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An Assessment of Geospatial Analysis Combined with AHP Techniques to Identify Groundwater Potential Zones in the Pudukkottai District, Tamil Nadu, India

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Abstract: Groundwater is critical to the socioeconomic development of any region. Infiltration of surface water into the ground is influenced by a variety of factors such as soil pores, folds, fractures, faults, and joints, all of which contribute to groundwater recharge. Groundwater is an important source of freshwater in the drought-prone Pudukkottai district of Tamil Nadu, India. Therefore, the search for groundwater potential zones (GWPZs) is critical. The present study focuses on the investigation of potential groundwater zones using geospatial techniques. Geology, land use and land cover, geomorphology, soil, drainage density, lineament, and groundwater levels were obtained from state and non-state associations. ArcGIS version 10.8 was used to create all thematic layers and classified grids. The intensive use of groundwater in arid and semiarid regions is becoming a problem for the public to meet their freshwater needs. The condition of arid and semi-arid regions due to intensive groundwater extraction has become one of the most important environmental problems for the public. In this study, a powerful groundwater potential mapping technique was developed using integrated remote sensing data from GIS-AHP. Using AHP techniques, thematic layers for geology, geomorphology, and soil followed by drainage, drainage density and lineament, lineament density, slope, water level, and lithological parameters were created, classified, weighted, and integrated into a GIS environment. According to the results of the study, it is estimated that 14% of the groundwater potential in the study area is good, 49% is moderate and 36% is poor. A groundwater level map was used to verify the groundwater potential. In addition, the model was validated with a single-layer sensitivity analysis, which showed that geology was the most influential layer and water level was the least influential thematic layer. The low-potential areas identified on the groundwater potential map can be used for further study to identify ideal locations for artificial recharge. In low potential areas, the groundwater potential map can be used to find ideal locations for artificial recharge. The water table in the area must be raised by artificial recharge structures such as infiltration basins, recharge pits, and agricultural ponds. Artificial recharge structures such as infiltration basins, recharge pits, and agricultural ponds can be used for groundwater development in the low potential zones. The GWPZ map was successfully validated with three proxy data, such as the number of wells, groundwater level, and well density, obtained from well inventory information. The results of this study will improve our understanding of the geographic analysis of groundwater potential and help policy makers in this drought-prone area to create more sustainable water supply systems.

Keywords: remote sensing; GIS; thematic layers; AHP; weighted overlay; groundwater potential zone

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1. Introduction

Since the turn of the millennium, surface water accessibility has been compromised by insufficient precipitation due to global climate change, increased urbanization, and industrial development in rain-fed areas. As a result, potential groundwater areas have been designated [1]. On a global scale, the quantity and accessibility of drinking water are two of the most important environmental, social, and political issues. It is challenging for environmental engineers and hydrologists to monitor water quantity and draw conclusions from the data, as every step from sampling to analysis is subject to uncertainty [2]. Predicting groundwater potential zones is difficult in rare areas, so standard methods for managing groundwater resources are needed. In the absence of understanding regarding groundwater accessibility, the main issues worldwide are the depletion of the water table and loss in well yield caused by excessive pumping. Below the surface of the earth, in the fissures of geologic strata, is where we can find groundwater, a precious natural resource [3–6]. Planning strategies to stop groundwater depletion and preserve the wellbeing of the groundwater ecosystem can benefit from assessments of the volume and spatial distribution of groundwater storage [7].

Hydrogeologists use a variety of techniques to determine the groundwater potential zone. In recent years, airborne electromagnetic (AEM) surveys have become the accepted method for determining groundwater pathways in fractured crystalline hard rock [8]. Traditional scientific methods for locating groundwater include the electrical resistivity technique and the magnetic method. The modern approach includes integrated remote sensing and GIS. Various thematic maps derived from satellite imagery and field surveys were overlaid to identify the potential groundwater zones GIS. The AHP technique was created in 1977 by Professor Thomas Saaty [9]. In addition, the Analytic Hierarchy Process (AHP) [10–13] is internationally recognized and employed a quantifiable technique. The evaluation of possible groundwater resource zones in rapidly urbanizing areas looks to be a flexible decision-making tool for multi-criteria problems. It enables problem hierarchy and guarantees that during the evaluation process, both qualitative and quantitative components of a problem are taken into account. Multi criteria Decision Making (MCDM), which gives judgments structure, verifiability, transparency, and correctness, has been shown in numerous studies to be a useful technique for managing water resources [14]. Even if these low-cost techniques are restricted to small-scale explorations, the variability of the Earth's subsurface makes it more difficult to locate groundwater potential zones. Using remotely sensed satellite photography, several surface characteristics can be utilized to determine the presence or absence of groundwater. In AHP inference, the mapping from a given input to an output is formulated using AHP logic [15–18]. The model that transforms input data into input membership categories is present in each AHP inference system—rules into a collection of output features, output features into output membership functions, and output membership functions into a single-valued output or a decision related to the output.

Geographic information system (GIS) based studies evaluated static groundwater storage volumes but did not offer information on how widely applicable the results are in identifying potential groundwater development areas [19,20]. On the other hand, current delineation methods are based on either a single indicator that may be insufficient to reflect numerous elements of groundwater development or an excessive number of indicators for which data are not readily available for a target area. For example, existing methods rely on the length of screened units of the aquifer. Volume of aquifer Satellite imagery has been used extensively and successfully to map regional groundwater potential zones, which is a cost-effective method. Identification of groundwater potential zones is improved when remote sensing and GIS are used together [21–25]. Pudukottai is a drought-prone, arid district in southern India. It is frequently affected by cyclic droughts due to failures of the monsoon in the last 100 years. The objective of the present study is to delineate groundwater potential zones to meet the freshwater needs of the region during droughts. It also aimed at producing a map using remote sensing and GIS to help reduce uncertainty in the identification of groundwater potential zones. By integrating GIS and AHP, a model was created to produce the map of groundwater potential zones. In addition, the model was validated with the single-layer sensitivity analysis.

2. Study Area

In the Pudukkottai district of Tamil Nadu, droughts are common. It lies between 9°50′ and 10°40′ north latitude N and 78°25′ to 79°15′ east longitude. The toposheets prepared by the Survey of India (SOI) are 58 J/9, 10, 11, 14, 15, 16, 58 N/2, 3, 4 and 58 O/1&2 at a scale of 1:50,000. It is a large festival with an area of about 4663 km^2. Pudukkottai is divided into 11 taluks, 13 blocks and 16 towns with 750 villages. Thanjavur is located in the northeast and east of the Pudukkottai district, Palk Road in the southeast, Ramanathapuram and Sivagangai in the southwest and Tiruchirappalli in the northwest. (Figure 1). The Pudukkottai district receives an average of 821 mm of rainfall annually. Most of the rainfall in this district occurs during the northeast monsoon (397 mm), followed by the southwest monsoon (303 mm). The main aquifers of the district consist of fractured and weathered crystalline rocks, mainly hornblende gneisses, granitic gneisses and pink granites. Sedimentary formations, ranging in age from Cretaceous to recent, include sandstones, limestones, shales, and unconsolidated alluvium. Precipitation patterns, surface conditions, land use, soils, and geology all affect water quality. Summer and winter precipitation amounts are 81 and 40 mm, respectively. Precipitation increases from east to southwest in the district. The main occupations of the population are agriculture and tourism. Of the total agricultural land, 1420.24 km^2 (31.97%) is arable land, 18.12 km^2 (0.38%) is fallow land, and 110.87 km^2 (2.37%) is plantation land. About 1188 km^2 of the land was fallow. Distribution of the study area: 24.32% of the total land use and land cover of the district. Shrubland and other fallow land are classified as wasteland. A total of 241.07 km^2 is covered by forests. The study region consists of Cauvery basin and sub-basins of Vellar, Agniyar, Ambuliyar, Koraiyar, Gundar and Pambar. At Manamelkudi, the Vellar is the main river that flows into the Bay of Bengal after flowing in an east-southeast direction. In this study, cropland, agricultural fallow land, and plantations constitute the agricultural land use. Built-up areas include both rural and urban settlements, industries and mines. Tanks, canals, rivers, coastal wetlands, backwaters, and impounded wetlands are examples of wetlands. Scrublands, alkaline soils, sandy areas, and salt pans are examples of bars. Finally, there is the category of forest use/cover. Maximum land use Thirumayam > Viralimalai > Manalmelkudi > Gandharvakottai. This has developed especially in the study area; it could be very useful for studying changes in land use/cover to predict weather extremes. Storativity in sedimentary formations ranges from 4.9×10^{-6} to 4.4×10^{-4}, while in hard rocks it ranges from 3.26×10^{-5} to 5.2×10^{-5}. In sedimentary rocks, the specific yield is 23% and in hard rocks it is 2.1%.

