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GIS based analytical hierarchy process (AHP) and frequency ratio (FR) models for groundwater potential zone mapping

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Abstract

The sustainable development and management of groundwater resource requires precise quantitative assessment based on scientific principle and modern techniques. The present study discusses with the utilization of GIS based analytical hierarchy process (AHP) and frequency ratio (FR) models for identification of the groundwater potential zones in Papanasam Taluk, Thanjavur district. The inventory of spring well locations were determined on the topographical map as detected by using field surveys and central groundwater board (CGWB) reports that is in total, 323 springs were identified and mapped in GIS; out of that, 226 (70%) locations were selected for training and the remaining 97 (30%) cases were used for the model validation. The effective thematic layers on the groundwater conditioning factors such as lithology, geomorphology, lineament density, drainage density, soil, slope, rainfall, land use/land cover and elevation were derived from the spatial database. Subsequently, groundwater potential maps were produced from map index calculated using AHP and FR models in GIS environment. The zones obtained were divided into three categories, *viz*., high, medium and low potential zones based on the availability of groundwater. Finally, the receiver operating characteristic (ROC) curves for the groundwater potential models were constructed and the areas under the curves (AUC) were computed. From the analysis, it is seen that the FR model (AUC=68.5%) performs better than AHP (AUC=41.1%) models. Hence, the outcomes attained from the present study indicated that the statistical model can offer an influential tool for delineation of GW resource. The produced groundwater potential maps can assist planners and engineers in groundwater development plans and land use planning.

Keywords: GIS, analytical hierarchy process, frequency ratio, groundwater potential, ROC, AUC

Introduction

Water is an important constituent of all forms of life; groundwater is a most important natural resource of the earth and is required in sufficient quantity and acceptable quality to meet the ever increasing demand for various domestic, agricultural and industrial processing operations. Thus, groundwater is emerging as a formidable poverty reduction tool in developing countries and can be delivered to poor communities far more cheaply, quickly and easily than the conventional canal irrigation water (IWMI, 2001) [14]. The significant contribution made for Green Revolution and also as primary reliable source of irrigation during drought years has further strengthened the people’s faith in utilization of groundwater as a dependable source (CGWB, 2013) [9]. Groundwater targeting is a very difficult task due to their typical hydrological properties of unconfined and fractured aquifer conditions (Basavarajappa *et al*. 2013) [7]. It is possible to identify the groundwater potential zones by observing the terrain features like geological structures, geomorphic units and hydrologic characteristics through both high resolution satellite images and field studies along with GIS (Lokesha *et al*. 2005; Rokade *et al*. 2007) [17, 25].

In the past, several researchers have used RS and GIS techniques for the delineation of groundwater potential zones with successful results (Saraf and Choudhary 1998; Rai *et al*. 2005; Neelakantan and Yuvaraj 2012; Anbazhagan and Jothibasu 2016; Hema Nair *et al*. 2017; Biswajit Das *et al*. 2019) [27, 24, 19, 3, 12, 8]. The identification of groundwater potential zone using remote sensing and GIS techniques involves interpretation of various thematic maps such as hydro geomorphology, land use / land cover, vegetation, lithology, drainage, subsurface lithology, structure, slope etc. which has been used in inferring the occurrence of ground water (Hung *et al*. 2002; Xiuwan 2002; Shaban *et al*. 2006) [13, 29, 28].

Several studies have been applied using index-based methods for assessing groundwater potential mapping (Prasad *et al*. 2008; Dar *et al*. 2011) [23, 10]. In some studies, probabilistic models such as frequency ratio (Oh *et al*., 2011; Naghibi *et al*., 2016) [20, 18], weight of evidence (Lee *et al*. 2012; Al-Abadi 2015) [16, 2], logistic regression (Ozdemir 2011; Pourtaghi and Pourghasemi 2014) [21, 22], and analytical hierarchy process (Adiat *et al*. 2012; Kaliraj *et al*. 2014) [1, 15] have been used for groundwater potential zone mapping.

As mentioned above, groundwater studies have become crucial not only for targeting groundwater potential zone, but also for monitoring and conserving this vital resource. The main objective of the present study was to assess and compare the results of groundwater potential zone maps using the analytical hierarchy process and frequency ratio model in the Papanasam Taluk, Thanjavur district.

2. Study area

The study area is situated in the northern part of Thanjavur district; it is one of the eight taluks. Papanasam taluk is one of the most important agricultural based areas, which is lying in Cauvery river deltaic region. The branch of the Cauvery and Coleroon Rivers are bounded this taluk. It occurs in between Kumbakonam and Thanjavur, Thiruvaiyaru taluk to the eastern and western direction. Papanasam taluk is located at North latitude of 10°70′19″ to 11°00′30″ and East longitude of 79°11′64″ to 79°44′70″ and cover the Survey of India topographic sheet no. 58 N/1, N/2,N/6, N/5, M/8, in 1:50,000 scale and shown in Fig 1. The talk encompasses eleven blocks and the total areal extent is about 581.83sq.km.

