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# Fuzzy logic based multi criteria analysis for exploration of groundwater potential in Karawan watershed, Madhya Pradesh, India

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**Abstract:** As per international reports, about 71 percent of the earth's surface is covered by water. However, 96.5% of the entire water resource available on the planet is occupied by oceans, which makes the water saline and only 3.5% of the total resource is freshwater (https://water.usgs.gov/edu/earthhowmuch.html). Out of this freshwater, about 68 percent of the freshwater resource is actually inaccessible, as it is found in glaciers and ice caps, and just 30 percent of the overall freshwater is accessible to mankind (https://www.nationalgeographic.org/media/earths-fresh-water). Out of this 30%, a small portion of the freshwater resource is found as ground water. As evident from the data presented, ground water is a precious resource, hence it is important to explore the potential of ground water in hard rock areas in order to fully access it. Remote sensing and Geographic Information System (GIS) is a technology that opens up new vistas in the exploration of groundwater potential. The objective of this study is to develop a spatial model using fuzzy approach in GIS environment to delineate zones with high groundwater potential. This study has been conducted in Karawan watershed, Sagar district (Madhya Pradesh, India) which has an area of 275.61 km$^2$. The Advanced Space Borne Thermal Emission and Reflection Radiometer (ASTER) DEM and LISS-IV images have been used to prepare various thematic maps. The groundwater potential zones have been delineated by integration of these thematic layers using weight based analysis approach. Fuzzy approach has been used to assign weights to various thematic layers as well as to the classes of each layer based upon the influence on ground water. The fuzzy logic membership helps to determine the probability that a site is poor or good in terms of groundwater potential.

**Keywords:** GIS, Groundwater potential, Fuzzy logic, Multi criteria analysis, Karawan

## 1. Introduction

World is facing a great crisis of freshwater and as per reports by 2025, one-third of the population of the developing world will be facing severe shortage of potable water. Freshwater is a fundamental resource for natural ecosystems and human sustenance and access to it is considered a universal human right (United Nations Committee on Economic, Social and Cultural Rights, 2003). Water problems in Madhya Pradesh are related to the availability of potable freshwater associated with land use activities. Groundwater caters to the various purposes of freshwater, such as domestic, industrial and agricultural needs. As development increases, so does the demand for freshwater. Developing surface water is far more expensive compared to harnessing groundwater resources. Hence it becomes important to identify suitable potential areas.

High resolution satellite imageries are increasingly being used in groundwater investigation because of their utility in identifying various ground features, which serve as direct or indirect indicators to the presence of ground water (Krishanmurthy et al., 1996; Bahuguna et al., 2003). Remote sensing helps in delineating various terrain features such as geological structures, geomorphology and hydrological parameters, which control the groundwater system. The relationship between the various terrain features is very complex and difficult to evaluate. The geospatial technology provides an effective tool in analyzing and quantifying such multivariate aspects of groundwater system and is very helpful in delineation of groundwater prospect zones (Carver, 1991).

During recent period, many related topics have been explored by researchers in GIS community (Smith, 1984; Foster, 1988; Altman, 1994). The methodology used in this paper takes advantage of the fuzzy logic to evaluate the interrelationship of terrain features defining the groundwater system. GIS is used for the generation and analysis of the thematic layers, such as slope, lithology, geomorphology, soil, lineament, land use / land cover and drainage density, which are assigned fuzzy membership values according to their influence on groundwater. Defining the criteria of delineation of potential zone is the most important analytical step in fuzzy logic because it helps to determine the type of data to be expected for the analysis. Fuzzy membership is a vital reclassification step. Reclassification process has been used to generalize the interpretation of raster (depend on pixel value) data by changing a single input value into a new output value. Fuzzy overlay allows to overlay the different reclassified raster layers to analyze the possibility of a distinct phenomenon. This can then be used to calibrate the results and use them to delineate the suitable zones. The fuzzy operators such as fuzzy product, fuzzy sum and fuzzy gamma have been used for factor maps integration. The final groundwater potential map has been categorized into five categories viz. very good, good, moderate, poor and very poor.

