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Groundwater potential studies using remote sensing and geographic information system – a research focus

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ABSTRACT

Digital elevation model based extraction of micro watershed helps to demarcate suitable site for groundwater modeling studies using remote sensing and GIS. The present study was explored in over-exploited zones of which out of 15 blocks in Tirunelveli District are under over-exploitation as per Dynamic GW-Resources-2011 while 2009 there was only 4 over-exploited blocks and in 1998 there was no any over exploitation. So, this has to be given more priority for recharge measures as soon as to control this depletion rate. As part of this, the first step is to identify suitable site for artificial recharge. In this paper, the study is undergone for Nambiyar Watershed, hard rock terrain in Tirunelveli District which covers an area of 758.87 km^2. Existence of the scale of groundwater in the study area is determined by four classes ranging from high, moderate, low and poor predicting groundwater potential zones. To derive potential recharge, Landsat 8 satellite data for each month is utilized to estimate evapotranspiration (ET) from the normalized difference vegetation index (NDVI) in the ArcGIS environment. The potential zone map is extracted based on the geomorphology, soil, slope, potential recharge, geology, landuse/landcover, drainage density, aquifer depth, groundwater fluctuation parameters. The weights are assigned to each parameter according to the priority importance to groundwater potential using analytic hierarchy process method. This research identifies site suitable for groundwater recharge and these results are validated and used for groundwater modelling studies.

Keywords: Groundwater; Remote sensing; GIS; Potential map

1. Introduction

Groundwater is the hidden treasure of the earth being the most valuable resource. Predicting the potential zones of the resource is an exigent task done with the emerging of remote sensing and GIS technology. Groundwater is the most precious resource of mankind for the survival and economical growth which varies spatially with respect to time. Groundwater is the main source of both drinking water as well as agriculture in India and it is under threat with depletion. It is estimated that 70%–80% of the total production from irrigated areas in India may ultimately depend on groundwater utilization [1]. Being a significant integrated part of the hydrological cycle, its availability depends only on the rainfall and recharge conditions and it is our responsibility in maximizing the utility of Potential recharge completely. The study area is an over-exploited zone as the groundwater utility exceeds recharge from the only source (precipitation and surface water contribution). Analysis of water table fluctuation for a certain period predicts changes in groundwater recharge. Groundwater, on the other hand, is a replenishable resource widely distributed under the ground. It is free from

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pollution and can be utilized with small principal cost in the least feasible time [2]. The current state of water resources and watershed modeling has been highly developed by the use of GIS and associated technologies [3]. An overview of artificial recharge is given by Bouwer [4]. In addition, the recognition of suitable sites for flood spreading as an artificial groundwater recharge technique has been practiced in recent years [5]. Attention in quantifying recharge rate has improved because of concerns that land-use changes may reduce recharge and that groundwater resources in some areas may not be sustainable during drought periods [6]. Effective management of aquifer recharge is fetching core aspect of water resource management strategies [7]. Many researches have been carried out on site suitable for identification of artificial recharge [8–16] and many studies on groundwater potential zones [17–19].

The drainage map reflects the source of groundwater. The zones of high drainage density will have poor groundwater prospects, and gradually, the zones of lower and lower drainage density zones will have better groundwater prospects [20]. Higher degree of slope results in rapid runoff and increased erosion rate with feeble recharge potential [21]. An area of high density also increases surface runoff compared with a low drainage density area. Depth of groundwater levels was calculated during various monsoon seasons, and the spatial variation of depth of average annual groundwater levels were plotted using GIS [22]. Remote sensing techniques play a great role in unearthing potential groundwater, even in the semi-arid hard rock areas of Bankura District [23]. Qualitative analysis is carried out using map overlying techniques to distinguish the groundwater potential zones [22]. The over exploitation of groundwater is due to increasing population, urbanization, industrialization. The gradual depletion of groundwater table, due to inadequate recharge, defines a threatening water crisis in the national capital of India, Delhi [22]. In this paper, the groundwater levels based on the study of all nine parameters are used for predicting the site suitable for groundwater potential zones. Thus the study reveals that remote sensing and GIS techniques are useful for groundwater prospecting and recharge sites.