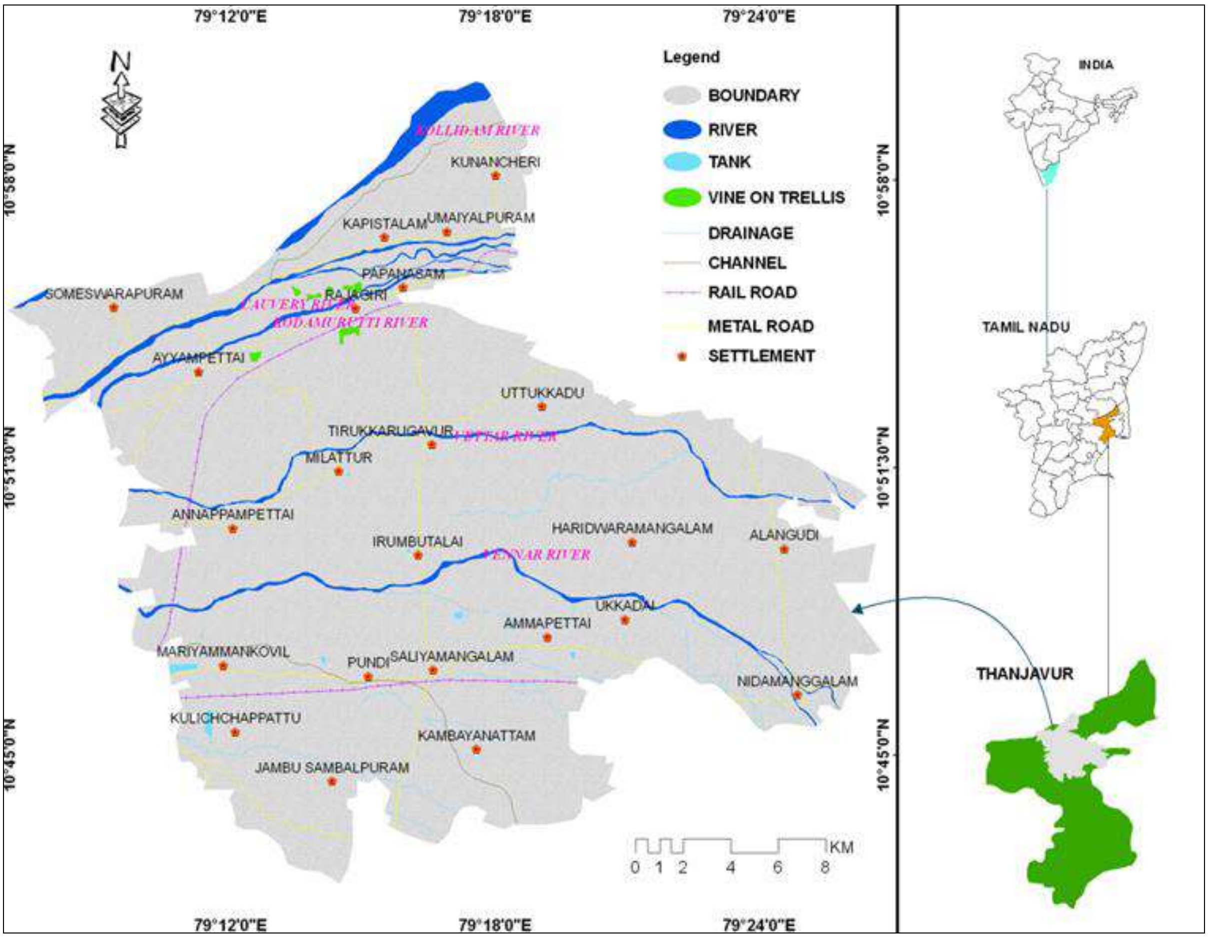


Fig 1: Study area key map

3. Methodology and data preparation

The methodology adopted for the identification of groundwater potential zone mapping using analytical hierarchy process (AHP) and frequency ratio (FR) model is described in Fig 2. The data such as remote sensing data, topographical data and existing map from various departments are collected for the successful completion of the study. The basic information about the study area, drainage and density are derived using topographical data 58 M/8, N/1, N/2, N/5, and N6 on 1:50,000 scale. The well location data were collected from the central groundwater board (CGWB) department. Various thematic databases like Lithology, Geomorphology, Lineament density, Drainage density, Soil, Slope, Rainfall, Landuse/Land cover and Elevation were generated to identify groundwater potential zones (Fig. 3). The factors like geomorphology, lineament and density, and landuse and land cover, were interpreted from IRS-LISS III satellite data. The slope and elevation factors were derived in GIS environment using Shuttle Radar Topographic Mission (SRTM) data. The lithology map of the study area was prepared from geological society of India map source. The soil map of the study area was prepared from published maps of soil survey department.

