CHAPTER - 6

GEO-ENVIRONMENTAL PARAMETERS CONTROLLING GROUNDWATER POTENTIAL ZONES

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6.1 Introduction

Groundwater is a highly dynamic and a replenishing resource. The groundwater potential of any region is the cumulative result of interaction between the various geo-environmental parameters (GEPs) viz., geology, geomorphology, slope, drainage density, lineament density, land use and soil. The role of each GEP is broadly highlighted in the paragraphs to follow.

The occurrence and movement of the groundwater is significantly affected by the porosity and permeability of the lithology. In case of Deccan traps, the groundwater availability is of limited extent and is essentially restricted to the weathered horizons, joints and fractures (Saraf & Choudhury, 1998). The other important parameters that govern the groundwater potential are geomorphology, drainage density, lineament density, slope, land use - land cover and soil (Sarkar et al., 2001). The geomorphic features based on their porosity and permeability characteristics may facilitate groundwater recharge and lead to a good groundwater repository. The areas with low drainage densities support more infiltration compared to areas having high drainage densities (Pancholi et al., 2022). The regions with high negative lineament density would support groundwater recharge and hence increase the groundwater potential. The land uses such as water bodies, dense forest, agriculture, scattered forest etc. have varying water infiltration capacity and thus influence the groundwater potential. Slope of the terrain will also have a significant impact on the water infiltration and there by the groundwater potential. Hence, the understanding of interdependency of all the GEPs in toto will be useful to demarcate the groundwater potential zones.

The present chapter deals with the delineation of groundwater potential zones in Khapri watershed by employing multi-criteria decision analysis (MCDA) technique. Analytical Hierarchical Process (AHP) is one of the MCDA techniques originally proposed by Prof. Thomas L. Saaty in (1980), to organize and analyse the multifarious decisions based on mathematics. It is a competent method for organizing perceptions, performing judgements into a multi-level hierarchical format that helps in making appropriate decisions. In this method the inputs for pair wise comparison matrix are

derived based on the subjective opinion of experienced personnel in the respective field (Saaty, 1987). The techniques of remote sensing and GIS are utilized to generate the database of various GEPs and smooth as well as grievance free application of the AHP-MCDA technique.

6.2 Groundwater Potential Zones

Groundwater Potential Zones are perceived differently by various workers around the world. Many assume that groundwater potential zone map gives an idea about the variations in the groundwater storage/yield while, others understand it as an index of groundwater occurrence (Díaz-Alcaide & Martínez-Santos, 2019). The above conceptualization takes into account all the governing parameters and their spatial variation for effective groundwater exploration. Overall, the assessment of groundwater potential primarily focuses on identification and delineation of promising zones for groundwater exploitation. In literal sense, the term "potential" indicates the latent quantity or probable capability of zones for direct exploitation of groundwater or in relevance with geophysical data. In other words, the groundwater potential can be explained as the physical ability of a terrain to yield sufficient groundwater for the definite uses (domestic, agriculture or industrial) (Díaz-Alcaide & Martínez-Santos, 2019).

6.3 Remote sensing and GIS in Groundwater Potential Zone Mapping

The assessment, interdependency and capability of previously mentioned GEPs can be considered to generate the groundwater potential zone map. The collection of field data on the above GEPs and transferring them to a map is typically a time and resource consuming process. Moreover, the conventional exploration techniques may not always effectively surface out the details of GEPs controlling groundwater occurrence and movement (Oh et al., 2011). The remote sensing and GIS techniques are most widely used and accepted as cost and time effective alternative for collection of datasets. Satellite images when combined with reference data and knowledge, results into valuable information on the hydrogeological variables controlling the groundwater occurrences. In other words, the remote sensing datasets may unveil lithological, structural and geomorphological characteristics of the region which are difficult to recognize during conventional field surveys. GIS environment facilitates the comprehensive analysis of multiple GEPs, their interdependency, importance and capability to derive groundwater

potential zones. Thus, remote sensing and GIS promotes systematic and effective mapping of groundwater potential zones. Numerous researchers from the country and abroad have employed the techniques of remote sensing and GIS to map the groundwater potential zones by considering the different geo-environmental parameters. Few significant studies from different time frames have been cited in paragraphs to follow.

