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Research Article

Spatio-temporal analysis of groundwater recharge potential and optimal siting of artificial recharge structures using geographic information system -aided analytical hierarchy process approach to improve groundwater quantity and quality

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ABSTRACT

Groundwater extraction poses a significant challenge to water security in rapidly urbanizing and industrialized regions. This study assesses groundwater recharge potential zones in Tiruppur, the major textile hub of South India, using a Geographic Information System (GIS)–based Analytic Hierarchy Process (AHP). Multiple thematic layers including lithology, soil, slope, land use/land cover, lineament density, drainage density, and rainfall were integrated through weighted overlay analysis. The resulting recharge potential zones were classified as very low (159.40 km^2), low (124.23 km^2), moderate (64.25 km^2), high (82.11 km^2), and very high (215.14 km^2). Villages such as Tiruppur, Perumanallur, Mangalam, Veerapandi, and Chettipalaiyam demonstrated high recharge potential and were identified as suitable locations for artificial recharge structures, including percolation tanks, check dams, and nala bunds. The study provides a spatially explicit framework to support groundwater sustainability planning in industrially stressed regions and contributes to long-term water security management strategies.

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INTRODUCTION

Water is the most extensively available and distributed natural resource essential for all living organisms and for maintaining environmental and ecological sustainability [1]. Groundwater, a key source of freshwater for domestic, agricultural, and industrial uses, supports over 95% of freshwater demand, making it vital for human welfare and economic growth [2]. However, the exploitation of groundwater resources has increased sharply in recent decades due to rapid population growth, industrial expansion, and recurring droughts [3]. Consequently, the world faces growing challenges in balancing human needs with environmental water demands. Overexploitation has led to significant depletion and contamination of aquifers, particularly in countries such as India, the United States, and China, which together account for more than half of the global groundwater abstraction [4].

Groundwater management through artificial recharge strategies, which allow for increased groundwater storage and sustainability, can be used to achieve such management [5]. Groundwater recharge planning is particularly important in dry and semi-arid areas where it is important to capture and store the runoff for post-drinking, irrigation and industrial uses [6]. There are several advantages to subsurface recharge, such as reducing evaporative losses, enhancing aquifer levels and decreasing salinity. The identification and prediction of groundwater recharge potential zones is thus crucial in order to guarantee the reliability and sustainability of the resource [7].

In recent years there have been significant developments in geospatial technologies which have enabled multi-criteria decision support frameworks to integrate under a variety of hydrogeologic conditions to delineate groundwater recharge zones. In semi-arid watersheds, for example, Guduru and Jilo [8] used GIS-AHP to delineate recharge zones in the Webeso watershed in Ethiopia, showing the effectiveness of multi-criteria integration for delineating recharge areas in semi-arid watersheds. Likewise, Naeem et al. [9] applied the GIS-enabled AHP to identify recharge areas in Punjab, Pakistan, highlighting the critical role of decision-support modelling in agricultural areas. The studies emphasize the wide use of AHP-GIS frameworks in the assessment of groundwater resources but the majority of them have been conducted in an agricultural or semi-arid scenarios.

The present investigation highlights the town of Tiruppur, which is the main textile center of South India, where the groundwater resources are in a critical condition due to contamination, over-exploitation and industrial activities. This study is unique in the fact that it is a combination of recharge potential mapping with practical recommendations of artificial recharge structures (check dams, percolation tanks, nala bunds), based on local hydrogeological and industrial conditions. This integrated approach both detects potential recharge areas and offers a management-inspired framework to address recharge quantity and quality issues in a landscape of industry.

A number of recent studies have investigated the spatiotemporal changes in groundwater quality, contamination patterns and purification strategies [10]. Similarly, [11] pointed out the impact of anthropogenic and geogenic parameters on groundwater quality and spatial variability. These studies highlight the need to integrate groundwater quality assessment and recharge mapping for complete groundwater resource management. The present work fills an important gap and is a step towards the development of sustainable groundwater management in industrial areas by incorporating the spatial recharge potential with site specific recharge strategies.

The review of available literature shows that GIS–AHP based approaches were successfully used to determine the recharge potential zones, but they are not used in the industrial urban setting of the city. This study aims to fill this gap by using a GIS–AHP based multi-criteria analysis to identify the groundwater recharge zones in Tiruppur and then identifying the suitable locations for artificial recharge interventions in the area using the spatial prioritization approach. This integration will increase methodological rigour and provide useful information for sustainable groundwater resource management.

Need for the Study

The two sources triggering chemical agents for environmental degradation in Tiruppur Taluk are industrialization and urbanization. Somanur, Avanashi, Palladam, and Koduvai are some of those towns nearby Tiruppur involved in textile-related work. Groundwater vulnerability and water scarcity are issues to be reckoned with Tiruppur Taluk and its sourroundings. Moreover, the bleaching and dyeing units of Tiruppur Taluk are located mainly on the banks of rivers Noyyal and Nallar, into which they discharged their effluents. For this reason, the groundwater in the vicinity of bleaching and dyeing units has become so polluted that it is unfit even for drinking. Groundwater scourge, vulnerability, environmental pollution, and degradation are contemporary problems faced by the Tiruppur Taluk. The conditions are worsened by the presence of dyeing industries along with the rapid urban population growth. Studies on Groundwater Recharge Potential Zonation and mapping of Artificial Recharging Structures are essential to promote further groundwater development in the area.

Possible causes of groundwater pollution in the study area are the heavy concentration of textile factories, dyeing units, and chemical processing plants in the Tiruppur city area. These industries have been degrading groundwater quality through disposal of untreated or poorly treated wastewater. Hence, the study advocates certain mitigation strategies, which entail establishment of decentralized treatment units for wastewater, strict compliance of industries to wastewater management regulations, and continuous monitoring of groundwater quality in the vicinity of at-risk areas. Linking the pollution sources with viable solutions gives these changes practical significance to the study.

Crucial gaps remain notwithstanding the substantial knowledge surrounding groundwater recharge and contamination [12]. Current knowledge predominantly examines general assessments of groundwater quality or the potential for groundwater recharge through mapping, which are ultimately disconnected from practical site-specific recharge solutions [13]. Further, there is an inadequate number of studies that make meaningfully implementable recommendations for artificial recharge structures that consider the specific hydrogeological and anthropogenic contexts of highly industrial cities like Tiruppur. Identifying these gaps is critical, given a full understanding is necessary to establish groundwater management strategies to support sustainable water resources given the rate of urbanization and industrialization.

Description of the Study Area

Tiruppur is recognised in Tamilnadu, India, as the textile city and thesixth largest city in the state. Survey of India (SOI) Topo sheets on a 1:50.000 scale (58- F/01, 58- E/03, 58- E/04, 58- F/05, 58- E/07, and 58- E/08) were used to demarcate the study region. It is between the Latitudes of 10.5° N and 11.15° N and the Longitudes of 77.10° E and 77.30° E. The Noyyal River flows between East to West of the study area. This specified location has a Tropical Climate and is Semi-Arid. The location has an elevation of round 295 mabove mean sea level and occupied an area of 645 km^2 and it is shown in Figure 1. This region's annual rainfall average was 694 mm/year. The main crops in this area are sorghum and coconut. Maize, bananas, cotton, vegetables and sugarcane are among the other crops grown.