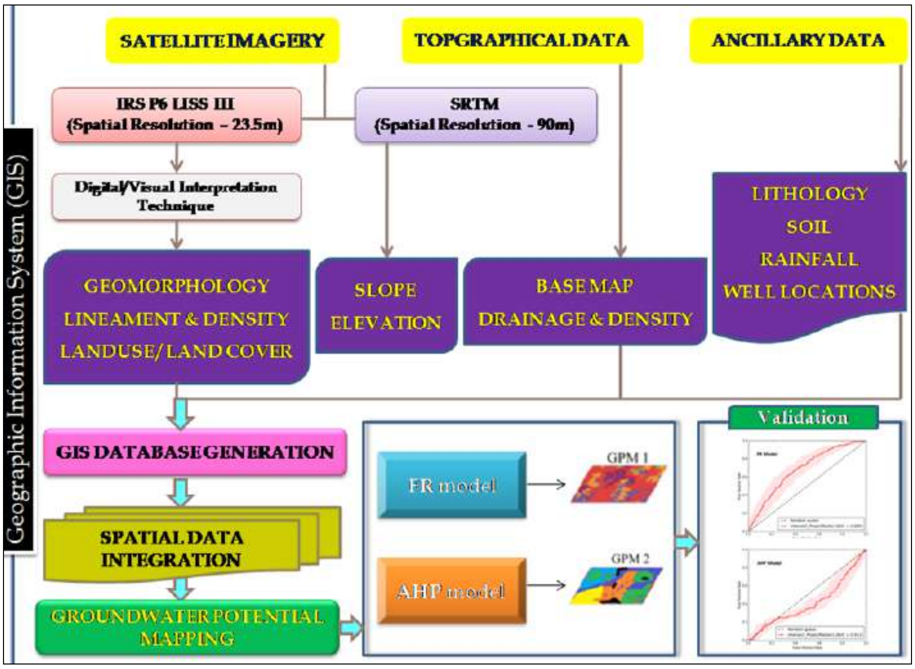


Fig 2: Methodology flow chart

The rainfall map of the study area which is prepared from station data (non-spatial). A vector to raster conversion of all the thematic maps with 23.5 x 23.5 m pixel size. The total study area covers 33, 267 pixels, and the total number of well location points is 323 pixels. Among the spring wells, 70% (226 wells) were selected as training data set for GWPZ mapping using FR model and remaining 30% (97 wells) were selected as testing data set for validation of the model. The groundwater potential zones were obtained by overlaying all the thematic maps in terms of frequency ratio and analytical hierarchical process methods using spatial analysis tools in GIS environment. Finally, the different methods of output results of the groundwater potential map are classified into three classes *viz.* high, medium, and low potential zones.