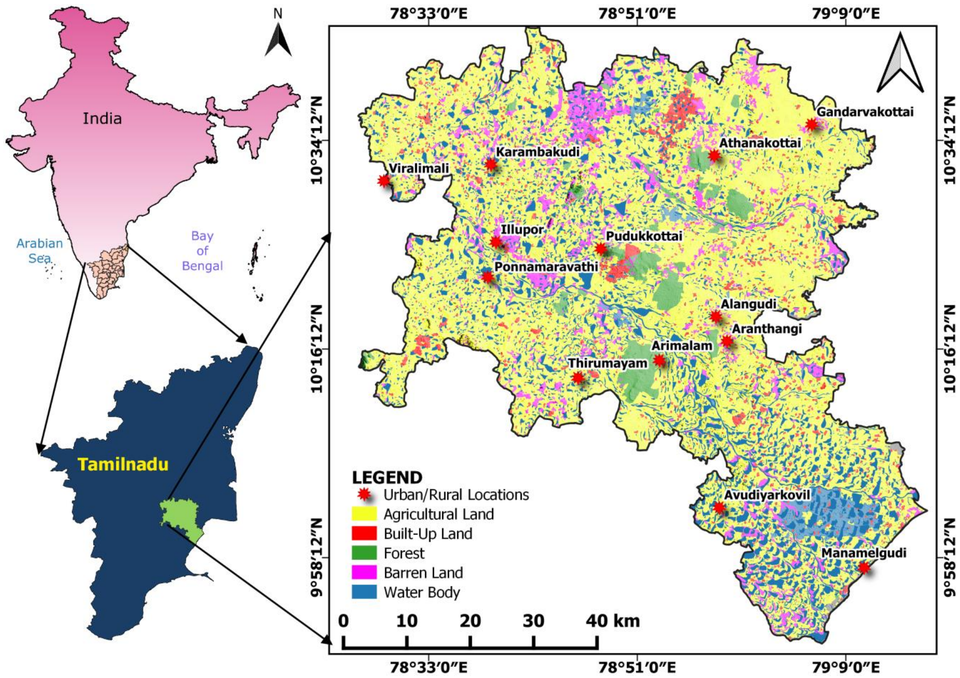

Figure 1. Pudukkottai district map.

3. Materials and Methods

Groundwater potential (GWP) mapping requires the following thematic layers: geology, geomorphology, soil, drainage density, line density, and slope. A base layer of the study area was created using the toposheet, and all other thematic layers were created using remote sensing data. The approach developed for this study is shown as a flowchart in Figure 2, and the thematic layers were also categorized. A 1:50,000 scale toposheet was used to create the basemap of the study area. IRS -P6 LISS-IV MX Satellite imagery with SRTM (Shuttle Radar Topographic Mission) DEM data with a resolution of 50 m was used to create the different types of thematic layers such as geomorphology (GM) and geology (GG), drainage density (DD), line density (LD), and slope gradient (SL) and soil type (ST) related to the occurrence of groundwater. These thematic layers are more commonly used for mapping groundwater potential as they control recharge, infiltration, runoff and groundwater movement. The lithologic nature of a rock outcrop is critical to groundwater recharge because weathering and fracturing create secondary porosity as an aquifer. Therefore, the geology of the study area was considered along with other strata because of its influence on water percolation and groundwater availability. The subsurface lithology and structural features of a study area influence the geomorphology. Visual interpretation of processed satellite imagery for geomorphologic mapping can identify and delineate structural features and different landforms. Soil infiltration conducts precipitation water from the surface to groundwater by gravity and capillary forces and is therefore an important criterion for identifying potential zones. Soil texture and structure, soil moisture and density, biological shells and vegetation controls the infiltration and are influenced by soil temperature as well as human activities at the soil surface. Drainage represents the lithology of the surface and subsurface. The distance between channels is represented by the unit of drainage density, km/km^2. Drainage density, expressed as the number of km/km^2, can be used to calculate the distance between channels. The drainage, catchment area and its specifications were determined using SRTM Dem data. The following formula was used to determine the drainage densities (DD) for the drainage map:

$$DD = \Sigma TLWS/TAWS$$

where TLWS is the total stream length in the watershed and TAWS is the total area of the watershed.

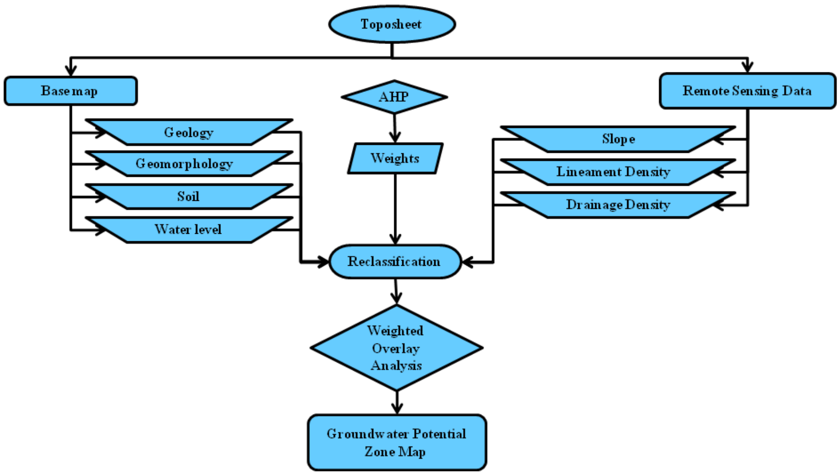

Figure 2. Flowchart of methodology Adopted.