MATERIALS AND METHODS

Assessment of Groundwater Recharge Potential Zones

Exploration, exploitation, and land use planning all require an understanding of the geology and structure of a terrain. Satellite remote sensing has become a vital and successful tool for water resource evaluation, planning, and development due to its capacity to offer a synoptic picture of a broad region over time [14]. The capability of remote sensing technology to handle different watershed management challenges for sustainable development is widely recognised. Remote Sensingis a strong input medium that can aid in the interdisciplinary approach for water resources management [15].

The drainage map should be generated from a digital elevation model. The soil map was created by integrating data from land use planning and the National Bureau of Soil Survey (NBSS & LP). Thematic layers such as LULC and geomorphology were delineated using satellite imagery captured by the Landsat-8, OLI/TIRS sensor with a 30-meter resolution. The lithology map was compiled using data sourced from the Geological Survey of India. Rainfall data was gained from the State Ground Water and Surface Water Resources Data Centre. Prior to integration into the

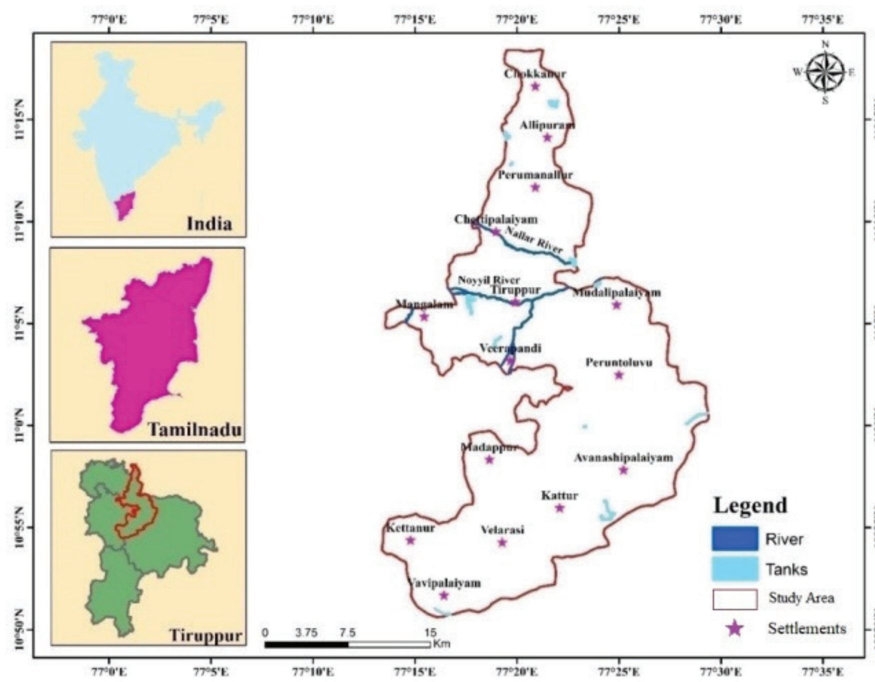

Figure 1. Location map of the research area.

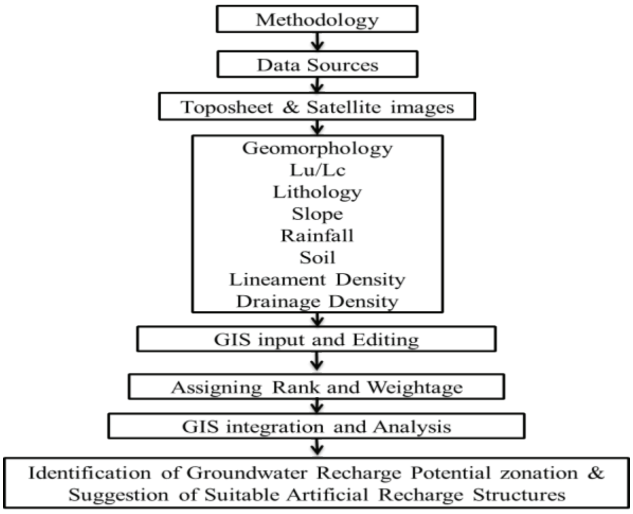

Figure 2. Flow chart exposes the technique for groundwater recharge potential zonation mapping andartificial recharge structures demarcation.

GIS system, all thematic layers underwent a conversion process to be represented in raster format.

Analytic Hierarchy Process for Groundwater Recharge Potential Zoning

The AHP developed by Saaty [16] was used to assign comparativeweightiness to the thematic layers influencing groundwater recharge potential. This multi-criteria decision-making (MCDM) technique provides anorganizedbackground for comparing various factors based on pairwise comparisons using a standardized importance scale. Saaty's scale choices from 1 (equal position) to 9 (extreme position of one element over another). AHP that uses expert judgement in giving relative weights to thematic layers is thereby sometimes prone to subjectivity. Efforts to minimize this bias were rigorously followed. The views of the experts were solicited from hydrogeologists, geospatial analysts, and water resource managers so as to include a multidisciplinary view. Pairwise comparison matrices have been developed that would show the comparative importance of factors such as lithology, soil, slope, drainage density, lineament density, land use/land cover, geomorphology, and rainfall.

Pairwise Comparison Matrix and Weight Derivation

In this study, eight thematic Layers-Lineament Density (LD), Drainage Density (DD), Geomorphology, Slope, Lithology, Soil, Rainfall, and LULC-were evaluated. Each layer was compared pairwise, and values were assigned using expert judgment. A sample of the pairwise matrix is shown in Table 1. For example, LD was assigned the highest influence (weight = 0.32), followed by DD (0.15), and LULC had the least influence (0.064). The normalized weights were derived by averaging the standardised rows of the pairwise comparison matrix.

The weight wi for each factor was calculated using:

$$w_i = \frac{1}{n}\sum_{j=1}^{n}\left[\frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}\right] \quad (1)$$

Where, w_i = weight of the i^{th} criterion, a_{ij} = value in the pairwise assessment matrix between criteria i and j, n = total number of criteria.

Consistency Ratio (CR) Evaluation

The Consistency Ratio (CR) was computed for each matrix, and only those weightings whose CR values were less than an accepted threshold of 0.1 were maintained to ensure logical consistency in the expert inputs. To safeguard the reliability of the pairwise evaluation, the CR was computed. First, the Consistency Index (CI) was determined using:

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (2)$$

Where λmax is the maximum eigenvalue of the comparison matrix, and nis the number of criteria. The CR was then intended by:

$$CR = \frac{CI}{RI} \quad (3)$$

Here, RI is the Random Index, which be contingent on the number of criteria (RI = 1.41 for n = 8). A CR value of less than 0.10 indicates acceptable consistency; in this study, the CR was computed to be 0.08, confirming logical coherence in the judgments [17].

Thematic Layers and Reclassification

Each theme was reclassified into five or more subclasses based on their inspiration on enhance groundwater recharge (Kushwaha et al., 2025). Each of these subclasses was given a rank value (1–5), and a relative weight as listed in Table 2. However, the built-up and mining LU/LC classes were given low ranks because they contributed little recharge, and low slope areas (0–2.4°) were given high ranks because they have high infiltration potential.

The final Groundwater Recharge Potential Map was developed by applying the AHP-derived weights and ranks in a weighted intersectioninvestigation within a GIS environment. The overlay was conducted using the following equation:

$$GWP_Z = \sum_{i=1}^{n}(W_i \times R_i) \quad (4)$$

GWPZ was calculated using the formula: GWZ = Wi × Ri, where Wi represents the weight assigned to each thematic layer and Ri denotes the rank given to individual feature classes within that theme. This integrated geospatial and weighted overlay approach enabled the classification of the study area into zones fluctuating from very low to very high enhancing groundwater recharge potential. Such delineation supports informed decision-making for identifying suitable artificial recharge sites and promoting sustainable groundwater management.