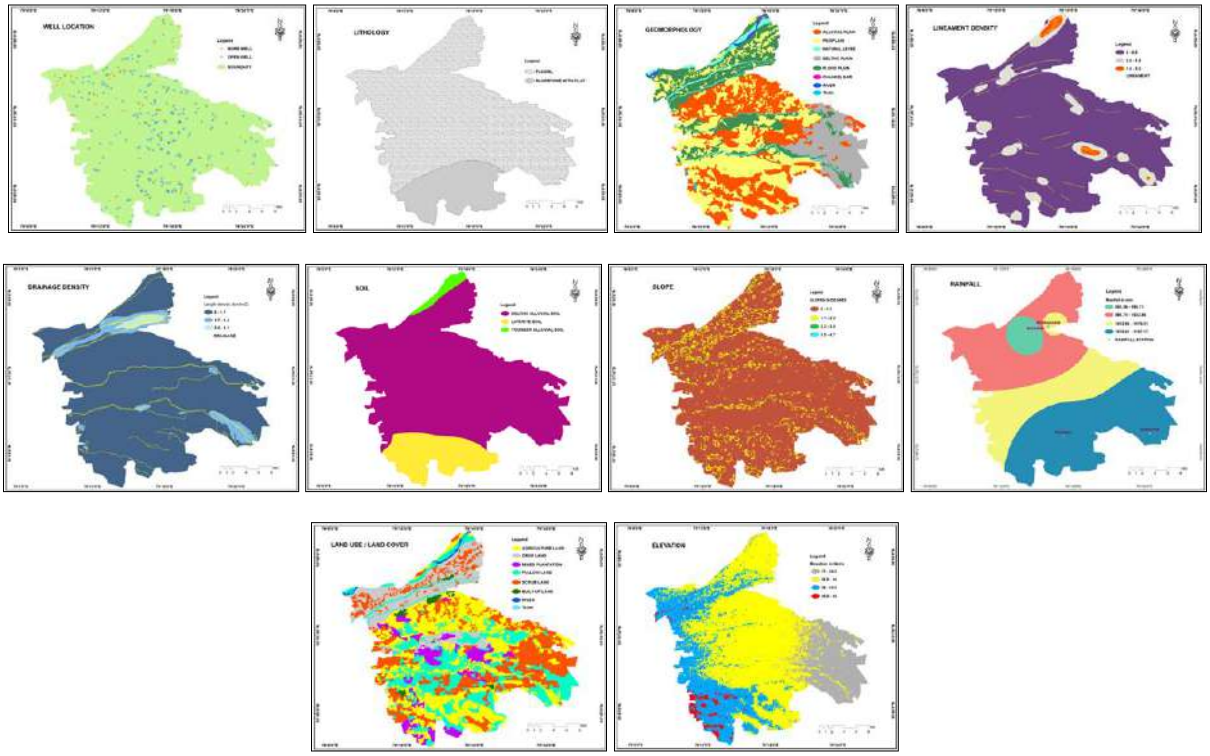


Fig 3: Thematic maps of the study area

4. Analytical Hierarchy Process model

AHP is a widely used multi-criteria decision making MCDM technique in the field of natural resources and environmental management. The analytical hierarchical process was used to determine the weights of the thematic layers (Saaty 1980) [26]. The comparison ratings are in Saaty's 1–9 scale (Saaty 1980) [26]. In order to determine the weight of each thematic layer, the higher the weight, the more important the corresponding criterion. Next, for a fixed criterion, the AHP assigns a score to each option according to the decision maker's pair wise comparisons of the options based on that criterion. The higher the score, the better the performance of the option with respect to the considered criterion. The AHP combines the criteria weights and the option scores, thus determining a global score for each option, and a consequent ranking. The global score for a given option is a weighted sum of the scores it obtained with respect to all the criteria. The table 1 shows the procedure of assigning weightage for each parameter and classes within the parameter based on the importance of it. The value 9 in the table shows higher important while 1/9 shows the least important while 1 shows the equal weight of a parameter or a class. Based on these weightage criteria each parameter in the study has been classified. The weightage of each main parameter has been determined and shown in Table 2, further, the weightage for the subclass of main parameters have been assigned as mention in Table 3.

Table 1: Continuous rating scale of Satty's analytical hierarchical process

1/9	**1/7**	**1/5**	**1/3**	**1**	**3**	**5**	**7**	**9**
Extremely	Very strongly	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely
Less important ⟵		---------------------------		Equal 1		-------------------------	⟶	More important

Source: Satty (1980) [26] Note: 1/8, 1/6, 1/4, 1/2, 2,4,6,8 can also be used if more number of classes exits

Table 2: Percentage of influencing factor based on Satty's analytical hierarchical process

Influencing factor	**Value**	**Sattys Scale (in Frac.)**	**Sattys Scale (in Dec.)**	**% influence = (Satty Scale/sum)*100**	**Relative influence value**
Lithology	High	1	1	35.46	35
Geomorphology	↓	*1/2*	0.5	17.73	18
Lineament density		*1/3*	0.3	10.64	12
Drainage density		*1/4*	0.25	8.87	9
Soil		*1/5*	0.2	7.09	7
Slope		*1/6*	0.16	5.67	6
Rainfall		*1/7*	0.14	4.96	5
Landuse / land cover	Low	*1/8*	0.12	4.26	4
Elevation		*1/9*	0.11	3.90	4
			Σ=2.82		Σ =100

Table 3: Assigned weight according to Satty's analytical hierarchical process

Influencing factor	**Class interval**	**Sattys Scale (in Frac.)**	**Sattys Scale (In Dec.)**	**% influence = (Satty Scale/sum)*100**	**Relative Weight**
Lithology					
	Sandstone with clay	1/2	0.5	66.67	67
	Fluvial	1/4	0.25	33.33	33
			Sum=0.75		
Geomorphology					
	Pediplain	1	1	37.17	37
	Flood plain	1/2	0.5	18.59	19
	Alluvial plain	1/3	0.3	11.15	11
	Deltaic plain	1/4	0.25	9.29	9
	Natural levee	1/5	0.2	7.43	7
	Channel bar	1/6	0.16	5.95	6
	River	1/7	0.14	5.20	5
	Tank	1/7	0.14	5.20	5
			Sum=2.69		
Lineament density					
	1.5 – 2.3	1	1	66.67	67
	0.8 – 1.5	1/3	0.3	20.00	20
	0 – 0.8	1/5	0.2	13.33	13
			Sum=1.5		
Drainage density					
	0 – 1.7	1	1	66.67	67
	1.7 – 3.4	1/3	0.3	20.00	20
	3.4 – 5.1	1/5	0.2	13.33	13
			Sum=1.5		
Soil					
	Laterite soil	1/2	0.5	54.95	55
	Deltaic alluvial soil	1/4	0.25	27.47	27
	Younger alluvial soil	1/6	0.16	17.58	18
			Sum=0.91		
Slope					
	0 – 1.1	1	1	48.78	49
	1.1 – 2.3	1/2	0.5	24.39	24
	2.3 – 3.5	1/3	0.3	14.63	15
	3.5 – 4.7	1/4	0.25	12.20	12
			Sum=2.05		