Lineaments indicate groundwater recharge zones, and the density of lineaments indicates high groundwater potential [26–28]. The lineaments of the study area were identified by edge formation techniques using high-pass and low-pass filtering, and lineament density was calculated using information on the sources of lineament density. The degree of slope affects the infiltration of groundwater into the subsurface, providing information about the potential groundwater zone. On steep slopes, stormwater drains more quickly, while on gentle slopes it drains more slowly, which increases infiltration because stormwater remains on the surface of the slope longer. GIS Software such as ERDAS IMAGINE: 8.7 and ArcGIS 10.8 were used to allow processing of the digital images using statistics and geographic analysis. The base map was used to draw ground control points (GCP) for geometric rectification of the satellite data [29–31]. AHP logic is a type of site selection that is commonly used [32,33]. It assigns membership values between 0 and 1 to sites (ESRI). Based on their relative position in the groundwater determination, the weights for each layer were controlled using analytical hierarchical processing (AHP). The variables controlling surface runoff, infiltration, and groundwater flow are used in the pairwise comparison method to determine the more favorable layer. The pairwise comparison matrix developed by Saaty (1980) was checked for accuracy using the formulas below (Equations (1)–(5)). The standardized principal eigenvector is given in Table 1. The pairwise comparison matrix table (1) was developed based on the relative importance of the thematic strata in determining groundwater potential. Here, geology is the most fundamental layer that forms the aquifer of the water-bearing formation in a study area. Geomorphology is the second most important layer, followed by soil, drainage density, lineament density, slope and water table. In general, the eigenvalue (λ) describes the scalar factor change of a vector as a result of a linear transformation. Using equation 4, the maximum eigenvalue estimate was calculated for all layers (Table 2).

$$Wi = \frac{\sum_{i=1}^{n}\left[\frac{Ci}{\sum_{i=1}^{n} Ci}\right]}{n} \tag{1}$$

$$Cj = \frac{\sum_{i=1}^{n}[Ci \times Wi]}{Wi} \tag{2}$$

$$\lambda max = \frac{\sum Cj}{n} \tag{3}$$

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

$$CR = \frac{CI}{RI} \quad (5)$$

where *Ci* is the indicator value consigned. Each measure from the pairwise comparison matrix has a weight called *Wi*. *Cj* stands for consistency judgement factor, the calculation of the greatest Eigen value is λmax, and the number of criteria is n.

Table 1. Pairwise comparison matrix.

Layers	Geology	Geomorphology	Soil	Drainage Density	Lineament Density	Slope	Water Level
Geology	1.000	3.000	4.000	5.000	6.000	7.000	8.000
Geomorphology	0.333	1.000	3.000	4.000	5.000	6.000	7.000
Soil	0.250	0.333	1.000	3.000	4.000	5.000	6.000
Drainage density	0.200	0.250	0.333	1.000	3.000	4.000	5.000
Lineament density	0.167	0.200	0.250	0.333	1.000	3.000	4.000
Slope	0.143	0.167	0.200	0.250	0.333	1.000	3.000
Water level	0.125	0.143	0.167	0.200	0.250	0.333	1.000
SUM	2.218	5.093	8.950	13.78	19.58	26.33	34.00

Table 2. Normalized principal eigenvector for comparison matrix.

Layers	Geology	Geomorphology	Soil	Drainage Density	Lineament Density	Slope	Water Level	Weights
Geology	0.451	0.589	0.447	0.363	0.306	0.266	0.235	0.404
Geomorphology	0.150	0.196	0.335	0.290	0.255	0.228	0.206	0.243
Soil	0.113	0.065	0.112	0.218	0.204	0.190	0.176	0.150
Drainage density	0.090	0.049	0.037	0.073	0.153	0.152	0.147	0.092
Lineament density	0.075	0.039	0.028	0.024	0.051	0.114	0.118	0.055
Slope	0.064	0.033	0.022	0.018	0.017	0.038	0.088	0.032
Water level	0.056	0.028	0.019	0.015	0.013	0.013	0.029	0.024
Eigen vector	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

CI, *RI*, and *CR* are denoted for consistency index, random index and consistency ratio of derived weights. The presence of lineaments indicates rechargeable zones in the aquifer, and the density of lineaments indicates excellent groundwater potential. Edge development with low- and high-pass filters was utilized to discover the lineaments in the study region using the source of lineament closeness [34]. The weights are consistent under all conditions and can be used in a weighted linear combination. Using Equation (6) and the weighted linear combination approach, the groundwater potential index was obtained. The groundwater potential index was computed using the weighted linear combination method.

$$\text{Groundwater Potential Index (GWPI)} = \sum_{i=1}^{n}(\text{GGw.wi, GMw.wi, STw.wi, DDw.wi, LDw.wi, SLw.wi}) \quad (6)$$

Here, GWPI—groundwater potential index, GG—geology, GM (geomorphology), ST (soil type), DD (drainage density), LD (line density), and SL (slope) are used. The index "w" represents the standardized weights of each layer and the index "wi" represents the normalized weights of each thematic layer [35]. The groundwater potential area is divided into five categories based on the GWPI values: poor potential, moderate potential, and good potential-excellent, good, moderate, low, and poor. The groundwater potential index is also converted to a GIS database file, which is then used to create the groundwater potential zone map (GPZM). The groundwater potential zone map (GPZM) is created in the recommendation by first converting the groundwater potential index to a GIS database file. A random survey of the region was conducted to confirm the groundwater benchmarks.

3.1. Weighted Overlay Analysis

Each thematic map received an AHP comparative weight assignment to create a collective weight of the individual thematic maps. The weight value of each map was then determined based on the actual field conditions. The consistency ratio of their thematic maps and the instantaneous weights of the features of the various thematic layers were calculated and assigned for each thematic map. All thematic layers were integrated with ArcGIS 10.8 to produce the GWPZ map by applying the below Equation (7):

$$\text{GPZM} = ((\text{TM1w} \times \text{SC1r}) + (\text{TM2w} \times \text{SC2r}) + (\text{TM3w} \times \text{SC3r}) + (\text{TM4w} \times \text{SC4r}) + (\text{TM5w} \times \text{SC5r}) + (\text{TM6w} \times \text{SC6r}) + (\text{TM7w} \times \text{SC7r}) + (\text{TM8w} \times \text{SC8r})) \quad (7)$$

where GPZM stands for the groundwater potential zone map, TM1–TM8 stands for the major criterion (1 to 8 thematic layer maps), w stands for the thematic map's weighting, SC1–SC8 stands for the sub-conditions of each thematic layer map, and r stands for the sub-criteria class rating [36].

3.2. Sensitivity Analysis

The relative importance of each thematic layer can be evaluated by sensitivity analysis. It also helps to evaluate the feasibility of the chosen method by calculating the uncertainty of the results. In the present study, a single-layer sensitivity analysis was performed. This method was used to evaluate the influence of each thematic layer on GWPI. It defines the effective weight of each thematic layer. Equation (8) gives the effective weight of the selected thematic layer, which can be compared with the AHP weight assigned to the same layer:

$$W = \left(\frac{TLi.Sj}{GWPI}\right) \times 100 \quad (8)$$

where W is the effective weight of the selected layer, TL_i is the assigned ranking, and S_j is the AHP-derived weight for the selected layer. The overall index of groundwater potential was given by *GWPI*. The results of the above equation help to identify the thematic layer that has a greater effective weight than the AHP-derived weight and thus has a greater impact on the overall GWPI [37].

4. Discussion

4.1. Geology

Hard rocks from the Archean era and Quaternary sedimentary deposits make the study area's geological structure (Figure 3). The entire research region falls within the hard rock and sedimentary rock categories geologically. While sedimentary formations developed on the east side of the study area, hard rocks developed on the west. The research region is made up of around 45% Archean hard rocks and 55% sedimentary rocks that range in age from the Precambrian to the Quaternary. Along with the primary rock types, the Pudukkottai block's central and southern regions are mostly home to charnockites, hornblende gneiss, biotite gneiss, granite, and quartzite charnockites and granitic rocks. In the western portion of the study region, gneissic rocks of various sorts can be discovered. The Annavasal and Thirumayam blocks have modest amounts of quartzite deposits. In this area, mining is taking place. Shaley sandstone, sand, clay and gravel make up the sedimentary deposits of this area. Sandstone, clay and mudstone make up the tertiary sedimentary deposits. The Arantangi, Gandharvakottai, Alangudi, and Thiruvarankulam blocks include these deposits, which create a healthy groundwater zone. Sand, gravel, and silt comprise the unconsolidated coastal alluvium that lines the riverbank. Silt and clay deposits from the Quaternary can be found in the Avudaiyarkoil and Manamelkudi blocks [38]. Near the Pudukkottai district's coastline limit, the beach has sand deposits with ridges and dunes. The geology of an area forms the aquifers of the region. When a geologic formation has the properties to hold water, it is called an aquifer. Often, aquifers are distinguished based on their location and the arrangement of the overlying formations. Therefore, geology plays an important role in identifying groundwater potential zones. In this study, geological formations were classified into three groups, namely good groundwater potential, moderate groundwater potential, and poor groundwater potential. This classification is based on the evaluation of the water storage capacity of each formation. The reclassification of the region based on the geological formation shows that 49% have poor potential, 40% have moderate potential, and 11% have good potential (Figure 4). However, this classification refers only to the primary relative capacity of the formations and does not take into account the capacity created by secondary processes. To overcome these limitations, other thematic strata were used to determine groundwater potential.