Further minimization of subjectivity was done by applying the cross-validation of weight assignments with the values reported in previous groundwater recharge studies carried out in similar hydrogeological settings. A sensitivity analysis was then carried out to assess how variations in weight assignments would affect the final recharge zonation results. Even after all standardizations, nevertheless, possible sources of error still exist: differences in how experts interpret the problem, differences in data set scales, and hydrogeological heterogeneities on the regional scale. Given these limitations, the study holds that while AHP provides a fair and systematic framework for decision-making, the results should be supplemented with validation in the field and refinements based on adaptive learning during implementation.

Utilizing the spatial analysis tool within ArcGIS 10.4, the GWPZ were established by overlapping all thematic maps through weighted intersection methods. While in weighted overlay (WO) analysis, weights were allocated based on the influencing role of every single parameter of every thematic map on the Hydro-Environment of the TiruppurTaluk [18]. Finally, the Drainage Network and High & Very High range of DRASTIC LU vulnerable zones were overlaid above the Recharge Zonation and the Potential Groundwater Artificial Recharging Structures were suggested scientifically for the study location [19]. The mapping of Groundwater Recharge Potential zonation and the flowchart depicting the approach to Artificial Recharge Structures can be found in Figure 2. Table 1 shows the data layers used for this research.

The current research used a combination of satellite images, field data, and secondary literature to guarantee thorough analysis and replication. The drainage density was estimated from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model with spatial resolutions of 30 m. Lineament density and land use/land cover (LULC) were extracted from Landsat 8/9 OLI/TIRS, also with a resolution of 30 m, with the same acquisition dates that referred to the period of the study in order to capture current situations. Soil Information from the NBSS&LUP obtained at scale 1:250,000, while lithological information the same scale was from Geological Survey of India-GSI Maps. Rainfall data were acquired from the Ground Water and Surface Water Resources Data Centre through observation cases of rainfall stations. Ground validation points were included to check classification accuracies while applied against Receiver Operating Characteristic (ROC) curve for validating the recharge potential models. Quality assurance steps included pre-processing the satellite data such as geometric and radiometric corrections, cross-verifying the thematic layers with field observations, and consistency checks against existing regional datasets a multi-source, quality-controlled dataset that could then suffice to delineate recharge zones into aquifers and assure replicability in study outcomes.

ROC Curve Analysis

For validation of the zonation for groundwater recharge potential, the study area borewell yield data were subjected to Receiver Operating Characteristic (ROC) curve analysis. A total of 42 borewell locations were selected within the study area considering spatial distribution, depth uniformity, and existence of yield data to provide for adequate representative coverage. The borewell points were placed over the classified recharge potential map and their yield values were categorized into two binary classes with high yield (≥ threshold value) representing the recharge-favourable zones and low yield (< threshold value) representing less favourable zones. The classification thresholds were determined based on average regional yield, as well as groundwater availability benchmarks as published by the Ground Water and Surface Water Resources Data Centre.

The ROC curve was plotted by plotting sensitivity (true positive rate) against 1–specificity (false positive rate) to quantify the area under the curve (AUC) for model performance; an AUC value closer to 1 indicated stronger predictive accuracy while closer to 0.5 would suggest random prediction. Statistical analysis has verified a good correlation between the predicted recharge zones and the observed borewell performance, thus attesting to the strength of the GIS–AHP approach. However, the limitation of this

Table 1. Data layers used for this research

SI.No.	Data	Data Sources	Resolution/ Scale
1	Drainage Density	Digital Elevation Model-SRTM	30m
2	Lineament Density	Landsat - 8/9 (OLI/TIRS)	30m
3	Soil	National Bureau of Soil Survey (NBSS & LP)	1:250,000
4	Lithology	Geological Survey of India	1:250,000
5	Rainfall	Ground Water and Surface Water Resources Data Centre	Rainfall Station
6	LULC	Landsat - 8/9 (OLI/TIRS)	30m
7	Geomorphology	Landsat - 8/9 (OLI/TIRS)	30m

validation is that there are only a few borewell data points in a number, which, when viewed as a sample, could not represent the entire variability of hydrogeological conditions being present in the entire study area. Nevertheless, despite the constraints, ROC-based validation strongly argues evidence in support of the accuracy and fielding of the groundwater recharge potential mapping.

RESULTS AND DISCUSSION

Mapping of Groundwater Recharge Potential Zonation and Artificial Recharge Structures

The action of artificial groundwater recharge increased the groundwater reservoir at a rate that was significantly faster than what would occur under normal replenishment conditions (M. Lenin Sundar *et al*. 2022). In relation to each thematic aspect, numerousinfluences such as LULC, geomorphology, lithology, slope, drainage density, lineament density, rainfall, and soil play significant roles in governing the attendance and flow of groundwater within a region with potential for artificial groundwater recharge. The subsequent sections delve into the discussion of lineament density, drainage density, rainfall, and the slope of the study area.

Lineament Density: It was hydrologically very important for providing the pathways of groundwater movement. It was derived in four directions E-W, NE-SW, NW-SE and N-S [20]. For analysis purposes lineament density has been equipped and classified into five groups: very low, low, medium, high and very high as show in Figure 3. The higher density of lineament was very good and acts as favourable zones for groundwater recharge than lesser one, thus higher weightage was assigned for from top to bottom density and less weightage to low lineament density [21].

Drainage Density: Porosity and permeability of the terrain has been identified through the drainage design [22]. The study location has been identified with dendritic drainage pattern and it has been grouped into five groups very low, low, medium, high and very high drainage density as shown in Figure 4. Drainage density of the study area should be obtained from the digital elevation model of the research area.

Slope: Slope of the area was a measure of infiltration rate. The popular of the study area was enclosed by nearly level slope category (0-2.4°). Due to slight rolling topography with considerable runoff, the area with almost level slope category was regarded as a promising area for groundwater storage. It was identified that the steep (6.5 – 10.5°) and very steep (10.5 – 14.8°) slope category with maximum runoff and also minimum infiltration rate was

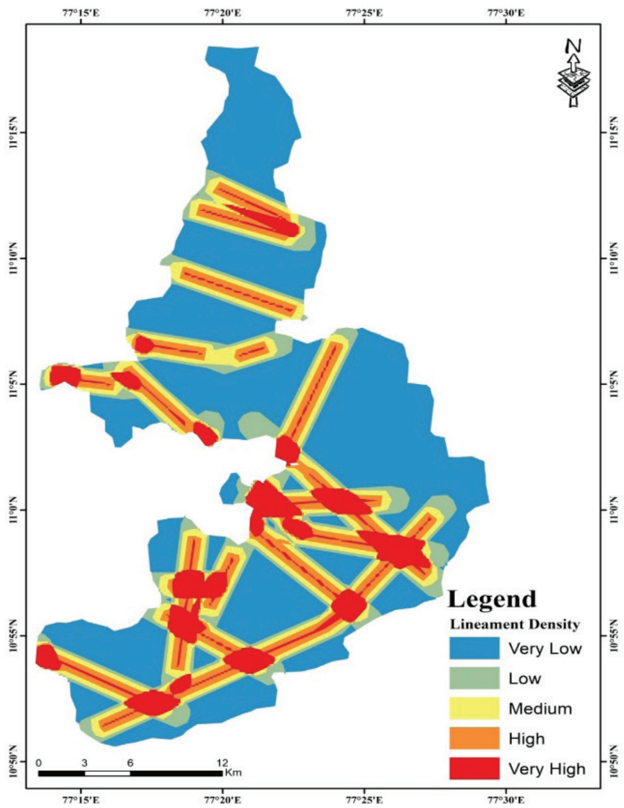

Figure 3. Lineament density map.