Rainfall					
	1070.01 – 1107.17	1	1	52.36	52
	1032.86 – 1070.01	1/2	0.5	26.18	26
	995.71 – 1032.86	1/4	0.25	13.09	13
	958.56 – 995.71	1/6	0.16	8.38	8
			Sum=1.91		
Landuse / land cover					
	Agriculture land	1	1	39.84	40
	Crop land	1/2	0.5	19.92	20
	Mixed plantation	1/4	0.25	9.96	10
	Scrub land	1/5	0.2	7.97	8
	Fallow land	1/6	0.16	6.37	6
	River	1/7	0.14	5.58	6
	Tank	1/7	0.14	5.58	6
	Built-up land	1/8	0.12	4.78	5
			Sum=2.51		
Elevation					
	17 – 26.5	1/2	0.5	40.00	40
	26.5 – 36	1/3	0.3	24.00	24
	36 – 45.5	1/4	0.25	20.00	20
	45.5 - 55	1/5	0.2	16.00	16
			Sum=1.25		

4.1. Weighted Overlay Analysis

Based on the weightages the Satty's Analytical Hierarchical process the GIS analysis has been carried out, integration of thematic maps for overlay analysis using GIS environment. After integration of all the thematic layer, the GWPI had a minimum value of 151, and a maximum value of 394, with a mean value of 291.32 and a standard deviation of 42.61. Further, the result of overlay analysis has been classified into three classes as high, medium, and low potential zones and shown in Fig. 4. From the result of classification it has been found that, 136.98 km^2 areas are having high, 407.77 km^2 area is having medium, and 37.08 km^2 having low for groundwater potential zones.

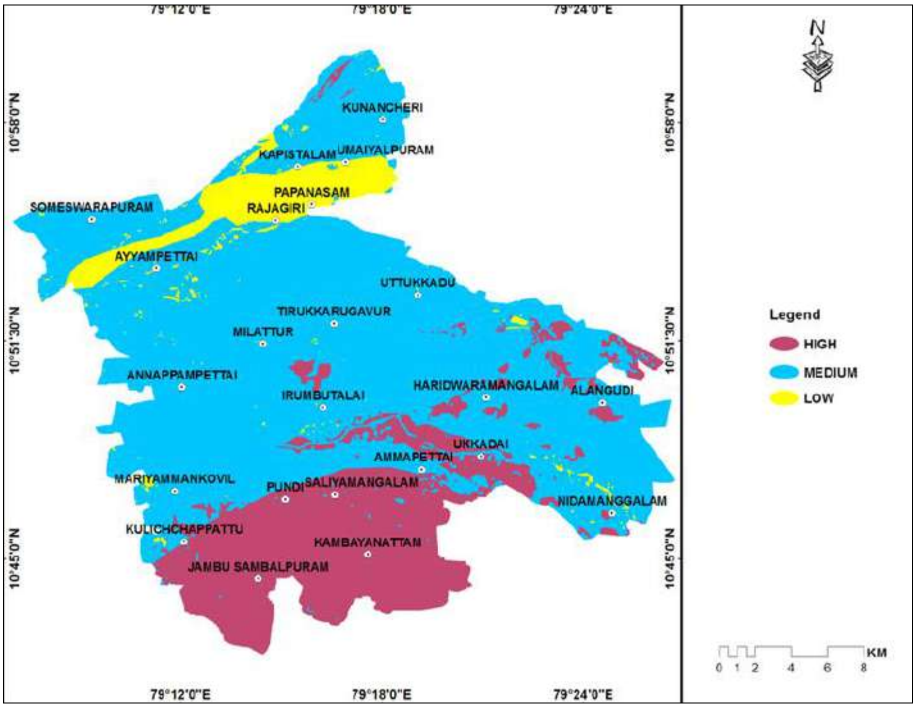


Fig 4: Groundwater potential zone map derived from AHP model

5. Frequency Ratio model

Frequency ratio (FR) model as bivariate statistical technique can be utilized as a simple tools for geospatial valuation and computation of the probabilistic association between dependent variable and independent variables. The method has been used for groundwater spring potential mapping by Ozdemir (2011) [21]. The spatial relationships between groundwater well locations and each factor contributing groundwater occurrence. For groundwater potential analysis, the calculated and extracted factors were converted to a 23.5 x 23.5 m^2 grid using ArcGIS software. In the study area, the total number of pixels was 33,267, and the number of well location pixels was 323. Among the spring wells, 70% (226 wells) were selected as training data set for GWPZ mapping using FR model and remaining 30% (97 wells) were selected as testing data set for validation of model on the basis of random dividing method (Lee *et al.* 2012) [16]. The correlation of coefficients was calculated from the analysis of the relationship between the well location and the relevant factors. The rating of each factor's type or range was assigned from the relationship between distribution of groundwater well location and each groundwater conditioning factor's. To compute the frequency value in each class of the groundwater-related factors can be expressed based on the equation.