2. Watershed management

The main criteria of watershed management are to control the runoff and degradation of water level and thereby to manage conservation of soil and water to an extent and to utilize the runoff water in an effective way. To protect, conserve and improve the land of watershed for more efficient and sustainable production of resources and to enhance the water resource, effective watershed management is indispensable.

3. Data and software used

For the implementation of this work, the following data were used:

1. Toposheet map for study area 58H
2. Landsat 7 satellite image
3. Digital elevation model (DEM) data from SRTM, spatial resolution 30 m
4. Groundwater level measurement data, bore hole lithology and water quality data from State Ground and Surface Water Resources Data Centre, Tamil Nadu
5. GIS Software: ArcGIS 10.1

The focus of each watershed development is to promote the economic development of that community which depends on the natural resources of watershed by optimum utilization. The focus is to induce proper management of watershed's natural resources such as land, water, vegetation which will balance the conditions prevailing to prevent droughts and prevent further water level degradation.

4. Study area and methodology

The study area represents hard rock terrain situated in a part of Tirunelveli District in Tamil Nadu state, India, bounded by longitudes 77°30′ E and 78° E and latitudes 8°30′ N and 8°10′ N. The major river draining is Nambiyar, the entire Nambiyar Watershed is studied. The study area showing the Nambiyar watershed is shown as Index Map in Fig. 1.

The analytic hierarchy process (AHP) captures the idea of uncertainty in judgements through the principal Eigen value and the consistency index [24]. The AHP is a theory of measurement through pairwise comparisons and relies on the judgements of experts to derive priority scales shown in Table 1 representing the Saaty's scale.

The Saaty's scale is determined by a score of 1 representing equal importance between two parameters, and a score of 9 indicating the extreme significance of one parameter compared with the other one [25].

$$\mathrm{CI} = \frac{(\lambda \max - n)}{n-1} \tag{1}$$

where λ_{max} is the largest Eigen value of the pairwise comparison matrix and n is the number of classes or features. Since inception, AHP has been used in numerous applications in natural resources, environmental planning and management [26–28]. The methodology flowchart is described in Fig. 2. Mapping and prediction of potential zone is done using ESRI ArcGIS Software which is widely used in analysis of point data, polygons, images as raster and vector data.

5. Results

The resulting values were reclassified into four classes with groundwater potentiality from high to low of equal intervals. The high potentiality for groundwater in the Gneiss bed rock is attributed by the high amounts of rainfall and potential recharge. To identify new water supply sources, the groundwater potentiality map is a useful tool. Satellite data supply rapid and functional baseline in sequence information about various parameters that directly or indirectly manage the incidence and movement of groundwater such as geomorphology, soil types, drainage patterns, land slope, land use/land cover (LULC), and lineaments of thematic maps [29–32]. The geomorphology, soil, slope, potential recharge, geology, LULC, drainage density, aquifer depth, groundwater fluctuation are the nine parameters used in