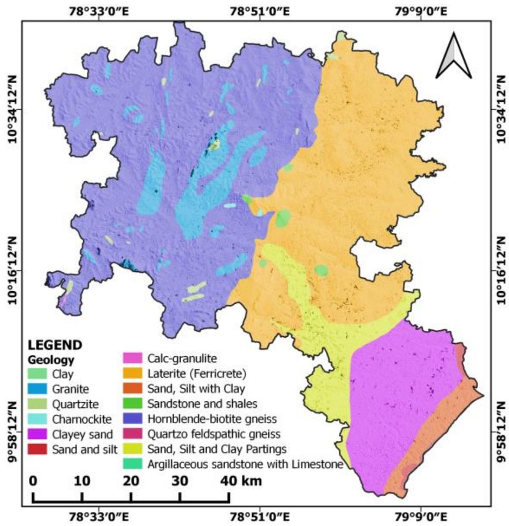

Figure 3. The study area geology map.

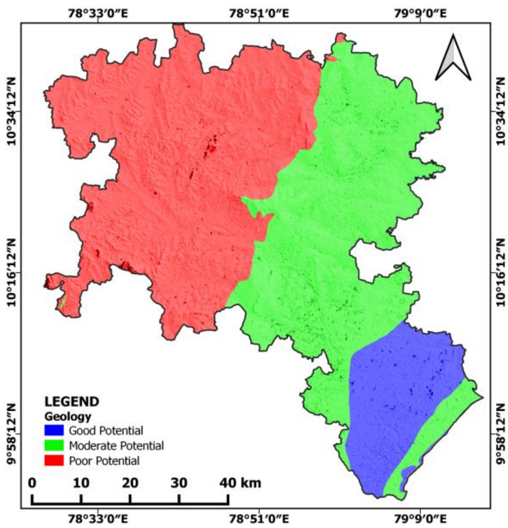

Figure 4. Ground water Potential map based on Geology.

4.2. Geomorphology

Seven zones are identified on the geomorphological map (Figure 5) as majorly plains of lateritic, alluvial, pediment and floods, structural hills, uplands, and denudation hills. In the Pudukkottai region, the alluvial plain makes up the majority (49.1%), followed by the alluvial plain (35.6%), upland (11.5%) and flood plain (1.7%) mixed with lateritic plain cover (1.2%), structural hills around 0.7%, and denudation hills (0.4%). The district's north, west, and southern regions have residual hills that create topographical undulations and flat terrain with alluvial plains in the eastern portion of the district. While it is 1.5 m above sea level close to the coast, the terrain in the western section of the district is roughly 125 m above sea level. Denudation, structural, and fluvial processes dominate the geomorphological evolution of the area. The development of the different landforms has been substantially influenced by the geologic formations' resistance to these processes. In the region, there are pediments, buried pediments, erosional plains, residual mounds, and deltaic plains. Lateritic Plains > Alluvial Plain > Pediplain > Structural Mounds > Upland > Buried Mounds. With thin soil cover, the shallow pediments produce low to moderate yields. Groundwater is abundant in the buried summits and delta plain [39]. In general, geomorphology represents the features of the earth's surface created by various geological impacts. Based on the nature of these surface features, an area can be differentiated by groundwater potential zones. Geomorphologic features are one of the most important controlling factors for surface water runoff, infiltration, and groundwater recharge. Earth surface features in an area that support stormwater runoff into the groundwater system are considered to have good groundwater potential. This characteristic of geomorphological features led to the classification of a study area into good, moderate, and poor groundwater potential (Figure 6). In this study, 72% of the study area has good groundwater potential, followed by 16% moderate potential, and 12% poor potential (Table 3).

Table 3. Weighting and ranking for each category of thematic layers.

S.No	Parameter	Class	Score	Weights	Area %
1	Geology	Hornblende-biotite gneiss	1	0.404	41.69
2		Quartzo feldspathic gneiss	1	0.404	0.02
3		Argillaceous sandstone with limestone	3	0.404	0.30
4		Quartzite	1	0.404	0.62
5		Laterite (Ferricrete)	2	0.404	29.82
6		Charnockite	1	0.404	0.21
7		Granite	1	0.404	5.98
8		Clay	2	0.404	0.13
9		Sandstone and shales	2	0.404	0.46
10		Sand and silt	3	0.404	0.50
11		Sand, Silt and Clay Partings	2	0.404	6.85
12		Calc-granulite	2	0.404	0.02
13		Clayey sand	3	0.404	11.47
14		Sand, Silt with Clay	2	0.404	2.29
15	Geomorphology	Shallow and moderately Weathered Pediplain	3	0.243	66.50
16		Upland	1	0.243	10.11
17		Pediment	1	0.243	0.81
18		Shallow Flood Plain	3	0.243	4.90
19		Inselberg	1	0.243	0.02
20		Linear Ridge/Dyke	1	0.243	0.11
21		Bazada	3	0.243	0.15
22		Pediment-InselbergComplex	1	0.243	0.47
23		Pediplain Canal Command	3	0.243	0.21
24		Channel bar	1	0.243	0.17
25		Structural Hills	1	0.243	0.06
26		Shallow alluvial plain	2	0.243	13.43
27		Coastal Plain	2	0.243	2.20
28		Lateritic	3	0.243	0.04
29		Salt flat	2	0.243	0.07
30		Brackish water creeks	1	0.243	0.02
31		Beach ridge complex	1	0.243	0.24
32		Dune complex	3	0.243	0.05
33	Soil	Clay	1	0.15	45.66
34		Sandysilt	1	0.15	24.13
35		Sandyclay	2	0.15	22.47
36		ClayeySilt	1	0.15	5.03
37		Sandstone	3	0.15	2.66
38		Silty sand	2	0.15	0.022

Table 3. *Cont.*

S.No	Parameter	Class	Score	Weights	Area %
39		Low	3	0.092	82.85
40	Drainage density	Moderate	2	0.092	15.47
41		High	1	0.092	1.68
42		Low	1	0.055	62.34
43	Lineament density	Moderate	2	0.055	26.06
44		High	3	0.055	11.60
45		0–4.5 (gentle slope)	3	0.032	99.54
46	Slope	4.5–7.9 (moderate slope)	2	0.032	0.44
47		>7.9 (steep slope)	1	0.032	0.02
48		<10 (Good)	3	0.024	6.56
49	Water Level	10–50 (Moderate)	2	0.024	17.51
50		>50 (Poor)	1	0.024	75.9

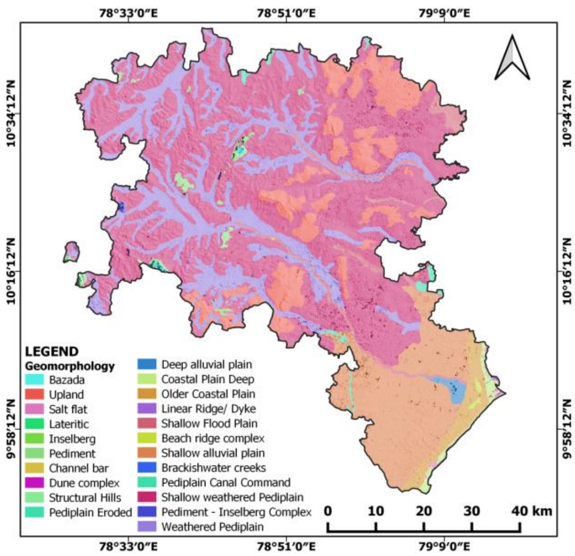

Figure 5. Geomorphological map.