$$\mathbf{FR} = \frac{W/TW}{CP/TP} \qquad (1)$$

Where, FR is the frequency ratio of the class of factor, W is a number of pixels of well locations for each class of thematic maps; TW is a number of total pixels of well in the study area. CP is a number of pixels in each thematic class and TP is a total number of pixels in the study area. The calculated values have given in Table-4. In the FR model, the FR value of each class in a thematic layer was considered as the weight of that particular class in thematic parameters to determine groundwater potentiality. The accuracy of the FR model was validated using R-index method.

Table 4: Spatial relationship between each conditioning factor and well locations using FR

Factor	Class	No of pixel in a class	% of pixel in class	No of pixel of wells	% of pixel of wells	FR ratio
Geomorphology						
	Alluvial plain	9789	29.43	74	32.74	1.11
	Pediplain	11175	33.59	88	38.94	1.16
	Natural levee	1216	3.66	6	2.65	0.73
	Deltaic plain	4236	12.73	15	6.64	0.52
	Flood plain	6579	19.78	43	19.03	0.96
	Channel bar	40	0.12	0	0.00	0.00
	River	148	0.44	0	0.00	0.00
	Tank	84	0.25	0	0.00	0.00
Lineament density						
	0 – 0.8	30074	90.40	204	90.27	1.00
	0.8 – 1.5	2736	8.22	19	8.41	1.02
	1.5 – 2.3	457	1.37	3	1.33	0.97
Slope						
	0 – 1.1	30212	90.82	203	89.82	0.99
	1.1 – 2.3	2762	8.30	23	10.18	1.23
	2.3 – 3.5	184	0.55	0	0.00	0.00
	3.5 – 4.7	109	0.33	0	0.00	0.00
Landuse/land cover						
	Agriculture land	9974	29.98	69	30.53	1.02
	Crop land	4579	13.76	35	15.49	1.13
	Mixed plantation	2096	6.30	15	6.64	1.05
	Fallow land	7592	22.82	44	19.47	0.85
	Scrub land	8412	25.29	61	26.99	1.07
	Built-up land	382	1.15	2	0.88	0.77
	River	148	0.44	0	0.00	0.00
	Tank	84	0.25	0	0.00	0.00
Drainage density						
	0 – 1.7	30452	91.54	205	90.71	0.99
	1.7 – 3.4	2325	6.99	19	8.41	1.20
	3.4 – 5.1	490	1.47	2	0.88	0.60
Lithology						
	Fluvial	27277	81.99	177	78.32	0.96
	Sandstone with clay	5990	18.01	49	21.68	1.20
Rainfall						
	958 – 995	1481	4.45	15	6.64	1.49
	995 – 1032	10190	30.63	73	32.30	1.05
	1032 – 1070	8422	25.32	53	23.45	0.93
	1070 – 1107	13174	39.60	85	37.61	0.95
Soil						
	Deltaic alluvial soil	27647	83.11	185	81.86	0.98
	Laterite soil	4936	14.84	37	16.37	1.10
	Younger alluvial soil	684	2.06	4	1.77	0.86
Elevation						
	17 – 26.5	6742	20.27	24	10.62	0.52
	26.5 – 36	16910	50.83	126	55.75	1.10
	36 – 45.5	9110	27.38	74	32.74	1.20
	45.5 - 55	505	1.52	2	0.88	0.58

(Total no. of well location training set pixels – 226; Total No. of pixels in study area – 33267)

5.1. Data Integration

The calculated frequency ratio values were added to the attribute table of each thematic layer. These thematic layers were converted into a raster layer based on the frequency ratio field values. All the raster themes were integrated in the GIS environment by using raster calculator options in spatial analyst tool. The data integration has done to calculate the groundwater potential index by using the following equation.

$GWPI_{FR} = \sum (GEOM_{FR} + LD_{FR} + SL_{FR} + Lu\_Lc_{FR} + DD_{FR} + LI_{FR} + RF_{FR} + SO_{FR} + EL_{FR})$ (2)

Where, $GWPI_{FR}$ = Groundwater Potential Index using frequency ratio method.

$GEOM_{FR}$ = freqency ratio of geomorphology; LD_{FR} = frequency ratio of lineament density; SL_{FR} = frequency ratio of slope; Lu_Lc_{FR} = frequency ratio of landuse/land cover; DD_{FR} = frequency ratio of drainage density; LI_{FR} = freqency ratio of lithology; RF_{FR} = frequency ratio of rainfall; SO_{FR} = freqency ratio of soil; EL_{FR} = frequency ratio of elevation.