## 2. Karawan watershed

The watershed area of Karawan river is 275.61 km$^2$ and located between 23°44’45”N to 23°58’30”N latitude and 78°35’45”E to 78°46’15”E longitudes (Fig. 1). The Karawan river originates from the southwest part of the town of Sagar located at about 620 meter near the Gond village (23°46’30” N latitude & 74°40’30” E longitudes) and flows towards northeast, meeting the river Dhasan near Mehar village in Sagar district; Dhasan river is an important right bank tributary of the Yamuna river. Karawan river is 32.5 km. long and, although there are no main tributaries of the Karawan river, there are some small tributaries pouring into the river, notable amongst them being Molali Nala, Garhpahara Nala on the right bank. There are no major tributaries on the left bank. Sagar is a city in Karawan watershed area which has experienced rapid population growth and increased demand for groundwater in recent years. Wherever surface water storage or canal irrigation is absent or very limited, there is a greater activity of groundwater extraction for agricultural purpose. The problems associated with the overexploitation of ground water have escalated to alarming standards, which has necessitated immediate remedial measures towards addressing the situation in Karawan watershed area.

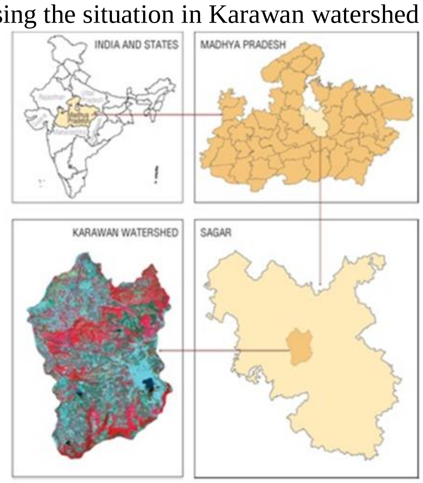


**Figure 1: Location map of Karawan watershed**

## 3. Methodology

IRS-P6 Resourcesat-1, LISS-III satellite images of Kharif 2014 and Rabi 2015 season along with ASTER DEM have been used for thematic mapping. Thematic maps of lineament, geomorphology, lithology, slope, soil, drainage density, drainage buffer and land use/land cover have been prepared. These thematic layers were assigned fuzzy membership values according to their influence on groundwater.

The flow chart in fig. 2 summarizes the methodology adopted.