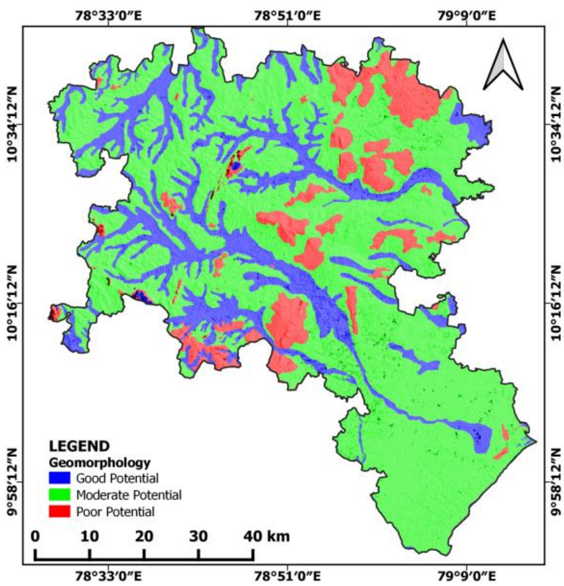

Figure 6. GWPZ map according to the Geomorphology.

4.3. Soil

The study area soils (Figure 7) fall into the categories of black, red, ferruginous, lateritic, alluvial, and beach soils. West of the study area was developed by black soils. Southern parts were constructed by red, ferruginous lateritic soils on the uplands. Alluvial soils are found in the coastal region of the study area. Black and brownish, sandy, and silty soils are found beside the riverine regions such as Vellar, Agniyar, and Ambuliyar. Whereas down the coast are beach sands. The different types of soil appear in the following order: Sand (30.53%) > sandy-loamy (20.27%) > sandy silt (19.28%) > clayey silt (17.66%) > silty sand (6.83%) > clayey (3.13%) > clayey (0.04%). The loamy sand dominates the middle part, while the northern, north-eastern region is dominated by sand. Clay minerals in the south region of the Pudukkottai area are shrinking and swelling. With the exception of the southeastern region, clay soils are found throughout the study area. In general, the infiltration rate of the top sand layer is higher than that of the other soil types. Following is a ranking of the soils based on their infiltration potential: alfisols > entisols > inceptisols > vertisols > silty sands > sandstone [40]. In the identification groundwater potential, soil type is considered an important criterion used in many previous literatures. The infiltration rate in a study area is different if the soil type is different. Different groups of soils have different infiltration rates. The granulometric arrangement of soil types causes them to have different infiltration rates. As mentioned earlier, the study area has different soil types on its surface. Based on the infiltration capacity of these soils, the study area was classified as 75% poor potential, 22% moderate potential, and 3% good potential (Figure 8).

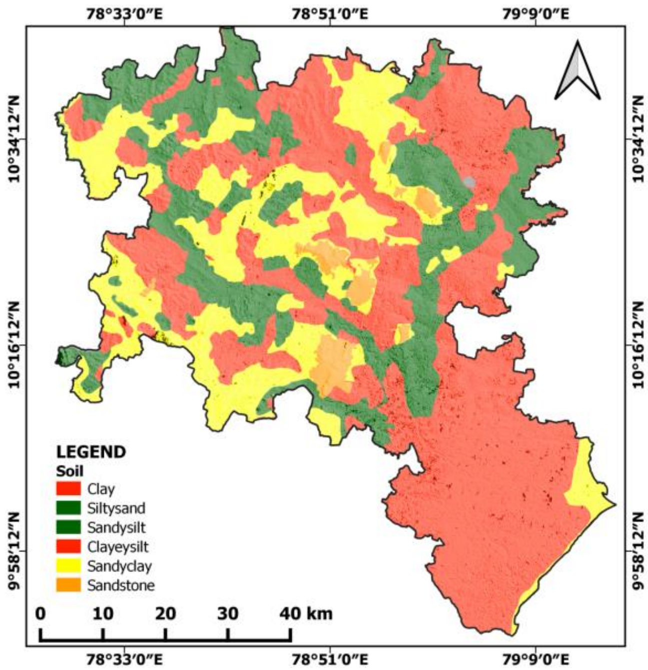

Figure 7. Soil type map.

4.4. Drainage and Drainage Density

Drainage density is divided into three zones on the basis of the proximity to rivers as high, moderate, and low (Figure 9). Pudukottai is a sub-basin of the Cauvery basin. The main river is the Vellar, which flows in a south easterly direction towards the Bay of Bengal [41]. Other rivers that drain in this study area are the Gundar, Pambar, Agniyar, Ambuliyar, and Koraiyar. Most of them are ephemeral rivers and cause structural flooding during the rainy season. Precipitating rainwater forms floods by accumulating in drains. The runoff density of a region controls flood movement at the earth's surface. This is because infiltration and groundwater recharge are relatively slow processes. Dense drainage zones drain floodwaters more quickly, so not enough water remains at the surface for infiltration and groundwater recharge. This phenomenon results in an area with dense drainage systems having low potential because most of the surface water is conveyed through channels or streams. Based on drainage density, the study area was divided into 83% zones with good potential, 15% with moderate potential, and 2% with poor potential (Figure 10).

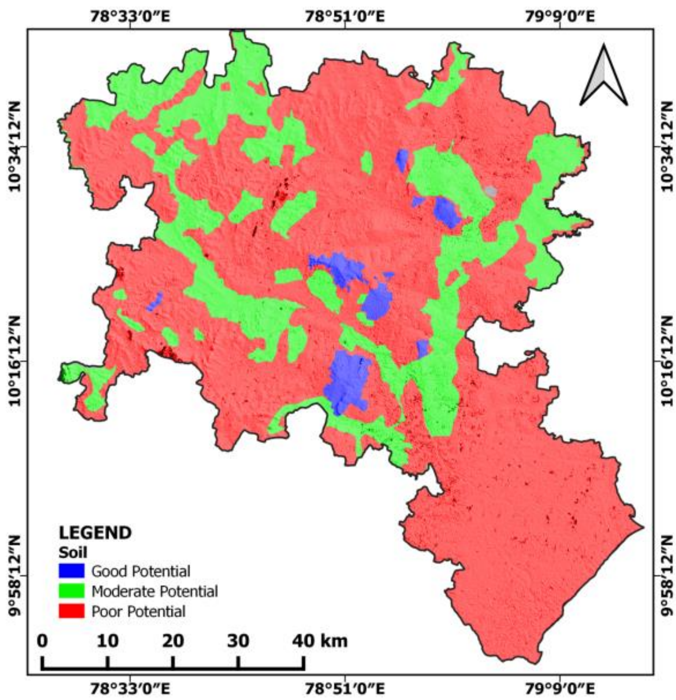

Figure 8. GWPZ map according to the Soil.