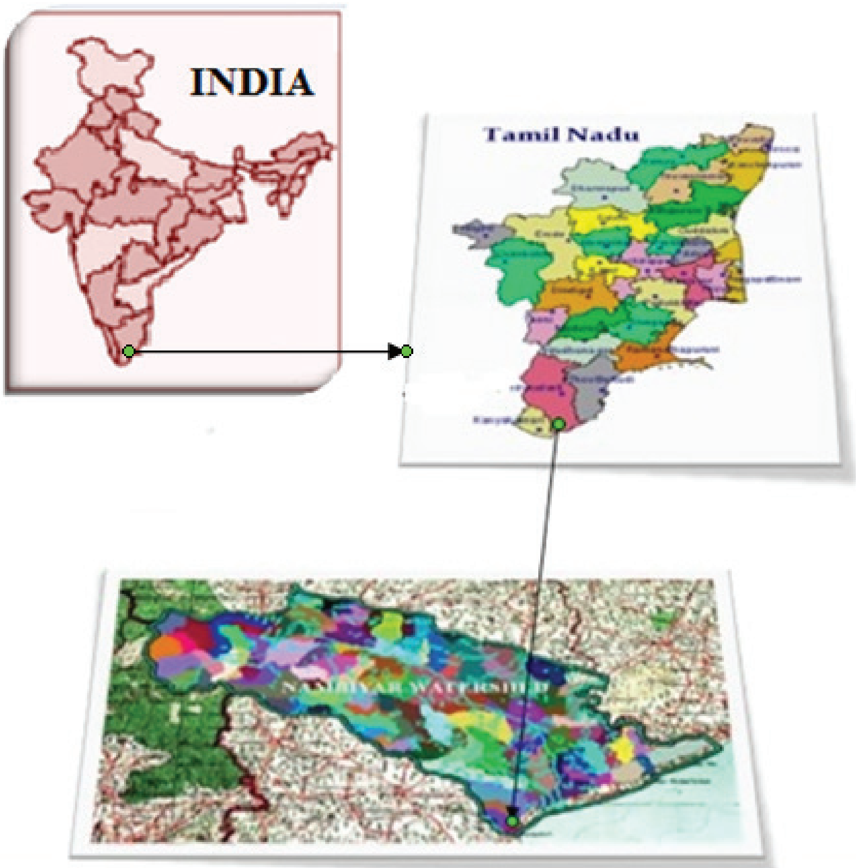

Fig. 1. Study area location with micro watershed of Nambiyar Watershed.

Table 1
Saaty's 1–9 scale of relative importance

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

this study, categorized based on the priority. The weightage assigned and the details are shown in Table 2.

The following thematic maps were prepared from SOI Toposheet map, GSI and Landsat 2014 satellite images and reclassified into different classes in ArcGIS as shown in Tables 2 and 3.

5.1. Geomorphology

The major geomorphic units identified in the study area consist of shallow pediments and few moderate pediments, coastal plane and slopy, hills and valleys. Geomorphology factor was assigned a weight of 25.4% (0.254) in the analysis.

5.2. Soil

The soil represents the top surface of the ground. Most of the soil surface is reddish brown in color and few soils are dull brown in color. These are the following hydrological soil category present in the study area. Soil factor was assigned a weight of 22.5% (0.225) in the analysis. The soil description based on soil group is shown in Table 4.

5.3. Geology

The Nambiyar basin is found with rocks of granite gneiss and biotite gneiss rocks underlain by igneous and metamorphic rocks of Archaean age. It is characterized by gentle slope with brown soil at top. Minor fracture was found above weathered zone. Geology factor was assigned a weightage of 9% (0.09) in the calculation.

5.4. Rainfall

This factor is one of the most important and main source in calculating potential recharge and the final groundwater potentiality value. When the rainfall intensity is more, the potential recharge will also be more improving the