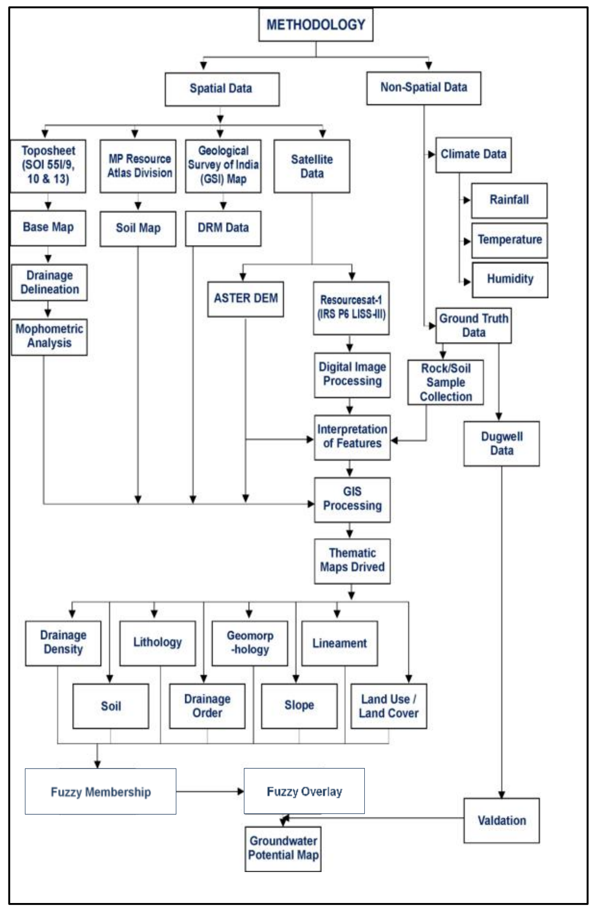


**Figure 2: Methodology adopted for exploration of groundwater in Karawan watershed**

### 3.1 Fuzzy logic approach

As mentioned earlier, fuzzy logic method has been used to delineate the groundwater potential map. The prospects for groundwater zone in the study area have been explored through the integration of thematic layers in fuzzy overlay function. Fuzzy logic assigns membership values to locations that range from 0 to 1. Fuzzy logic has similarities to Boolean logic. Boolean logic results are restricted to 0 and 1, whereas fuzzy logic returns values between 0 and 1. Therefore fuzzy logic is similar to human thinking and instead of just true or false; it defines the value based on degrees of truth.

The criterion workflow for fuzzy logic is as follows:

1. Define the problem and potential zone criteria
2. Collect criteria layers
3. Assign fuzzy membership values
4. Perform fuzzy overlay
5. Verify and apply results

**(a) Fuzzy membership** – Assigning the fuzzy membership values is most important for analysis of influence of various thematic layers. In order to produce the potential groundwater zone map, the interrelationship of thematic layers and their influence on groundwater system has been analyzed and according to their weightage the fuzzy membership values have been assigned to various classes in a thematic layer. Fuzzy Membership Function curve (Fig. 3) supports in defining how each point in the input interval can be mapped to a membership value from 0 and 1. This function helps to determine the influence of a parameter between lowest to highest.

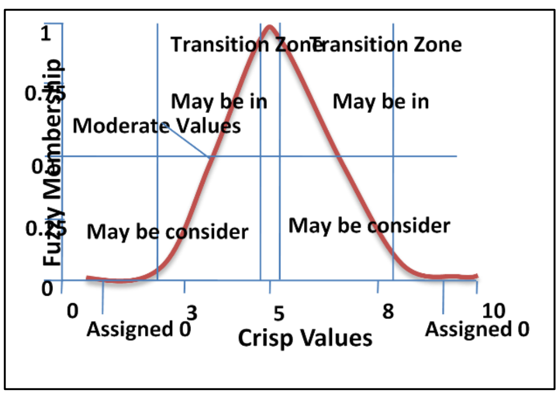


**Figure 3: Fuzzy membership function diagram**

**(b) Fuzzy overlay functions** - For fuzzy overlay, various methods have been defined to explore the relative relationships and quantify the interaction. These combination approaches are known as fuzzy operators viz. fuzzy And, fuzzy Or, fuzzy Product, fuzzy Sum and fuzzy Gamma etc. Each of these operators is based on fuzzy set theory and are discussed below:
Fuzzy AND: This is equivalent to a Boolean AND (logical intersection) query on classical set values. AND fuzzy algorithm is;

**μ combination =MIN (μA, μB,………μN)**

Fuzzy OR: This is equivalent to a Boolean OR (logical union) on classical set values;

**μ combination =MAX (μA, μB,…………..μN)**

Fuzzy Algebraic Product is

μ combination = μA* μB*…… *μN

Fuzzy Algebraic Sum is

μ combination = μA+ μB+…… +μN

Fuzzy Gamma is defined in terms of the fuzzy algebraic product and the Fuzzy algebraic sum by the representation;

**μ combination = (Fuzzy Algebraic Sum)$^{\gamma}$ * (Fuzzy Algebraic Product)$^{(1-\gamma)}$**

Here $\gamma$ is a parameter chosen in the range (0, 1). When $\gamma$ is 1 the combination is same as the Fuzzy algebraic sum, and when $\gamma$ is 0 the combination is equal to the Fuzzy algebraic product (Rather et al., 2012).