After integration of all the raster layer, the GWPI had a minimum value of 6.24, and a maximum value of 11.12, with a mean value of 9.0 and a standard deviation of 0.73. The range of minimum and maximum values were equally divided into three categories and classified as high, medium, and low potential classes and the groundwater potential zone map generated based on the frequency ratio model and shown in Fig 5. Based on the frequency ratio of the groundwater potential classes, 23.64% of the area fall in high, 64.22% of the area comes under the medium, and 12.14% of the area comes in low potential categories.

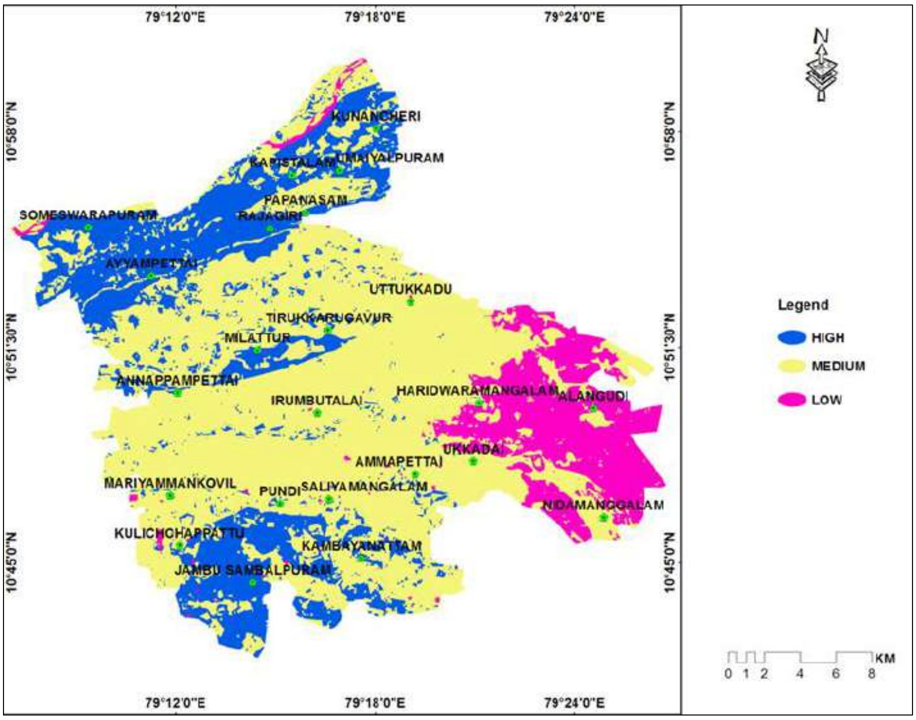


Fig 5: Groundwater potential zone map derived from FR model

6. Validation of groundwater potential zone map

Validating output maps is essential to assess the accuracy of models, methods, and applied techniques. Each model must be validated as asserts that a model finds its significance when validated. ROC curve analysis is a common methodology to assess the accuracy of a diagonstic test (Pourghasemi *et al*. 2013). There are sevel researchers examined the ROC and AUC analysis for the groundwater potential zone mapping (Das 2019; Ozdemir 2011; Andualem and Demeke 2019; Arfan Arshad *et al*. 2020) [11, 21, 4, 5]. In this study, the output map for groundwater potential were validated through the receiver operating characteristic (ROC) analysis by comparing the 97 (30%) existing well locations for validation purposes. The ROC curve of the groundwater potential zone maps obtained by the AHP and FR models and shown in Fig. 6. These curves indicate that the FR model (AUC=68.5%) performs better than AHP model (AUC=41.1%) model. Therefore, it can be seen that the FR and AHP models applied in this study showed reasonably good accuracy in spatial predicting of groundwater potential.