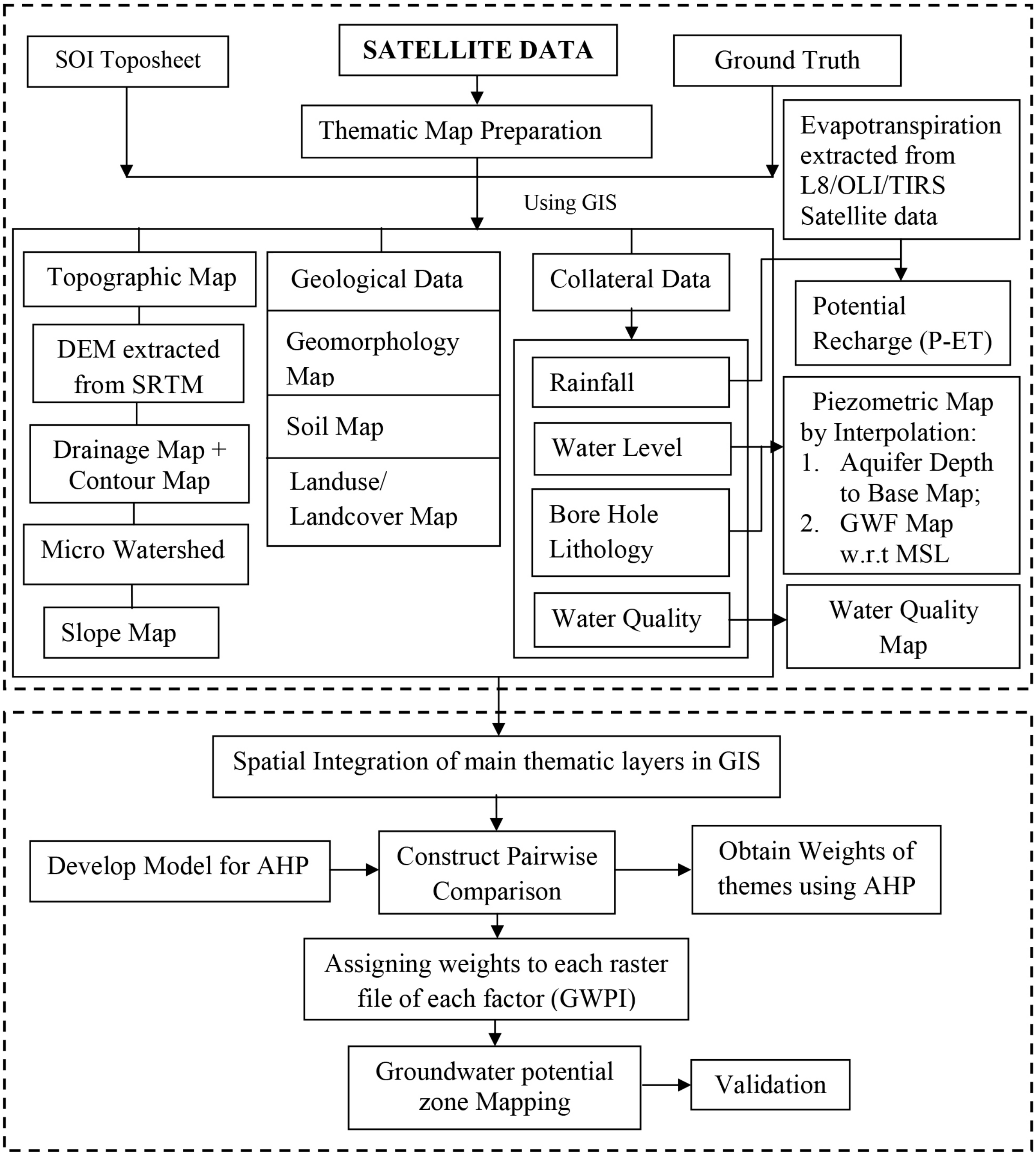

Fig. 2. Flowchart for groundwater potential mapping.

groundwater potentiality. During the present study, daily rainfall data were collected from 18 stations in and around the study area and processed.

5.5. Evapotranspiration

The evapotranspiration is derived from the L8/OLI/TIRS satellite of monthly data of 2014, Lmax and Lmin values, the NDVI is generated. From the NDVI, the ET is extracted for the study area. The spectral radiance for thermal radiation is computed from the digital number of each individual 30 m pixel. Spectral radiance is the outgoing radiation energy of the band as observed at the top of the atmosphere by the satellite data:

For January scene,
These following two values represent
LANDSAT_SCENE_ID = "LC81430542014019LGN00"
FILE_DATE = 2014-02-10T01:20:47, LMAX and LMIN for January 19th, 2014 for path 143, row 54 for band 11:
RADIANCE_MAXIMUM_BAND_11 = 22.00180
RADIANCE_MINIMUM_BAND_ 11 = 0.10033
that is, LMAX = 22.0018 $W/m^2/sr/\mu m$ and LMIN = 0.10033 $W/m^2/sr/\mu m$.

Table 2
Criterion table for identifying groundwater recharge potential zones for thematic layers

Parameters	Rank 1	Rank 2	Rank 3	Rank 4	Weightage
	4x weightage	3x weightage	2x weightage	1x weightage	
Geomorphology	Coastal plain, flood plain, buried pediment, bazada	Shallow pediment	Pediment	Slopy, Hills	25.4%
Soil	A	B	C	D	22.5%
Geology	Fluvium, garnet sillimanite graphite gneiss (oldest), garnet biotite gneiss (youngest)	Charnockite	–	–	9%
Land use/land cover	Wet crop/plantation	Dry crop/fallow	Scrub/barren	Rock outcrops, forest	5.7%