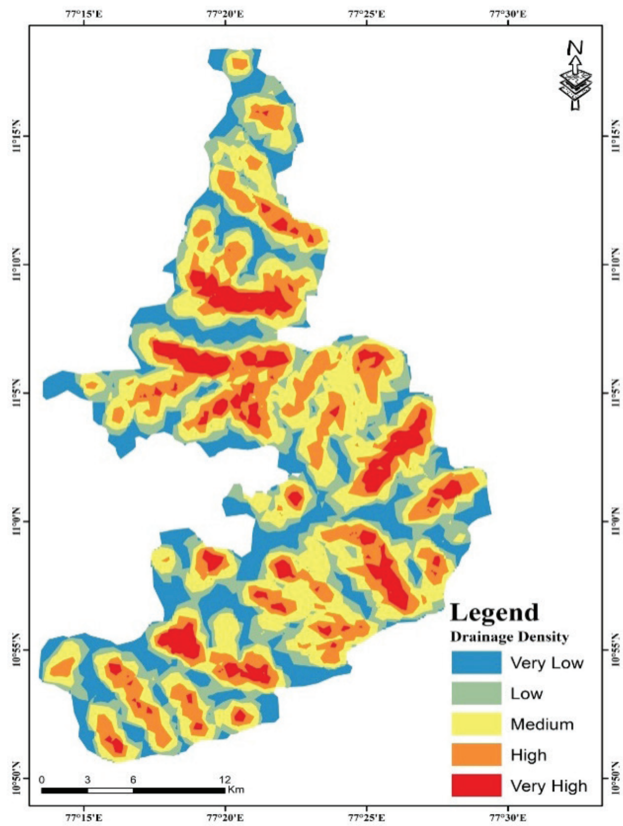

Figure 4. Drainage density map.

not suitable for natural recharge. Figure 5 shows the study location slope map.

Rainfall: Rainfall in the study location was almost low to medium seen from annual rainfall data. The rainfall data of provided twenty-four meteorological stations for a period of 1997-2016 (20 years) had been collected from State Ground Water Board and Surface Water Resource Data Centre, Tharamani, Chennai and an isohyetal map of the TiruppurTaluk region was also created using the IDW interpolation technique. The TiruppurTaluk's north and northwest are seeing an increase in annual rainfall, according to the spatial distribution of rainfall. The rainfall for the study area was distributed from 450 to 697 mm/year and it was regrouped into five major classes, which includesvery low (450-566 mm/year), low (566-591 mm/year), moderate (591-605 mm/year), high (605-640 mm/year) and very high (640-697 mm/year). Figure 6 shows the rainfall map of the study area.

Lithology: The Tiruppur region is mostly characterized by crystalline metamorphic formations, including Hornblende Biotite Gneiss, Fissile Hornblende Biotite Gneiss, and Charnockite, as documented by the Geological Survey of India in 1995. The Geological map of the study area is based on the Geological Survey of India 1: 250,000 scale map and shows that the southern section of the study area is underlain by Hornblende Biotite Gneiss. The lithological units were assessed according to their hydrogeological features, which are mainly the permeability, porosity and groundwater yield. Charnockite is less weathered and too dense to be weathered and hence, has low permeability and limited groundwater potential and hence, assigned lower weight of 2, (Overall Weightage = 18). Fissile Hornblende Biotite Gneiss with high foliation and fractures have good groundwater movement with highest weight (5; Overall Weightage = 45). The Hornblende Biotite Gneiss has medium permeability and recharge capacity therefore is assigned with medium weight (Overall Weightage = 36). The weight values are correct for the hydrogeologic effect on groundwater recharge in the AHP model. The area's water quality has been declining over the past few years because of a number of direct and indirect causes such as soil salinity, decreases in water levels affecting agricultural activities, water-rock reactions, evaporation and industrial effluents. Groundwater occurs in the phreatic zone in the weathered horizon and in semi-confined to restricted conditions in deep-seated fractures. Groundwater extraction mostly takes place from dug wells 15–18 m deep. The production of open wells is from 30 to 250 cubic meters per day and that of tube wells is 260 to 430 cubic meters per day. The geological map of the research area is given in Figure 7.

Geomorphology: The geomorphology map of the study area was produced using LANDSAT-8 images (30

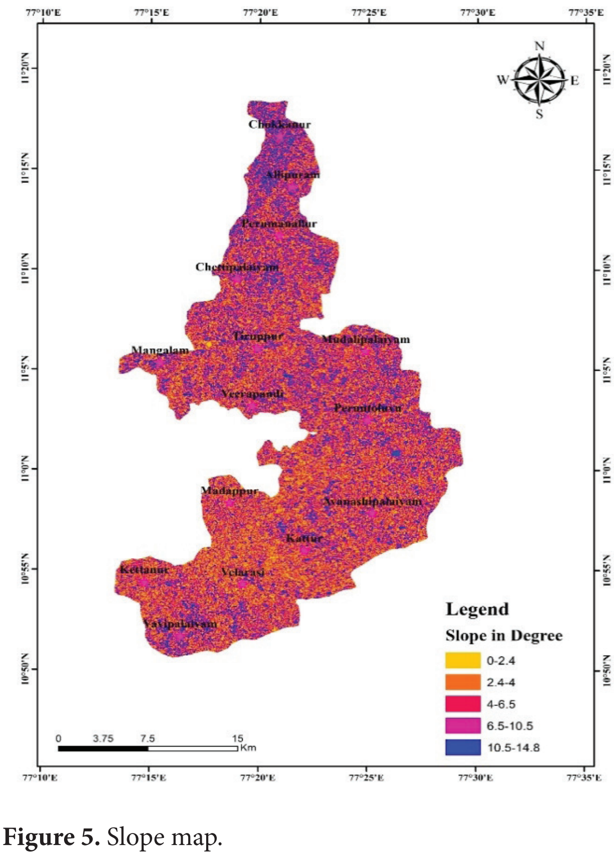

Figure 5. Slope map.

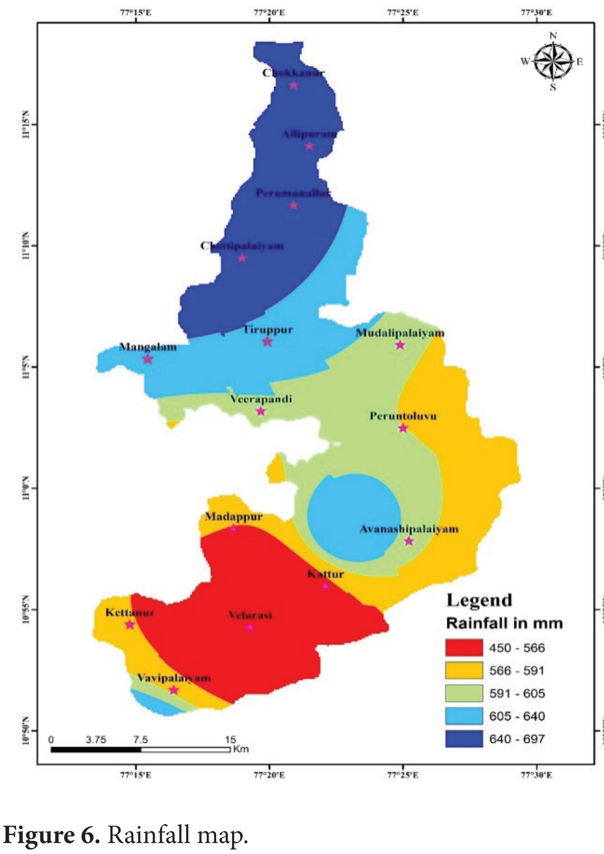

Figure 6. Rainfall map.

m) pixel-based geomorphology. Geomorphology: Pixel-based geomorphology was used to produce a geomorphology map for the study area from LANDSAT-8 images (30 m). Various geomorphic features have been identified and located within the study area, including Deep, Moderate, and Shallow Pediments, Rivers, Colluvium fill, and Flood plains.