**4. Result and discussion**

The fuzzy membership has been stipulated to the different thematic layers according to their classification on the respect of groundwater contribution. Different classes have been given the weightage by the different experts. All the expert weightages have been converted into the fuzzy membership value according to their ranks within the range of 0-1 (Delft, 2000). The value 0 represents very poor, 0.5 represents moderate and 1 represents very good groundwater potential zone. The weights have been assigned to thematic layers and ranking according to the ground water prospects as shown in table 1. The following thematic layers have been taken into consideration in the present study.

**4.1 Fuzzy membership and assigned weightage to thematic cases.**

**(a) Geology / Lithology**: Karawan watershed is covered mostly with Deccan Trap Basalt which is vesicular in nature whereas in southern most part it is massive and compact. In northern part patches of Vindhyan Sandstone and shale are found (fig. 4). The compact basalt is contributing the least to groundwater system whereas sandstone with high secondary porosity is contributing the most. The fuzzy membership values for lithological classes are ranging from 0.13 to 0.77.

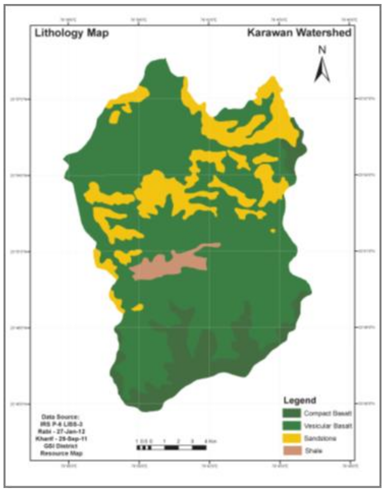


**Figure 4: Lithology map**

**(b) Geomorphology:** Geomorphology refers the identification characterization of various types landforms. Many of these landforms are favorable for the occurrence of groundwater and can be classified in terms of groundwater potentiality. Landforms that have been delineated in the study area are Structural hill, Denudational hill, Residual hill, Pediment and Pediplain/Buried Pediplain (fig. 5). The fuzzy membership values for geomorphological classes found in between 0.15 to 0.69.

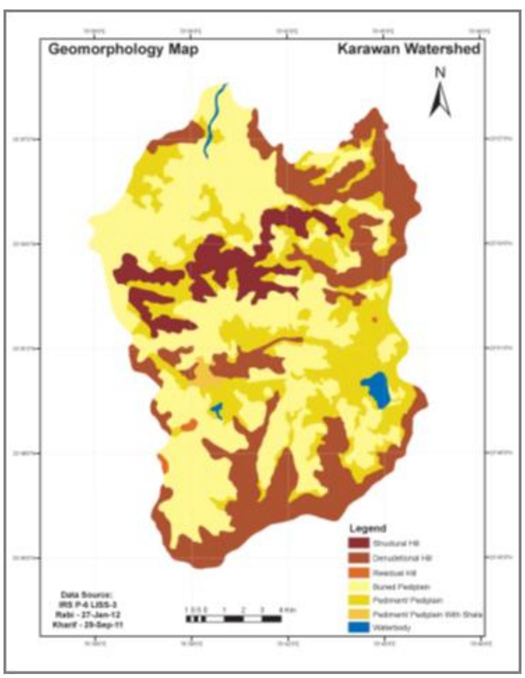


**Figure 5: Geomorphology**

**(c) Lineament**: Lineaments are indicators of weak zones such as joints, fractures and faults. These lineaments are hydro-geologically very important and may provide the pathways for groundwater movement based on interconnectivity. Broadly, three sets of lineaments have been found in the study area. These sets are extending in the directions NNW-SSE, NNE-SSW and NE-SW. Maximum lineaments in Karawan watershed are along with streams (Fig. 6). To evaluate the zone of influence these lineaments have been categorized as large, medium and small. Accordingly, the buffer zones of 150 m, 300 m and 500 m have been created. These buffer zones were analyzed and the fuzzy membership value of lineaments buffer is ranging from 0.58 to 0.85, whereas the area outside of these buffer zones is having the value 0.08.