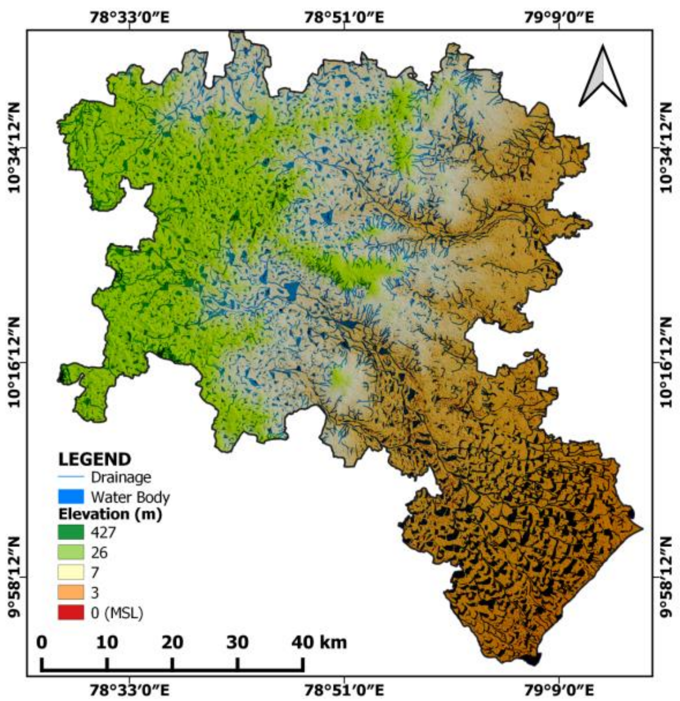

Figure 9. Drainage map.

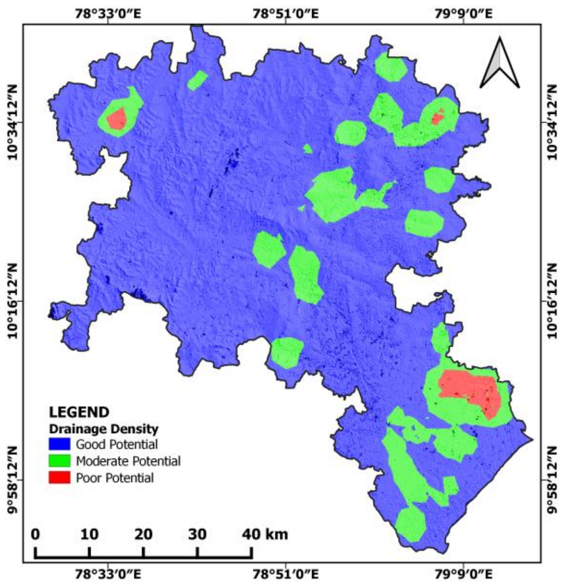

Figure 10. GWPZ map according to the Drainage Density.

4.5. Lineament (L) and Lineament Density (LD)

The study area was divided into low, moderate, and high according to line density and has a uniform distribution of lineaments that serve as conduits for groundwater flow. The highest density category ranks first, followed by moderate density, and low density [42]. The studied area has minimal lineament density throughout. Lineaments are observed in moderate and high density in the center and northeastern part of the study area, respectively (Figure 11). Lineaments act as subsurface conduits that convey infiltrated water to the groundwater regime. Therefore, lineaments are considered good markers for locating potential groundwater zones. Based on lineament density, the study area was divided into 62% low potential, 26% moderate potential, and 12% good potential zones (Figure 12).

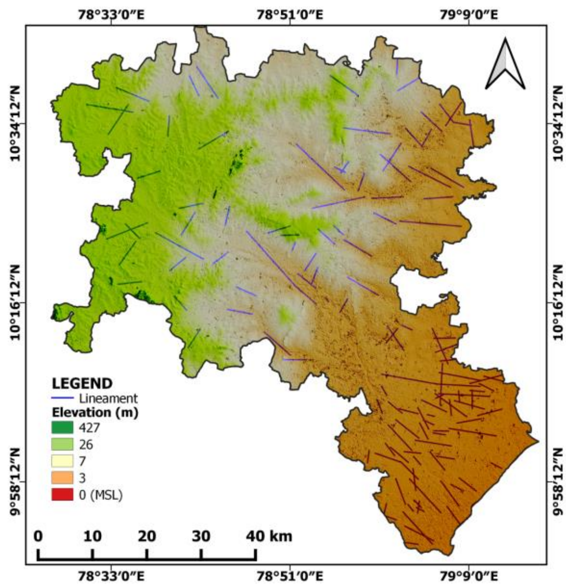

Figure 11. Lineaments density map.

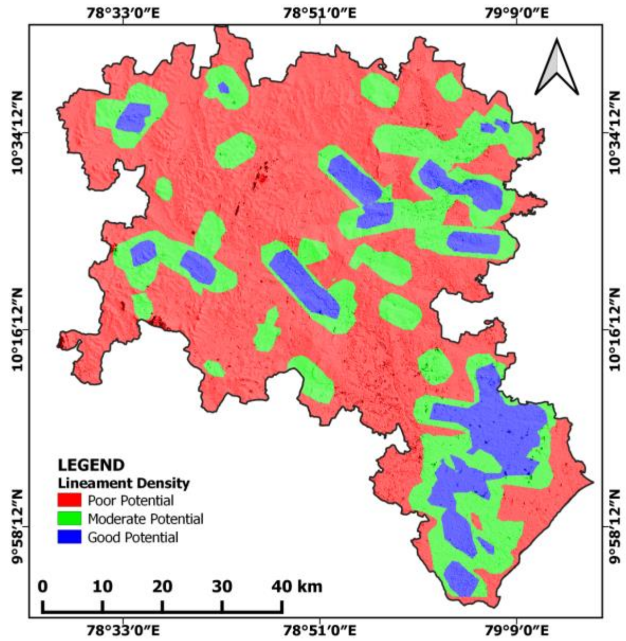

Figure 12. GWPZ map according to the Lineaments.

4.6. Degree of Slope

In contrast to the rest of the study area, which has a gentle (104.5%) to moderate (104.5–457.9%) slope that allows infiltration of rainwater into subsurface aquifers, the hilly terrain in the northwestern section has a steep slope of more than 457.9% (Figure 13) [43]. Consequently, the slope angle of the hillside is important in determining the infiltration and runoff capacity of a site. The amount of runoff increases with the steepness of the slope, but a gentle slope allows more water to infiltrate. Based on the slope factor, 99% of the study area was classified as having good potential, followed by moderate (0.4%), and poor (0.02%) potential (Figure 14).

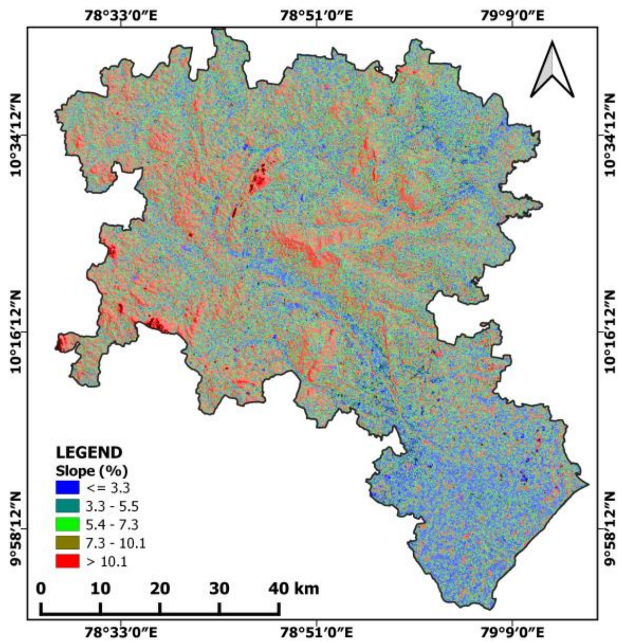

Figure 13. Slope % map of the study region.