Pediments, characterized as gently sloping erosion surfaces or plains with low relief, are formed by the action of running water in arid or semi-arid regions at the base of receding mountain fronts. Within this classification, there are three subtypes: Deep Pediments covering an area of 212.13 km^2, Moderate Pediments covering 255.20 km^2, and shallow pediments covering 117.76 km^2. The dominant geomorphic feature in the study area is Moderate Pediments. Flood Plains, defined as low, flat lands periodically inundated by river water, cover an area of 10.96 km^2. Additionally, the study area includes rivers and colluvial fill, with respective areas of 2.12 km^2 and 46.83 km^2.Figure 8 illustrates the geomorphology map of the study area. It should be useful to use the Jennes algorithm in determining geomorphological features in ArcGIS environment.

Soil: The soil map of the study area (Fig. 9) is prepared from National Bureau of Soil Survey and Land Use Planning data with a scale of 1:250,000 by manual digitization method. The soil of the TiruppurTaluk is gravely loam soil, which is followed by clayey soil. Mostly loam to clayey loamy and characterized by a hard and compact layer of lime. The middle part of the study area was covered by calcareous loam soil. The soil classes in the study area, calcareous clayey soil, clayey loam, clayey soil, and loam, covered an area of 185.23, 112.46, 226.54, and 120.77 km^2, respectively.

The LULC change analysis was carried out for the year 2020 using Landsat TM and OLI satellite imagery, respectively. The LULC features of TiruppurTaluk were classified as crop land, fallow land, land with shrub, land without shrub, mining, plantation, river/canal, rural and tank and urban. Figure 10 shows the LULC recent map of the study area. Most of the crop lands were occupied in the places of Avanashipalayam, Kattur, Vavipalaiyam and Chokannur. Mining activities were mainly noticed in Veerapandi and Mudalipalaiyam. The major urban area was identified mainly in Tiruppur corporation area. The crop land and fallow land were decreased noticeably in the recent time and urban land area is increased drastically for the year 2020 [23].

In the present study, each theme was allocated a specific weightage on the basis of their significance of potentiality to identify groundwater recharge potential zonation. For example, lineament density, drainage density and geomorphology play a prominent role in groundwater recharge

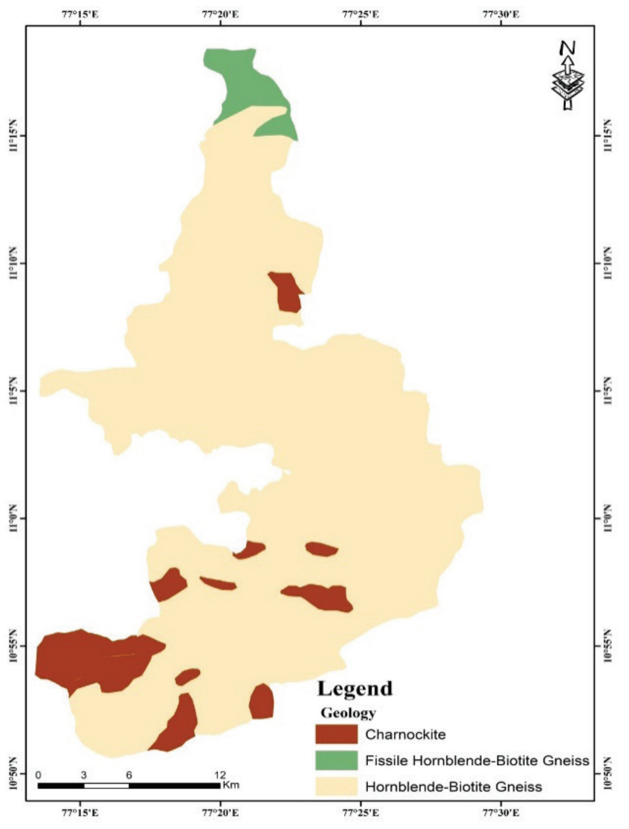

Figure 7. Lithology map.

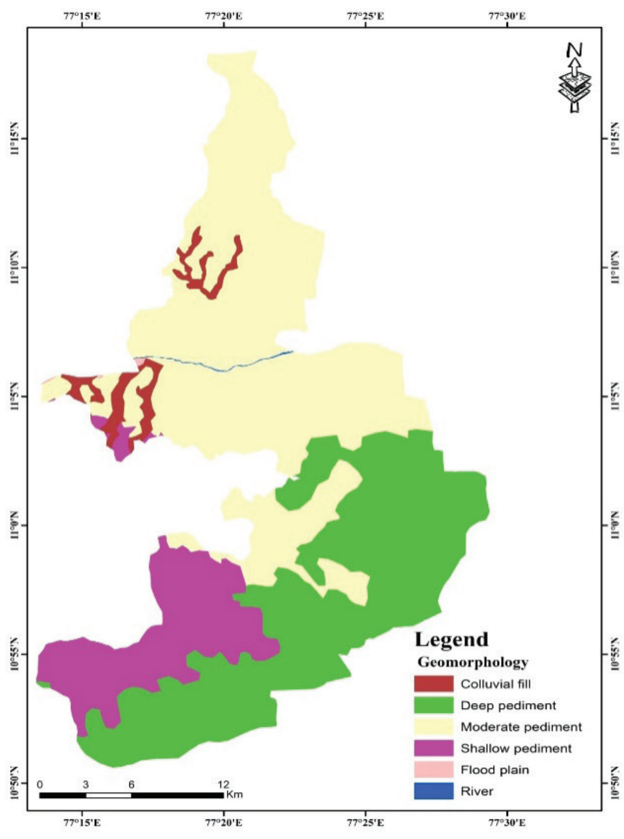

Figure 8. Geomorphology map.