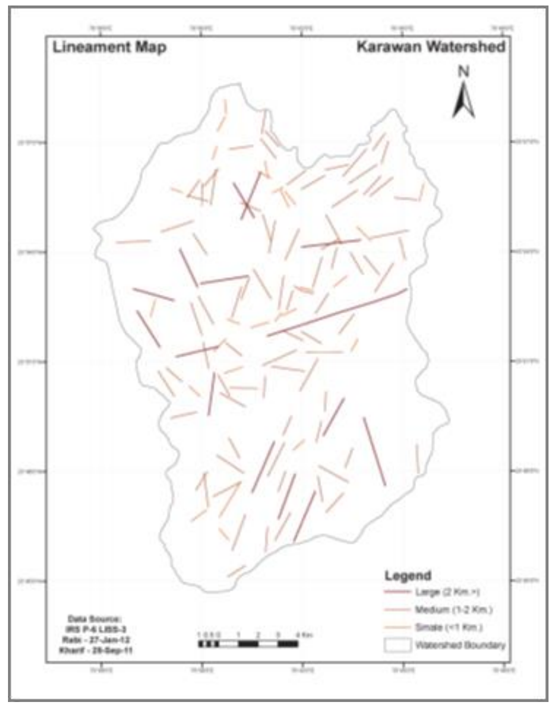


**Figure 6: Lineament map**

**(d) Slope:** Slope is the inclination or steepness of a surface and can be measured in degrees with respect to the horizontal (0-90). The slope map has been prepared using ASTER DEM. In relation to groundwater, flat areas, where the slope is gentle (i.e. up to 70), are more conducive for infiltration, which in turn facilitates groundwater recharge. Whereas elevated areas with slope moderate to high (70-200 and above 200) (Fig. 7), would experience high run-off and low infiltration. Based on these characteristics the weightage values as fuzzy membership value for slope classes have been assigned between 0.05 to 0.85.

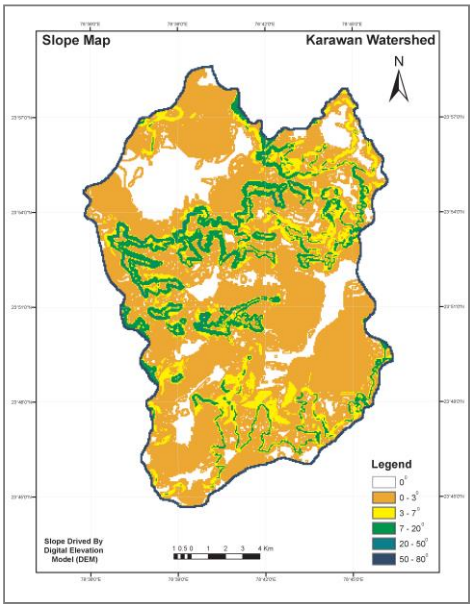


**Figure 7: Slope map**

**(e)** **Soil**: The soil texture has been defined in terms of the porosity and permeability of the soil. This is one of the most important features of soil, with respect to its water-holding capacity. These textural classes of soil are determined by the percentage of sand, silt and clay. The study area has been divided into six types of soil texture as fine, loamy skeletal, loamy, fine loamy, clayey and clayey skeletal shown in figure 8. The fuzzy weightage values are from 0.37 to 0.71.