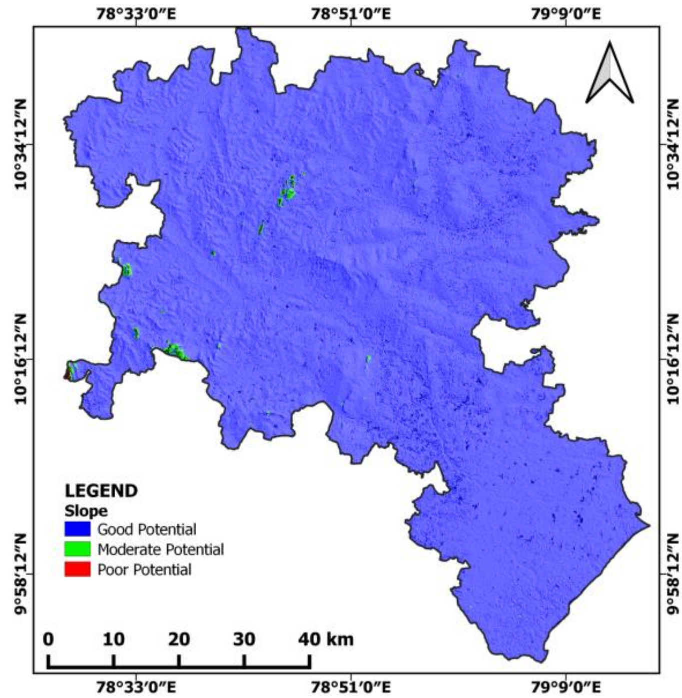

Figure 14. GWPZ map according to the Slope.

4.7. Ground Water Level

Comparison with the groundwater level map of the study area served as validation of the groundwater potential map. (Figure 15), which gives a direct indication of the potential availability of groundwater. The groundwater potential maps were also generated for different well types, and it was found that the GWPZs in 80 wells sampled at different locations correlate well with the groundwater level map. The groundwater potential zone is well associated with the cross-correlation of water level and precipitation [44]. The water table of a near-surface aquifer was measured in sedimentary rocks at depths ranging from 1.80 to 11.5 m and in weathered rocks at depths ranging from 12 to 32 mbar. Hard rock in sedimentary formations ranges from 35 to 125 mbgl, while massive rock ranges from 75 to 152 mbgl. Groundwater levels often provide information about the potential regions of an area. By measuring and monitoring the water table, we can determine its flow path. However, the water table in an area depends on the type or location of the aquifer system. In unconfined areas, the water table is near the surface and may have a low potential, while in confined aquifers it is in deeper horizons but may have a good potential. This leads to uncertainties in determining groundwater potential zones based on water level. In the current study, GWPZs were classified as 76% poor potential, 17% moderate potential, and 7% good potential (Figure 16).

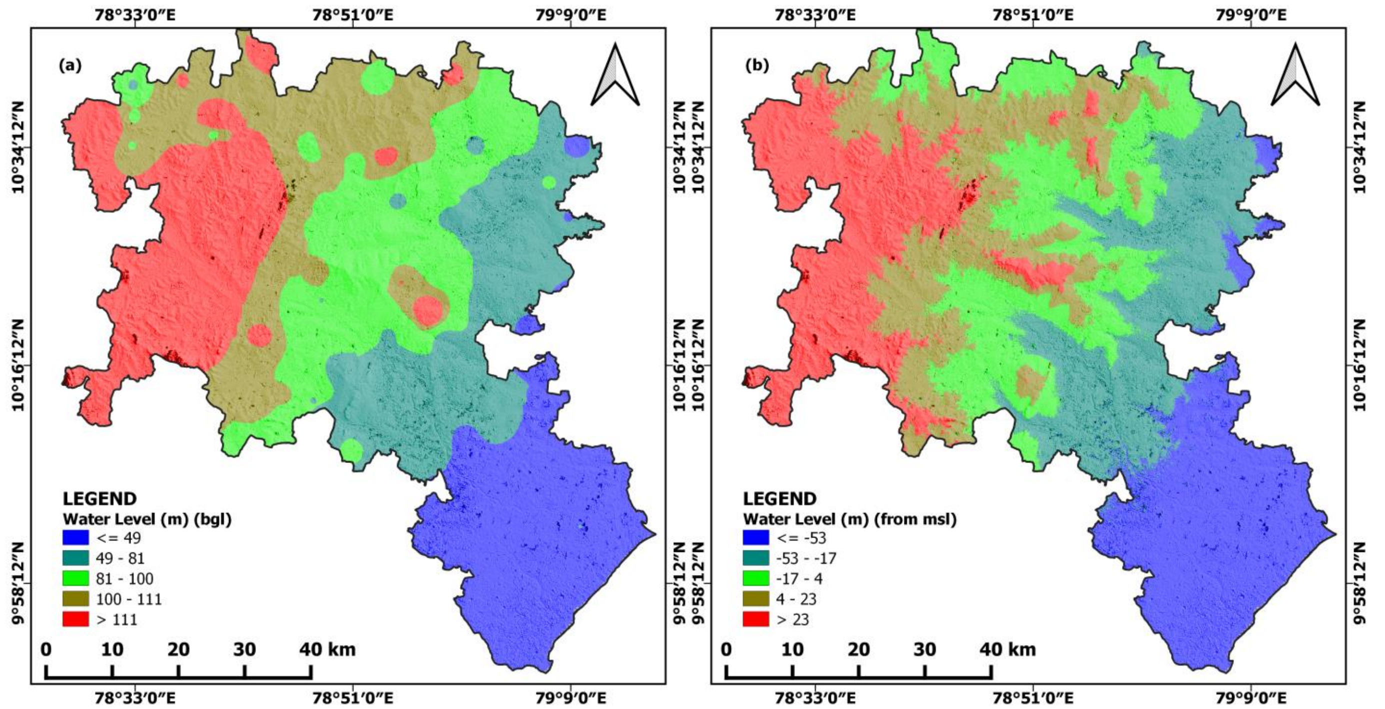

Figure 15. Ground water level of the study area (**a**) measured as below ground level and (**b**) measured as from mean sea level (positive values denote above msl and the negative values denote below msl).

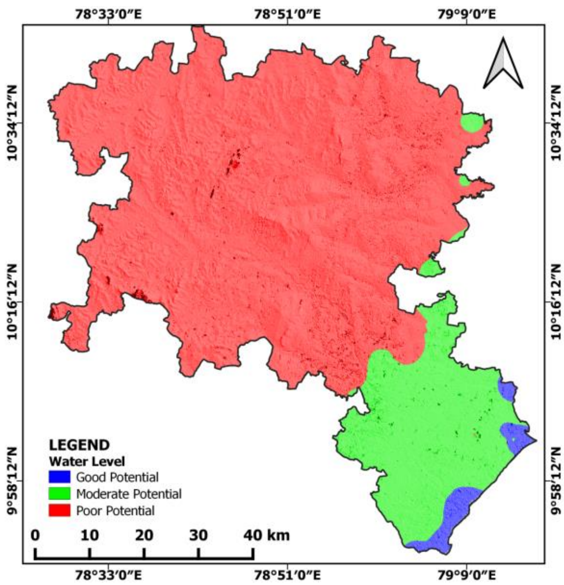

Figure 16. GWPZ map according to the ground water level.