Table 3
Ranks and weights for factors used for groundwater potentiality mapping

Parameters	Class	Range	Weightage
Slope	High	0–3	17.9%
	Mod	3–5	
	Low	5–10	
	Poor	10–80.2724	
Potential recharge	High	1–1.7	13.1%
	Mod	0.5–1	
	Low	0.1–0.5	
	Poor	–0.94 to 0.1	
Drainage density	High	0–1	3.4%
	Mod	1–2	
	Low	2–3	
	Poor	3–7.03	
Depth to basement	High	16– 18.7	1.9%
	Mod	14–16	
	Low	12–14	
	Poor	7.2–12	
Groundwater fluctuations	High	15–16.8	1.0%
	Mod	10–15	
	Low	5–10	
	Poor	0.0034–5	

5.6. Potential recharge

Potential recharge indicates the amount of water that can be utilized for potential recharge, adding to groundwater storage. Potential recharge represents important criteria on groundwater potentiality mapping and evaluation. The recharge areas depend on the amount of rainfall, the infiltration capacity of the soil, vegetation, etc. The total rainfall is the only income of water from atmosphere and is lost mainly by evapotranspiration, thus reduction gives the total potential of water from the surface to ground level, minimizing the runoff to an extent. When the potential recharge is maximum utilized infiltering into the water table, the groundwater is increased. Potential recharge factor was assigned a weight of 13.1% (0.131) in this analysis and can be estimated from the total rainfall minus total evapotranspiration.

Table 4
Hydrogeological soil group classification of the study area

Hydrogeological soil group	Soil description
A	Very deep, excessively drained, sandy soils on gently sloping lands; very deep well-drained soils
B	Deep, well drained; deep gravelly sandy loamy soil; moderately shallow well drained
C	Clay, clayed well drained; moderately well drained clayey soils; moderately shallow gravelly clay soils
D	Marsh as well rock outcrops

Potential recharge = [Total precipitation – Total evapotranspiration]

The weightage is given for the parameter, potential recharge, which is derived from rainfall and evapotranspiration.

5.7. Lithology

The lithology is related with the water permeability and the capability of the formations to mass groundwater. The soil type and the porosity influence the capacity and storage of groundwater among the various rock types. Aquifer depth in the lithology is given priority to be given weightage to obtain groundwater potential index (GWPI).

5.8. Slope

Slope is an important factor for the identification of groundwater potential zones. Slope maps were obtained from the Landsat satellite image and DEM. The values were reclassified into classes according Demek's classification. In general, slopes rule the ability of surface water to remain on the surface long enough to infiltrate or will continue to flow as runoff. Usually, the steep slopes indicate greater water velocity. Therefore, it is observed that in the areas of steeper relief, the runoff is increased. This in turn minimizes the degree of groundwater recharge [33]. In the study area, gently sloped area is predominant. The top of Nambiyar Watershed is a hilly forest region having slope aspect which influences the whole and in which there is a dam near Kalakkad. The slope factor was assigned a weight of 17.9% (0.179) in the calculation of the groundwater potentiality final map, according to AHP methodology.

5.9. Land use/land cover

The LULC is extracted from Landsat satellite image of LT51430542005106BKT00, Path 143 and Row 54. The major area of the watershed is under agricultural cropland. The LULC factor was assigned a weight of 5.7% (0.057) in the calculation.

5.10. Drainage density

Drainage pattern is one of the most important information of hydrogeological features. While the drainage network is thick denser, the flow will be in excess so that the recharge rate will be lesser; automated DEM processing [34]. The total length of all the streams and rivers, divided by the total area of the drainage watershed, determines drainage density. The raster drainage network density file was assigned a weight of 3.4% (0.034) in the calculation of the groundwater potentiality final map, according to AHP methodology.

5.11. Depth to basement

The depth to basement of the study area is the total depth of observation wells present in the study area which is interpolated and taken as a factor for the study. The depth to basement factor was assigned a weight of 1.9% (0.019) in the analysis.

5.12. Groundwater fluctuation

The difference between maximum water level and minimum water level with respect to mean sea level gives the groundwater fluctuation. The groundwater fluctuation factor was assigned a weight of 1.0% (0.01) in the analysis.

Analysis of water table fluctuations is a useful tool for determining the magnitude of both short- and long-term changes in groundwater recharge and has been widely applied under varying climatic conditions [6].

5.13. Lineament density

Linear features on the surface of the study area are recognized by satellite data. It gives the linear geomorphic features such as fault/fractures present. In the study area, there are micro traces of lineament so it is omitted in the analysis.