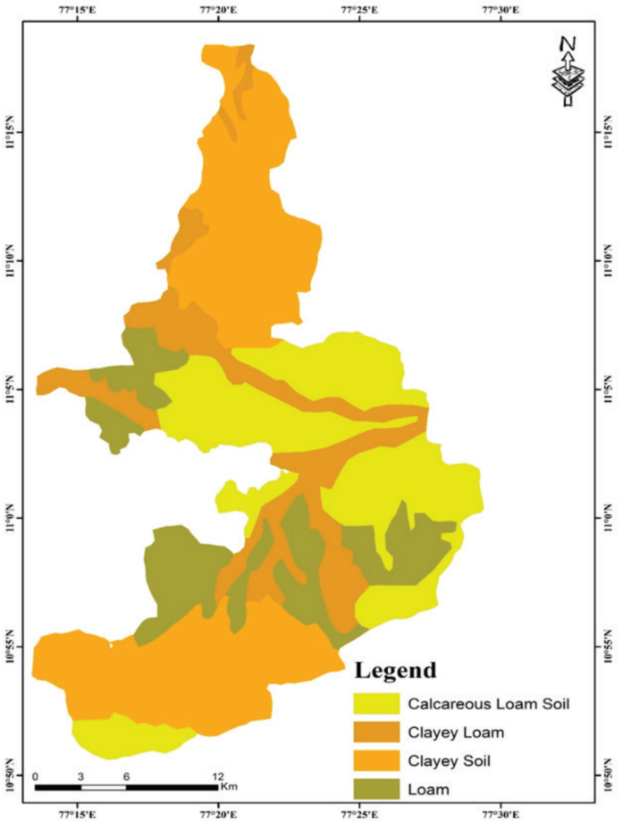

Figure 9. Soil map.

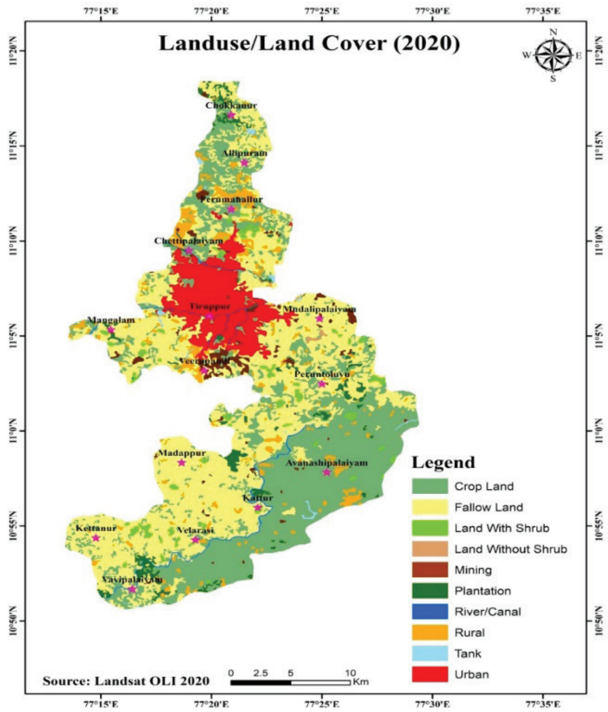

Figure 10. Land use/ land cover map.

potential, so it has been given with the maximum weightage and it was explained in Table 2. The weightages of GWPZ parameters namely Lineament Density, Drainage Density, Geomorphology, Slope, Lithology, Soil, Rainfall and LULC was 32, 15, 12, 10, 9, 8, 6.6 and 6.4 % respectively.

The different components in each theme were also given knowledge-based that should be grading from 1 to 5, with 1 as least favourable and 5 as most favourable. The weightage of each theme and the ranks for different units in each theme were given in the criteria of groundwater recharge, adopted from [24]. The Table 3 shows the rank and weightage of each variable.

The ranks of geomorphology variables factors were 4, 4, 3, 2, 5 and 5 for colluvial fill, deep pediment, moderate pediment, shallow pediment, flood plain and river. The lineament density parameter was classified as very high, high, medium, low and very low and the ranks were assigned based on Groundwater Recharge potential zonation as 5, 4, 3, 2 and 1 respectively. The major lithological classification in the study location was charnockite, fissile hornblende biotite gneiss and hornblende biotite gneiss and their groundwater recharge potential zonation ranks were 2, 5 and 4 respectively.

Table 2. Weights of eight themes used for groundwater recharge potential zoning

Aspects	LD	DD	Geomorphology	Slope	Lithology	Soil	Rainfall	LU/LC	Weight
Lineament Density	8.0	7.0	6.0	5.0	4.0	3.0	2.0	1.0	0.32
Drainage Density	8.0/2.0	7.0/2.0	6.0/2.0	5.0/2.0	4.0/2.0	3.0/2.0	2.0/2.0	1.0/2.0	0.15
Geomorphology	8.0/3.0	7.0/3.0	6.0/3.0	5.0/3.0	4.0/3.0	3.0/3.0	2.0/3.0	1.0/3.0	0.12
Slope	8.0/4.0	7.0/4.0	6.0/4.0	5.0/4.0	4.0/4.0	3.0/4.0	2.0/4.0	1.0/4.0	0.10
Lithology	8.0/5.0	7.0/5.0	6.0/5.0	5.0/5.0	4.0/5.0	3.0/5.0	2.0/5.0	1.0/5.0	0.09
Soil	8.0/6.0	7.0/6.0	6.0/6.0	5.0/6.0	4.0/6.0	3.0/6.0	2.0/6.0	1.0/6.0	0.08
Rainfall	8.0/7.0	7.0/7.0	6.0/7.0	5.0/7.0	4.0/7.0	3.0/7.0	2.0/7.0	1.0/7.0	0.066
LU/LC	8.0/8.0	7.0/8.0	6.0/8.0	5.0/8.0	4.0/8.0	3.0/8.0	2.0/8.0	1.0/8.0	0.064
TotalCR = 0.06; CI = 0.08; λ max = 8.56; RI = 1.41									**1**

Table 3. The allotted and normalized weights for the distinct features within the melodies used for groundwater recharge potential zoning

Factors	Weight	Rank	Over All Weightage
Lineament Density			
Very High		5	160
High		4	128
Medium	32	3	96
Low		2	64
Very Low		1	32
Drainage Density			
Very High		1	15
High		2	30
Medium	15	3	45
Low		4	60
Very Low		5	75
Geomorphology			
Colluvial fill		4	48
Deep Pediment		4	48
Moderate Pediment	12	3	36
Shallow Pediment		2	24
Flood Plain		5	60
River		5	60
Slope in Degree			
0 – 2.4		5	50
2.4 – 4		4	40
4 – 6.5	10	3	30
6.5 – 10.5		2	20
10.5 – 14.8		1	10
Lithology			
Charnockite		2	18
Fissile-Hornblende biotite gneiss	9	5	45
Hornblende biotite gneiss		4	36
Soil			
Calcareous loam soil		4	32
Clayey loam	8	3	24
Clayey soil		2	16
Loam		5	40
Rainfall in mm/year			
450-566		1	6.6
566-591		2	13.2
591-605	6.6	3	19.8
605-640		4	26.4
640-697		5	33
LU/LC			
Crop Land		4	25.6
Fallow Land		3	19.2
Plantation		3	19.2
Urban		1	6.4
Rural		1	6.4
Mining	6.4	1	6.4
Land With Shrub		2	12.8
Land Without Shrub		2	12.8
River		5	32
Tanks		5	32

The slope was classified with the interval of 0-2.4°, 2.4-4°, 4-6.5°, 6.5-10.5° and 10.5-14.8° and their respective ranks were assigned as 5, 4, 3, 2 and 1 based on groundwater recharge potential zonation. The ranks for the rainfall parameters namely 450-566, 566-591, 591-605, 605-640 and 640-697 mm/year were assigned as 1, 2, 3, 4 and 5. Soil parameter has factors namely calcareous loam soil, clayey loam, clayey soil and loam. The ranks of the respective parameters were 4, 3, 2 and 5. The LULC classes have ranks of 4 for crop land, 3 for fallow land, 3 for plantation, 1 for urban, 1 for rural, 1 for mining, 2 for land with shrub, 2 for land without shrub, 5 for river and 5 for tanks. The final parameter drainage density has 5 different modules like very high, high, medium, low and very low and their ranks of groundwater artificial recharge potential zone was 1, 2, 3, 4 and 5 respectively. The rank and weightages of all parameters have been multiplied and attributed in the attribute table of respective shape file. Tiruppur Taluk was divided into five different favourable zones, including very high, high, medium, low, and very low, as shown in Figure11, by integrating all thematic layers using a GIS-based prototypical to derive the Groundwater Recharge Potential Zonation map.