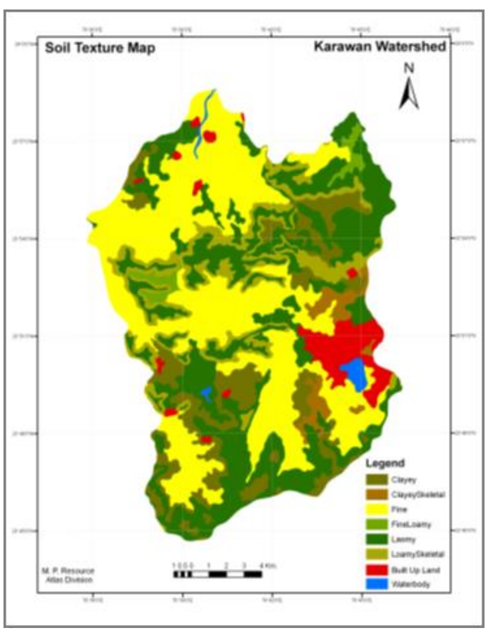


**Figure 8: Soil map**

**Table 1: Different thematic parameters considered in the groundwater prospect evaluation and their fuzzy membership**

| Raster layer | Feature classes or buffer distance | Fuzzy membership (Reclassify) |
|---|---|---|
| Lineament Buffer | **Lineament Buffer** | |
| | 0 – 150 m Buffer | 0.85 |
| | 151 – 300 m Buffer | 0.76 |
| | 301 – 500 m Buffer | 0.58 |
| | Other area | 0.08 |
| Geomorphology | **Landforms** | |
| | Buried Pediplain | 0.69 |
| | Residual Hill | 0.15 |
| | Denudetional Hill | 0.22 |
| | Pediment / Pediplain | 0.75 |
| | Structural Hill | 0.18 |
| | Pediment / Pediplain with Shale | 0.24 |
| Lithology | **Rock type** | |
| | Compact Basalt | 0.13 |
| | Vesicular Basalt | 0.55 |
| | Shale | 0.28 |
| | Sandstone | 0.77 |
| Soil Texture | **Soil type** | |
| | Fine | 0.71 |
| | Loamy Skeletal | 0.58 |
| | Loamy | 0.68 |
| | Fine Loamy | 0.69 |
| | Clayey | 0.42 |
| | Clayey Skeletal | 0.37 |
| Slope | **Slope gradient (in degree)** | |
| | 0 – 1.5 | 0.85 |
| | 1.5 – 9.4 | 0.73 |
| | 9.5 - 15 | 0.56 |
| | 15 – 29 | 0.38 |
| | 29 - 57 | 0.2 |
| | 57 - 80 | 0.05 |
| Drainage density | **Drainage density (km2)** | |
| | 0 – 0.8 | 0.88 |
| | 0.8 – 1.3 | 0.82 |
| | 1.3 – 2.18 | 0.71 |
| | 2.18 – 2.6 | 0.54 |
| | 2.6 – 3.14 | 0.41 |
| | 3.1 – 3.8 | 0.22 |
| | 3.8 – 5.5 | 0.14 |
| LU / LC | **Class name** | |
| | Built Up Land | 0.05 |
| | Kharif Crop | 0.85 |
| | Rabi Crop | 0.82 |
| | Double Crop | 0.86 |
| | Fallow Land | 0.58 |
| | Scrub Forest | 0.44 |
| | Dense Forest | 0.72 |
| | Open Land | 0.48 |
| | Barren Rocky | 0.18 |
| | Water Body | 0.89 |

**(f) Land use / Land cover**: Land use / land cover map has been prepared using supervised classification of IRS-P6 LISS-3 data. The entire study has been classified in ten lad use/ land cover units i.e. Barren rocky, Built-up land, Dense forest, Double crop, Fallow land, Kharif crop, Open land, Rabi crop, Scrub forest and water body (Fig. 9). These land use classes have been evaluated for groundwater availability and the values are ranging from 0.05 to 0.89.

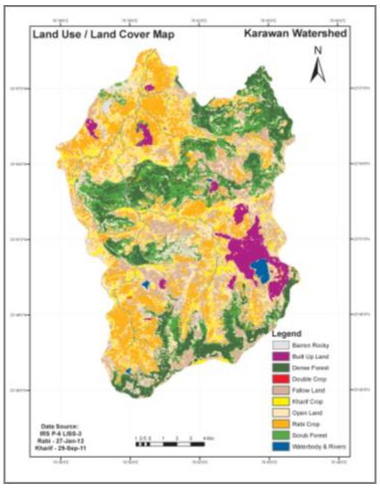


**Figure 9: Land use / land cover map**

**(g) Drainage density**: Drainage density is defined as the length of drainage per unit area. A high drainage density reflects a highly dissected drainage basin with a fast hydro-logic response to the rainfall, whereas a low drainage density indicates the poorly drained basin with a slow hydrologic response to the rainfall (Melton, 1957). The drainage density classes have been assigned the values between 0.14 to 0.88.

