infiltration and movement, particularly in the Southern portion of the research area, is not feasible. Prior research has demonstrated that areas with low stream densities exhibit elevated groundwater potentials [75,90,91]. The hydrological processes of runoff and groundwater penetration in the area are significantly influenced by the presence of linear and curved structural elements [72,79,81]. Water movements have greater intensity in regions characterized by a higher density of lineaments. Previous investigations have also documented similar findings, indicating a favorable correlation between groundwater output and lineament features [75,92,93].

The spatial arrangement of groundwater within a given area is contingent upon the geological attributes of that region, which in turn impact the processes of infiltration and percolation [32,94,95]. Unconsolidated sediments, such as alluvium, exhibit a deficiency in the partitioning process, resulting in a significant proportion (55%) of the region being classified as zones with low and very low groundwater potential. Granitic gneiss, which ranks as the second most prevalent geological formation within the region under study, has been determined to possess a moderate level of appropriateness in terms of its potential for groundwater resources. Other studies utilizing GIS and multi-criteria MCDA have yielded comparable results in the mapping of groundwater potential zones [75,95]. The study area exhibits a limited extent of high water infiltration soil types, namely red-yellow podzolic soils and alluvial soils, which are found in very high and high potential zones, accounting for only 19% of the total area. In contrast, a significant portion of the study area, covering 165 km^2, is characterized by reddish-brown earth with low infiltration capabilities, contributing to 74% of the area classified as having low potential for water infiltration.

5. Conclusions

The current study tries to delineate groundwater potential zones in the Thalawa division using GIS and AHP-MCDA techniques. Weights were assigned to eight potential criteria using AHP. A final groundwater potential map was generated by zoning the area into three classes: high, moderate, and low, using overlay analysis by the WLC method. The final map revealed that 10.6% of the study area has high groundwater potential, 55.08% has moderate potential, and 33.4% has low groundwater potential. Finally, the derived potential zone map was compared with the water discharge and depth data taken from representative groundwater wells in the study area. The mean discharge and mean depth of the groundwater wells in high-potential zones are 26 Ls^{-1} and 2.1 m. In the moderate zone, the mean discharge was 44 Ls^{-1} and the mean depth was 21.2 m, while ground wells in the low potential zone reported 0.92 Ls^{-1} mean discharge and 68 m mean depth. Thus, it revealed that the GIS-AHP integrated zoning map is acceptable and accurate. High groundwater potential areas are located in the Southern portion of the division and moderate potential zones are distributed over the Eastern and Southeastern portions. Low-potential areas are mainly distributed along the Western portion. Due to a lack of data, the relationship between groundwater potential and water yield was not used to validate the result. Incorporating those bivariate analyses into future research will be more helpful in deriving accurate and reliable results. This information will essentially support groundwater management planning decisions. The zoning map will provide policy guidelines for local planning authorities, especially for their agricultural water management. The study will pave the way for more advanced research that incorporates more criteria in national and international contexts.

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