The Groundwater Recharge Potential zone occupied an area of 159.4 km2 for very low favourable, 124.23 km2 for low favourable, 64.25 km2 for medium favourable, 82.11 km2 for high favourable and 215.14 km2 for very high favourable. The areal coverage of the GWPZ map was shown in Table 4. The villages such as Mudalipalayam, Kettanur and Madappur areas were identified with very low favourable of groundwater recharge zonation due to low lineament density, high slope condition, impermeable soil and land use/ land cover type. Similarly, Tiruppur, Perumanallur, Mangalam, Veerapandi and Chettipalaiyam areas were identified with very high favourable groundwater recharge potential zonation because of the high lineament density, low slope area, porosity and permeability high soil and land use / land cover area.

Model Validation Using ROC Curve

Figure 13 shows the ROC curve showing model validation for GWPZ using the AHP method. To assess the reliability of the GWPZmap, the Receiver Operating Characteristic (ROC) curve analysis was employed. The ROC curve was plotted from the comparison of the predicted recharge zones and the borewell yield data obtained from the field. The Area Under the Curve (AUC) was calculated to quantify the model's performance with an excellent value of 0.88 obtained. This validation shows that the AHP model is robust in delineating effective recharge areas. Table 5 shows the Summary of ROC Curve Validation for Groundwater Recharge Potential Zoning Model Based on AHP Method.

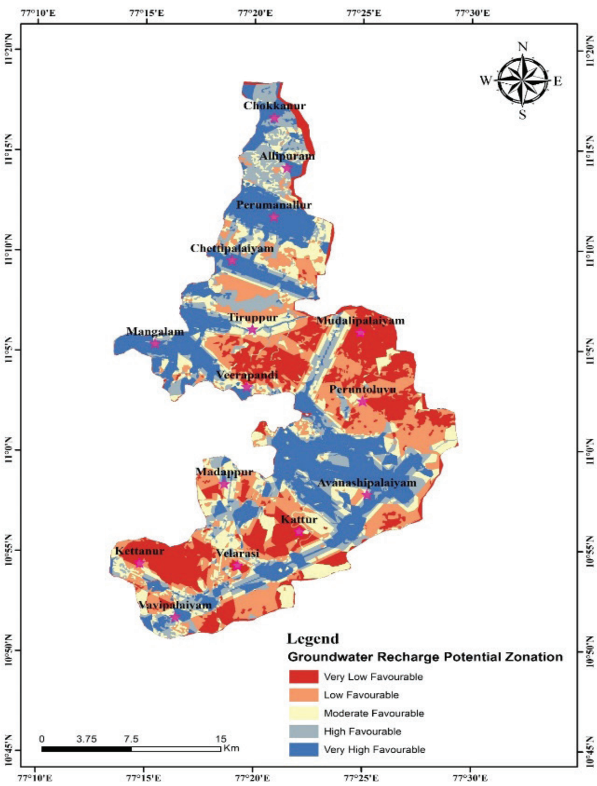

Figure 11. Groundwater recharge potential zonation.

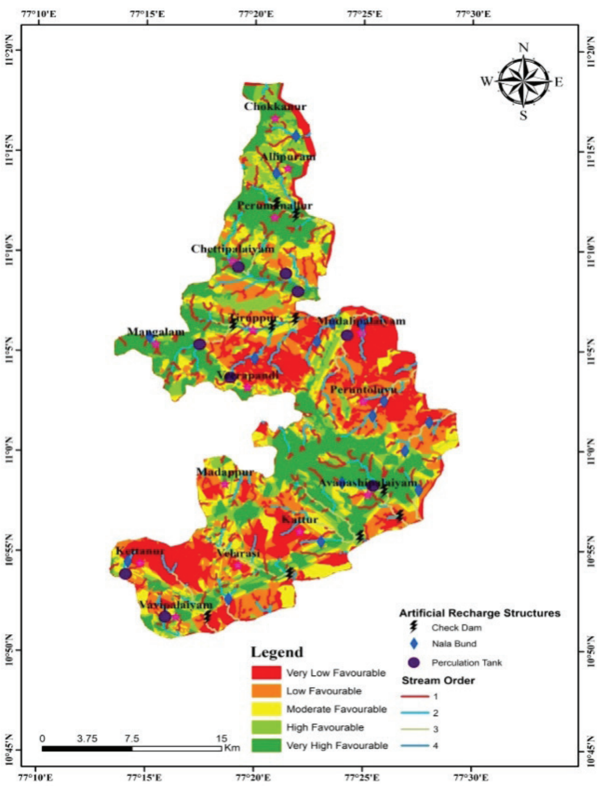

Figure 12. Artificial rechargestructures map.

Table 4. The areal coverage information for the GWPZ

S.No.	GWPZ	Area (km2)	Percentage (%)
1	Very Low Favourable	159.4	24.70
2	Low Favourable	124.23	19.26
3	Medium Favourable	64.25	9.96
4	High Favourable	82.11	12.73
5	Very High Favourable	215.14	33.35

Table 5. Summary of ROC Curve Validation for Groundwater Recharge Potential Zoning Model Based on AHP Method

Validation Method	Dataset Used	AUC Value	Accuracy Interpretation
ROC Curve	Bore well yield data (n = 42 wells; classified as high/low based on yield threshold)	0.88	Excellent (Highly Reliable)

The Drainage network map [25] was overlaid with the GWPZ map to study the terrain condition to locate appropriate places for setting up artificial recharge structures. Figure 12 shows the recommended groundwater recharge structures such as percolation tanks, check dams and nala bunds to improve the overall groundwater resources. Specifically check dams were built on slopes less than 50% and at least 2 feet of bedrock. These check dams were done only in the very high favourable recharge potential zones [26]. In low annual rain (less than 600 mm) zones, agricultural fields with permeable soils and a land slope of less than 6%, preferably within high favourable (recharge) zones and as per CGWB (2015) guidelines, nala bunds were recommended. In addition, the terrain in which percolation tanks are usually installed has very fractured and weathered rock, which allows for a fast recharge rate. The tanks are particularly appropriate in moderate recharge potential areas [27]. Percolation ponds were indicated in villages such as Avanashipalaiyam, Chettipalaiyam, Vavipalaiyam and Veerapandi based on the lithology of regions with almost 7 to 15 m thickness of weathered hornblende biotite gneiss and a mix of moderate slope, land without shrubs and fallow land. Construction of a percolation pond was recommended along downstream of the check dam, on the river or stream bank, rather than in the riverbed [28].