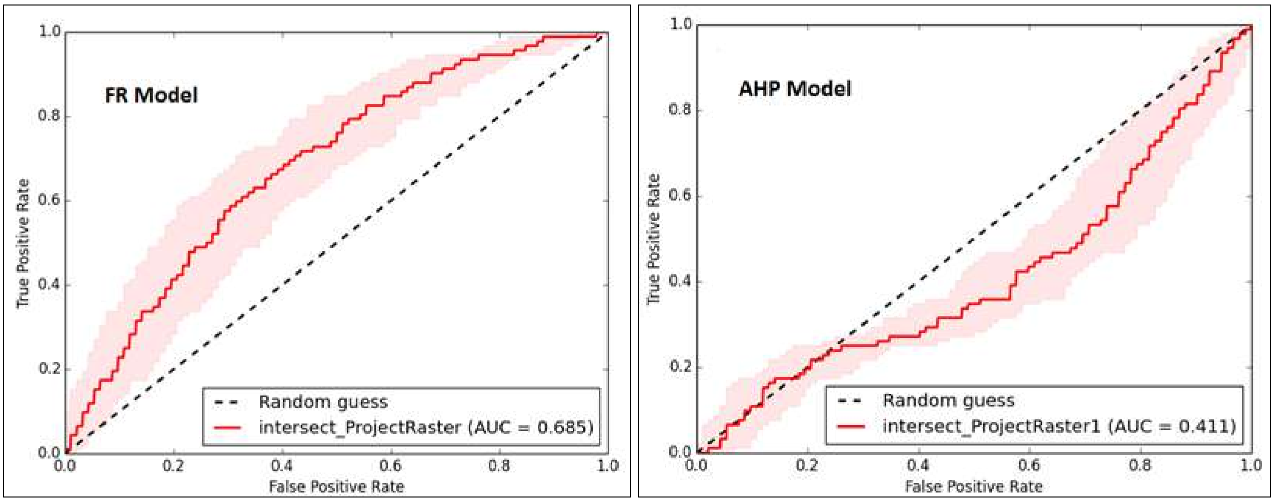
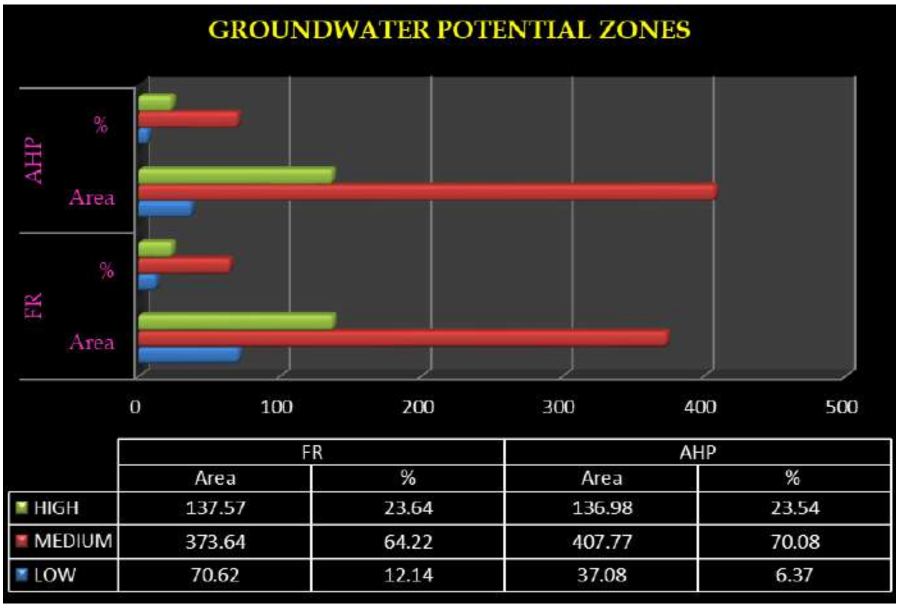


Fig 6: ROC curves for the groundwater potential zone maps

7. Summary and Conclusion

Generally various methods have been applied for regional groundwater potential assessment globally. In this study, analytical hierarchy process and frequency ratio models were applied by considering nine thematic layers such as lithology, geomorphology, lineament density, drainage density, soil, slope, rainfall, land use/land cover and elevation in order to identify groundwater potential zones. AHP multi-criterion analysis and FR models were used to evaluate the weight and rating values for thematic layers and their sub-classes respectively. All the thematic layers to be integrated and analyzed in the GIS environment. Subsequently, the groundwater potential index were calculated and reclassified in to high, medium and low groundwater potential zones. The result of FR model revealed that, around 462.39 km^2 (79.47%) area is high, 118.65 km^2 (20.39%) area is medium and 0.79 km^2 (0.14%) area is low potential zones. From the AHP model, mapping of groundwater potential zone shows that 136.98 km2 (23.54%) of the study areas are high and 407.77 km2 (70.08%) are medium and 37.08 km2 (6.37%) of the area remote chance of potential zones and shown in Fig. 7. The model's outcomes acquired in this research were validated with the distribution of existing validation purposes of groundwater wells locations using ROC curve method. The validation of the results showed that the FR model (AUC=68.5%) performs better than AHP (AUC=41.1%) models. The higher value of the AUC indicates the highly successful nature of the techniques used in this study. Hence, the outcomes attained from the present study indicated that the FR and AHP model can offer an influential tool for delineation of the groundwater resource. The results of groundwater potential maps can be useful for planners and engineers in water resource management and land use planning of the study area.



	FR		AHP	
	Area	%	Area	%
🟩 HIGH	137.57	23.64	136.98	23.54
🟥 MEDIUM	373.64	64.22	407.77	70.08
🟦 LOW	70.62	12.14	37.08	6.37

Fig 7: Graphical representation areas of groundwater potential zones

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