5.14. Water quality

The total dissolved solids (TDS) value has been used for the assessment of groundwater potentiality [15]. TDS represents the total amount of dissolved minerals present in the groundwater and is considered as a major factor to assess groundwater quality aspect. In the study, the water quality maps are prepared in ArcGIS, where the TDS value ranges from 265 to 1,586 mg/L in the Nambiyar Watershed. In the present study, this factor is omitted, as the groundwater quality is good and does not cause much impact, also immaterial factor for the assessment of groundwater potentiality.

5.15. Weighted index overlay method

The groundwater potential index (GWPI) is computed by the weighted linear combination method [35] is given by

$$\text{GWPI} = \sum_{(n=1)}^{9} (Wfn.Rfn) \tag{2}$$

= (0.254 x Geomorphology + 0.225 x Soil + 0.179 x Slope + 0.131 x Potential Recharge + 0.09 x Geology + 0.057 x LULC + 0.034 x Drainage Density + 0.019 x Aquifer Depth + 0.01 x Ground Water Fluctuation)

The weightage is calculated using AHP method based on the priority scales, and for each parameter the weightage is assigned to obtain GWPI.

6. GIS outcome

The final groundwater potential map is prepared and shown in Fig. 3. This particular method using remote sensing and GIS is applied to assess groundwater potential zones in the Nambiyar watershed. Over this, nine parameters with different weights (geomorphology, soil, slope, potential recharge, geology, LULC, drainage density, aquifer depth, and groundwater fluctuation) were analyzed and used. Evapotranspiration is extracted from satellite data, from that potential recharge is evaluated. Using these, final maps are categorized into four classes, namely, high, moderate, low and poor.

Based on the groundwater depth and discharge data from the pumping wells, the fitness correlation is drawn and RMS value is 0.9779 which matches to the potential zones and gives validation to the results shown in Fig. 4.

The groundwater potential zone map validated showed good correlation using the discharge and groundwater depth data [36]. The results show that there is good conformity between the predicted groundwater potential map and the existing groundwater borehole databases [37].

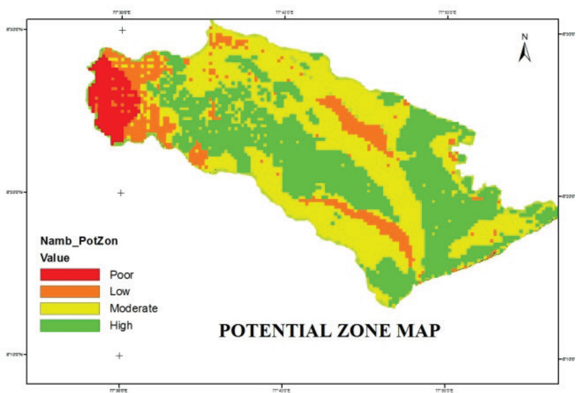

Fig. 3. Potential zone map for the study area.

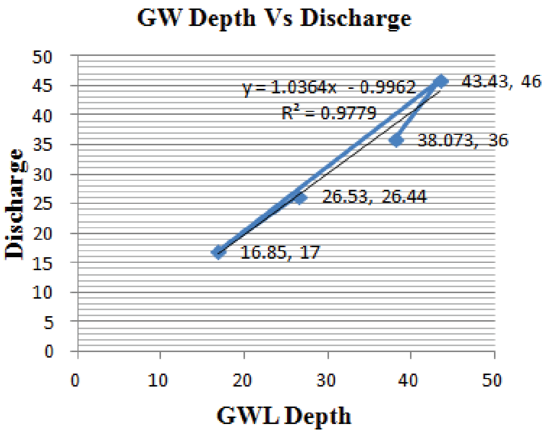

Fig. 4. Fitness curve on GW potential map.

7. Conclusions

Remote sensing and GIS techniques pave way to identify the groundwater potential zones. This study succeeds in proposing sites for groundwater zones, based on which suitable locations for groundwater withdrawals can be done. Therefore, the identification of suitable site for recharge is done effectively to undergo further studies to quantify amount of recharge available through groundwater modeling approach and suggest remedial measures for sustainable management. The results of the present study serve as guidelines for implementing future artificial recharge projects in the study area in order to ensure sustainable groundwater utilization. Also this technique can be widely applied to large area for exploration, identification of favorable zone for artificial recharge.

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