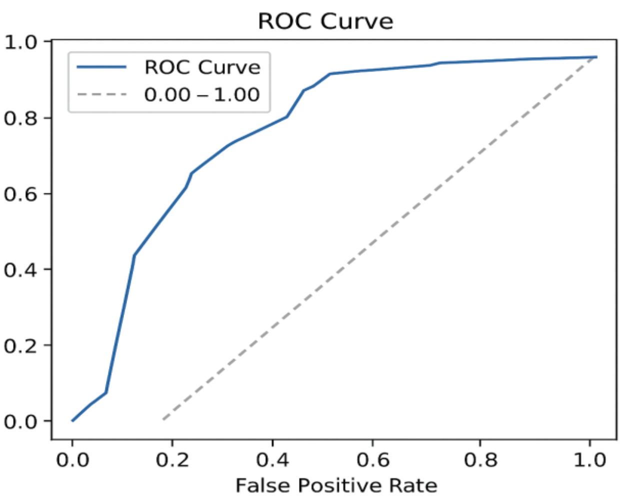

Figure 13. Groundwater recharge potential zoning justification model with a ROC curve.

The results of this study have been validated and supported by comparing it with other studies in the literature. For example, spatial water balance analysis results indicate the presence of groundwater recharge zones that are consistent with the findings regarding the significance of spatial trends, when considering groundwater quality assessment. Likewise, the suggestion of reproduction recharge techniques like percolation tank and check dams is found to be similar to that discussed, which shows that the engineered interventions are effective in enhancing groundwater quality [29]. The comparisons add to the trustworthiness of the current results and provide a comparison with previous studies; they also show the unique value of the current study in regards to recharge planning in an industrialized urban setting.

Studies [30] focused on water contamination and treatment in the groundwater, that utilized the geo statistical tools to study the groundwater quality trends. This study takes a different approach from the above-mentioned studies, combining spatial analysis with the practical implementation of recharge structures for improving groundwater quality and quantity. Comparisons validate results and show how this study builds on and extends current work, which has been conducted in a limited number of rural sites and yielded general strategies for groundwater management. This comparative discussion reinforces the novelty and broader applicability of the research outcomes.

The research recommends the construction of check dams in locations such as Perumanallur, Avanashipalaiyam, Tiruppur, Velarasi and Vavipalaiyam based on the geography, local rock type and stream characteristics. The choice for this recharge structure was small and straight streams and the building of a check dam would limit surface runoff and increase groundwater potential through rain water recharge. Nala bunding constructions were recommended in locations like Allipuram (South), Kettanur, Mangalam and Peruntolvu, according to the research. The weathered hornblende biotite gneiss and charnockite reached 45 meters below the surface of the earth. For the building of Nala bunds, locations with a mix of gradually slope, pediment and land use such as cropland and fallow land were appropriate. The integration of Remote Sensing, GIS and AHP techniques offered a solid base for identification of GWPZ but there were some limitations in the study. Firstly, the thematic layers utilized in the analysis were taken from secondary data like satellite imagery, geological maps, and rainfall records, and could contain discrepancies in scale and time. Secondly, the effective method of AHP is subjective, weights may be given differently according to the subjectivity of the AHP members, which can change the result of the AHP even with consistency checks. Thirdly, because of access difficulties in some terrain types, access to the field for extensive ground-truthing was limited. Further, the study does not consider transient conditions like seasonal recharge, subsurface water flow, or other changes in land use over time. The results are useful for preliminary planning, but should be supplemented by field-based hydrogeological investigations to better inform site-specific interventions.

In order to better capture temporal variability in recharge under various climatic and extraction situations, future research should build on this work by combining dynamic groundwater simulation models with the GIS–AHP framework. If socioeconomic indicators such as population growth, industry growth, and land use change were integrated with the understanding of groundwater stress and management priorities would be enhanced. Furthermore, machine learning-based weighting methods can improve the accuracy of the forecasts and reduce the subjectivity involved in factor weighting. The application, scalability, and resilience of groundwater management techniques would be improved by such interdisciplinary integration, especially in areas that are industrializing and urbanizing quickly.

It is important to take into account the study's limitations. Mapping recharge may be subject to data gaps of aquifer heterogeneity, soil infiltration, and rainfall distribution. Temporal variability was not adequately dealt with since only static data were used rather than multi-seasonal observations. The AHP approach is still subjective in regard to parameter weighting, but it is methodical. The results are also limited in their validity because the field experimental work (e.g., pumping tests) to achieve a hydrogeological understanding has not been performed in a well conducted manner. Furthermore, implementing localised artificial recharge recommendations at a larger scale for long-term management to ensure climate resilience is still difficult in developed areas. Multi-temporal data, dynamic hydrological models, field studies, and climate projections should be used in future research to further develop more accurate, resilient, and applicable groundwater management solutions [31].

In order to better capture temporal variability in recharge under various climatic and extraction situations, future research should build on this work by combining dynamic groundwater simulation models with the GIS–AHP framework. Understanding groundwater stress and management priorities more comprehensively would be possible by incorporating socioeconomic factors like population growth, industrial expansion, and land-use change. Moreover, ML-based weighting technique may improve the accuracy of the forecast and the subjectivity of the components' assignment. Such integration of different disciplines would increase the application and resilience of groundwater management techniques, particularly in fast industrializing and urbanizing regions [32].

Regular monitoring is necessary through periodic quality testing, community managed observation wells and automated water-level loggers. Adaptive management can be implemented by using feedback loops between field data and the GIS-based models that can help local governments optimize recharge interventions for policy goals and sustain the groundwater resource [33].

Future Scope and Limitations

The present study has some constraints in terms of interpretation that should be noted: Firstly, the AHP-based weighting process includes consistency checks, but still has a certain degree of subjectivity in the relative importance of the parameters. First of all, the AHP-based weighting process contains consistency checks; however, there is a sense of subjectivity in the relative importance of the parameters. Second, this analysis is largely secondary data-based; although quality assurance was applied to the secondary data used in this analysis, this data may not reflect the temporal changes of groundwater dynamics completely. Third, the existing approach considers static geospatial conditions that affect recharge potential and does not account for seasonal or inter-annual changes. These limitations can be overcome in future studies by incorporating the AHP–GIS framework with dynamic hydrological or groundwater flow models, which can then be used to simulate the recharge behaviour under changing climatic and extraction scenarios. Field based monitoring, such as hydro chemical and isotopic studies, would also help in understanding the recharge – ground water quality relationship, especially in industrial areas. Furthermore, using machine learning techniques may minimize the subjectivity in the subject weighting and enhance the prediction accuracy of recharge potential mapping. These will help build a holistic, adaptive strategy for sustainable groundwater resources management that helps meet long-term water security objectives.

CONCLUSION

- Based on the result of GIS–AHP analysis of the Tiruppur region, the region was divided into 5 recharge potential zones (very low, low, moderate, high, and very high). Some of the villages like Tiruppur, Perumanallur, Mangalam, Veerapandi, and Chettipalayam had high recharge potential but Mudalipalayam, Kettanur, and Madappur had low recharge potentials because of adverse lithological and slope conditions.
- The study also presents an innovative GIS–AHP integration combined with site-specific suggestions for the construction of artificial recharge structures in an industrialized urban environment. This will help with the data-driven planning of groundwater and improve the management of both water quantity and quality.
- Recommendations for Artificial Recharge Structures: Check dams are recommended in situ in Perumanallur, Avanashipalaiyam and Vavipalaiyam and percolation ponds in Avanashipalaiyam, Chettipalaiyam and Veerapandi and nala bunds at Allipuram (South), Kettanur and Mangalam to enhance infiltration and minimize runoff losses.
- The recharge potential map is a decision support tool for policy and future directions, for water resource managers and water developers, to prioritize where to take intervention and to optimize water resource allocation. To support sustainable groundwater management under industrial and climatic pressures, future studies need to combine field-based hydro chemical monitoring, dynamic hydrological modeling, and socioeconomic considerations.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

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

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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