4.8. GWPZ Map

According to the ranking and weighting assigned to the selected thematic layers based on their water storage capacity, they were reclassified (Table 3). The cumulative weighting percentages applied to the geology, geomorphology, soil, drainage density, line density, slope, and water level maps were used in a WOA to create the GWPZ map (Figure 17). The ability to hold the recharging water increases with weighting; conversely, the inability decreases with weighting. Based on the weighted overburden analysis, the groundwater potential map of the study area has three distinct zones of good, moderate, and poor potential. While the peripheral portion of the study area has moderate groundwater potential, the central to northern portions have good potential. Isolated areas in the northwest, southwest, and center have poor GWP. In most of the study region, the groundwater zone potential is excellent, moderate, or fair (Table 4). Validation of the GWPZ map was based on the groundwater level map of the study area, although groundwater level is the most obvious indicator of potential availability [45–47]. Groundwater level data were collected from 80 different well types in 2019. The map of spatial distribution of groundwater level was created using the Inverse Distance Weights (IDW) interpolator in GIS. The map spatially depicts the groundwater level of the study area. The southern and central parts of the study area merge with its northeastern part, which has a narrow groundwater table. The statistical summary of the sensitivity analysis results is provided in Table 5. The relative importance of the selected thematic layers is obtained by comparing the weights determined in the AHP with the effective weights. From the mean of the effective weights, it can be seen that the weights derived from the AHP are consistent in this study. Among the thematic layers, geology is the most important with a mean effective weight of 3.53, followed by geomorphology (2.10), soil (1.18), drainage density (0.87), and line density (0.52). Slope and water table elevations have relatively little influence on the identification of groundwater potential zones, with mean effective weights of 0.30 and 0.26, respectively.

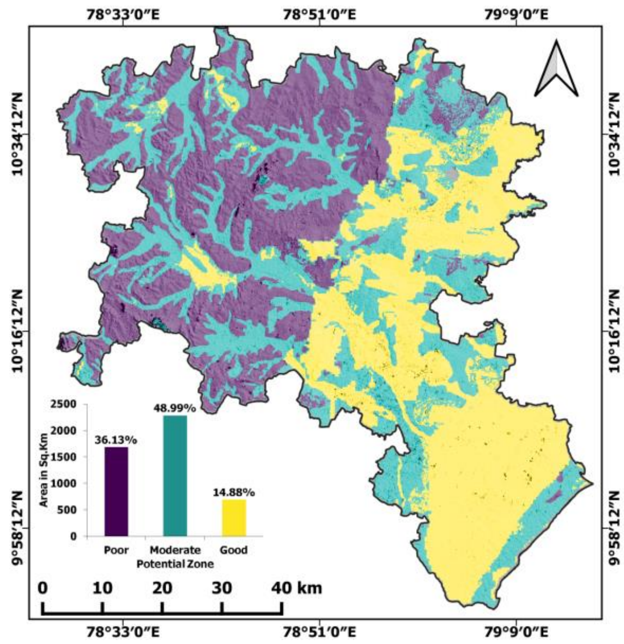

Figure 17. GWPZ classification map.

Table 4. Calculated areas of each zone in groundwater potential GWPZ map.

Zone	Description	Area in km^2	Area in %
1	Poor potential zone	1684.8	36.13
2	Moderate potential zone	2284.5	48.99
3	Good potential zone	693.7	14.88
	Total	4663.0	100

Table 5. Statistical summary of the single-layer sensitivity analysis.

Thematic Layer	AHP Weight	Effective Weight		
		Minimum	Maximum	Mean
Geology	0.404	1.90	5.71	3.53
Geomorphology	0.243	1.14	3.43	2.10
Soil	0.150	0.71	2.12	1.18
Drainage density	0.092	0.43	1.30	0.87

Table 5. *Cont.*

Thematic Layer	AHP Weight	Effective Weight Minimum	Maximum	Mean
Lineament density	0.055	0.26	0.78	0.52
Slope	0.032	0.15	0.45	0.30
Water Level	0.024	0.11	0.34	0.23

4.9. Validation of GWPZ Map

The validation of groundwater potential zone map is significant to evaluate its accuracy and the reliability of adapting the geospatial techniques. There are numerous methods available and widely used by many researchers to validate the GWPZ map [48]. Some of the previous studies compare the results with the bore well yield data [49,50]. However, the availability of these data is very limited in countries such as India. Hence, it is very complex to validate the results of GWPZ. Matching the well inventory data with GWPZ map is one of the validation techniques. In the present study, data from 80 pumping wells were collected through the reconnaissance survey. Among 80 wells, 38% (30 out of 80) fall under the poor potential zone with the average measured depth to water table of 106 m from surface. About 46% (37 out of 80) were found in the moderate potential zone with the average measured depth to water level of 80m. Whereas 16% (13 out of 80) of the wells present in the good potential zone with the average water table measured from the earth's surface at 36 m. Though the proxy of number wells and water table depth gives good matching results with GWPZ, it cannot be taken alone to evaluate the results. Hence, a well density method was used to determine which zone has the maximum number of wells in the total area. Good potential zones possess a greater number of wells in the total area and moderate potential zones contain a relatively fewer number of wells followed by poor potential. As a result, the ratio between the total area and the well count will give the well density. The equation to estimate the well density is given below.

$$Well\ Density = \frac{Total\ Area}{Well\ count}$$

The results of the well density show that in the good potential zone, for every 53 km^2 there should be a well. This is followed by the poor potential zone having a well with every 56 km^{2-} and moderate potential zone having a well in every 62 km^2 (Table 6). It proves that where the good potential of groundwater is present there will be a greater number of wells constructed. However, these findings still depends upon the resolution of the well inventory data. If the well count increases, the interpretation may change accordingly. As a result, it confirms that the GWPZ map produced by the geospatial approach is a reliable and cost effective technique and can be adopted to any part of the world.

Table 6. Summary of the well density estimation.

Zone	Description	Total Area (km^2)	Well Count	Well Density
1	Poor potential zone	1684.8	30	56
2	Moderate potential zone	2284.5	37	62
3	Good potential zone	693.7	13	53
	Total	4663.0	80	58

5. Conclusions

In designated low-potential areas, efforts must be made to improve groundwater levels. In the low-potential groundwater regions, appropriate artificial recharge structures must be created to increase groundwater recharge. Rainwater harvesting in all households must be facilitated in settlements in the low GWP areas. Groundwater pumping needs to be continuously monitored to prevent further drawdown of groundwater levels. Further studies need to be conducted to accurately identify suitable sites for the implementation of appropriate artificial recharge methods. In the critical zones, management strategies should be introduced at the legislative level to prevent further degradation. Geospatial knowledge, remote sensing, and the AHP method are considered the most effective tools for deciphering GWP zones in this region. GIS and the AHP method have been successfully used to create three groups of GWP zones. Thematic layers such as geology map, geomorphology map, soil map, drainage map, drainage and density map, lineament and lineament density map, and slope map are used in groundwater prospecting to distinguish four to three GWP zones as poor, moderate, and good, excellent, medium, moderate, and low potential. The maps were created using pre-processed remote sensing satellite data and data collected from governmental and non-governmental organizations. The results show moderate potential in the peripheral areas, while the central and northern parts have good potential for groundwater. The northwest, southwest, and some coastal areas are classified as low potential groundwater areas. More than 64% of the study area was classified as moderate to good potential for groundwater extraction. The sensitivity analysis for each stratum showed an effective weighting of the selected thematic strata, indicating that geology is the more influential criterion in mapping groundwater potential. Groundwater level maps were prepared and confirmed based on the groundwater potential map. This study shows how effectively GIS and AHP can be used to identify GWP zones. It also shows how GIS and AHP can be used to identify vulnerable, poor potential zones to consider when implementing artificial recharge structures and to reduce uncertainties in defining the boundaries of available groundwater resources. In this drought-prone region, policy makers will use the results of the study to manage water resources responsibly. This technique can also be used by other researchers interested in using spatial methods to map groundwater vulnerability in drought-prone regions.

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Data Availability Statement: The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

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