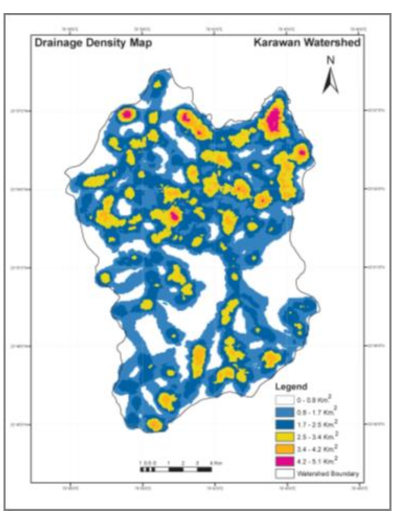


**Figure 10: Drainage density map**

**4.2 Fuzzy overlay function on thematic layers**

The different classes of the thematic layers have been classified and suitable fuzzy membership function value have been assigned as an attribute. Using the weight attribute the weight map of each layer is generated. The weighted thematic layers have been overlaid by using the fuzzy overlay function 'FUZZY GAMMA' as shown below, to yield the desired groundwater potential zone map.

$$\mu \text{ combination} = (\text{Fuzzy Algebraic Sum})^{\gamma} * (\text{Fuzzy Algebraic Product})^{(1-\gamma)}$$

This is the specific function used by fuzzy Gamma is

Fuzzy Gamma Value = pow(1 - ((1 - arg1) * (1 - arg2) * ...), Gamma) * pow(arg1 * arg2 * ..., 1 - Gamma)

Using overlay function an integrated layer with combined fuzzy membership values has been obtained. The gamma value 0.89 has been used which has closest resemblance to the ground truth. The delineation of groundwater potential zones has been made by grouping the combined fuzzy membership values of the integrated layer for obtaining five categories, viz. very good, good, moderate, poor and very poor. The final ground water potential map is shown in figure 11.

The grouped fuzzy membership values used for delineation of groundwater potential zone classes and their areas have been compiled in table 2.

The very good class ranges from 0.64 – 0.96 while the area covered by this category is 53.21 km$^2$. The range of very good zone should be above to the gamma value (0.89) and close to the value of maximum membership value. The good category ranges from the 0.51 – 0.63 and the area covered under this category is 44.31 km$^2$. The weight value for the moderate category is the 0.43 – 0.50 and the area covered by this category is 66 km$^2$.

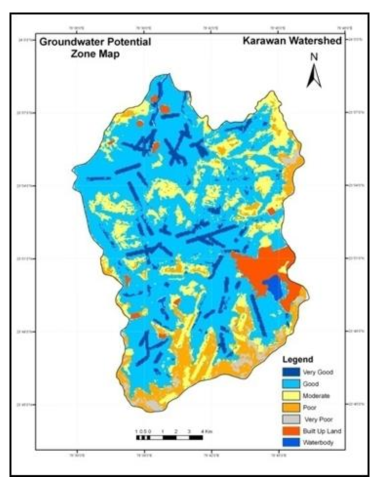


**Figure 11: Groundwater potential zone map**

The poor category varies from 0.35 – 0.42 and the area under this category is 62.67 km$^2$. The last category zone for the groundwater potential map is the very poor zone and has the fuzzy number extremely low i.e., between 0.20 – 0.34 and the area under this category is 18.41 km$^2$.

**Table 2: Ground water prospect zone with area**

| S. No. | Zone | Fuzzy Number | Area (km$^2$) |
|---|---|---|---|
| 1 | Very Good | 0.64 – 0.96 | 53.21 |
| 2 | Good | 0.51 – 0.63 | 44.31 |
| 3 | Moderate | 0.43 – 0.50 | 66 |
| 4 | Poor | 0.35 – 0.42 | 62.67 |
| 5 | Very Poor | 0.20 – 0.34 | 18.41 |
| 6 | Other (Null, Built-up, Waterbody) | 0 – 0.19 | 31.01 |
| **Total** | | | 275.61 |

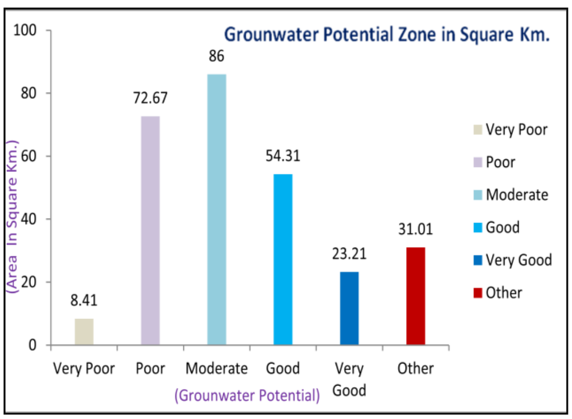


**Figure 12: Area of the groundwater potential zones**

### 4.3 Validation

The groundwater potential zones map generated through above technique has been verified with the depth to water table data to ascertain the validity of results. The verification showed that the groundwater potential zones demarcated through the model are in agreement with the depth to water table data obtained from observed 35 dug wells. Where out of 35 with dug well data collected from the study area 19 are in very good and good zones, 9 on moderate zones, 7 on poor and very poor zones shown in figure 13.

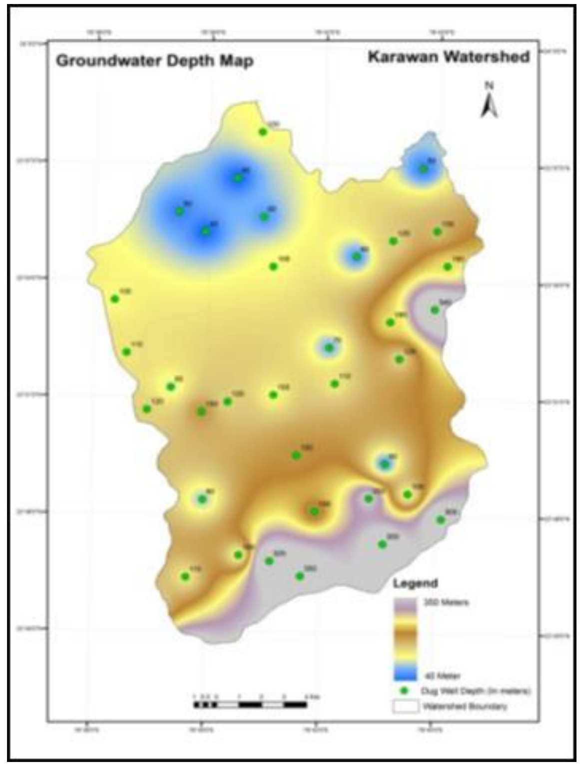


**Figure 13: Distribution of dug well depth**

## 5. Conclusion

A model has been developed to assess the groundwater potential of a Karawan watershed area by integrating seven themes through GIS. The verification of this analysis undoubtedly establishes the efficacy of the GIS integration tool using the fuzzy logic approach in demarcating the potential groundwater zone in hard rock terrain.

This study has shown that large spatial variability of ground water potential. This variability closely followed variability in the structure, geology, geomorphology and land use/cover in the project area. The most promising potential zone in the area is related to volcanic rock of which is affected, by secondary structure and having interconnected pore spaces, with plain geomorphic feature and less drainage density. Most of the zones with poor to very poor groundwater potential lie in the massive basement unit, which is far from lineaments. About 19.3% area has been identified in the very good ground water potential zone of the study area. Since, the present approach has been built with logical conditions and reasoning, this approach can be successfully used elsewhere with appropriate modifications.

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