Lamoreaux, (1984) stated that remote sensing is an excellent tool for hydrologists as well as geologists to better understand the confounding problems associated with groundwater exploration.

Compaore, (1988) considered that the efficiency of using remote sensing technologies for groundwater exploration is quite relative and its fate depends upon the correct interpretation of number of hydrological indicators or evidences. Shapes, patterns, tones and textures, identified through remote sensing, provide direct or indirect evidence of features of hydrogeological interest.

Teeuw, (1995) performed groundwater exploration programme to target probable sites of fractures zones for follow-up geophysical surveys and borehole drilling using Landsat TM data and cost-effective GIS software (IDRISI) with capabilities for image processing developed at Clarke University, USA. The Remote sensing and GIS targeted locations when compared with pre-existing successful boreholes indicated that more than 55 percent locations were within 200 m of wells. The use of RS-GIS improved the outcomes of earlier conventional groundwater exploration programmes where the success rate only ranged between 13-20 percent.

Panigrahi et al., (1995) prepared thematic maps of groundwater controlling parameters viz., geomorphology, lineaments, drainage, land use and land cover through visual image interpretation and information drawn from SOI topographic maps. The thematic maps were overlain on each other and were supplemented with electrical resistivity sounding data to demarcate the five different groundwater potential zones. The study revealed that mere 12% of the total annual utilisable groundwater is used and concluded that there is further vast reserve of groundwater in the aquifers and number of wells can be set up to augment the resources for different purposes.

Sarkar et al., (2001) successfully employed remote sensing and GIS approach in the assessment of groundwater resources of Shamri micro-watershed in Shimla. The

study emphasizes the controls and use of various geo-environmental parameters viz., drainage, lineament, lithology, slope and land use pattern in assessment of groundwater resource potential. The multi-criteria evaluation (MCE) approach used by authors has generated the groundwater potential zones model for the Shamri micro-watershed. The study accurately exemplifies the integrated approach used for groundwater exploration in hilly terrain.

Srinivasavittala et al., (2005) made an attempt to delineate and characterize the groundwater potential zones of nine sub-watersheds of Pennar river basin, Karnataka using remote sensing and GIS techniques by considering the geo-environmental parameters such as slope, geomorphology, lithology, lineament and bore well data parameters. The thematic maps of all the geo-environmental parameters were integrated using union function in Arc Info GIS software to delineate the groundwater prospect zones. The analysis revealed that remote sensing and GIS have proved as significant tool for integrating various thematic maps and delineate the groundwater prospective zones. The study concluded that the nearly level, very gentle and gentle sloping areas are better compared to steep hilly surfaces with respect to the groundwater potential.

Gupta & Srivastava, (2010) made an attempt to identify the groundwater potential zones in hilly terrain of Pavagarh region, Gujarat by employing integrated approach of remote sensing, GIS and field studies. The thematic maps of geo-environmental parameters viz., lineament density, drainage density, digital elevation model (DEM), slope map and land use/land cover (LULC) were generated to delineate the groundwater potential zones. To assess the suitability of a region for groundwater occurrence, a multi-criteria evaluation technique (MCE) has been used to investigate the number of choice possibilities as per the associated weight of each factor. Ultimately, map is obtained which showcase the different categories of groundwater potential zones in the study area.

Shekhar & Pandey, (2015), employed RS, GIS and Analytical Hierarchy Process (AHP) to identify the groundwater potential zones in Palamu district, Jharkhand, India. The authors highlighted the influence of various earth surface features such as geology, geomorphology, soil types, land use and land cover, drainage, lineament on aquifer characteristics and groundwater resources. Also, the authors emphasized that the satellite data provides a quick and meaningful baseline information regarding various geo-

environmental parameters controlling the groundwater occurrences. The use of remote sensing techniques offers advantages of better observation, systematic analysis, synoptic view, multispectral repetitive coverage and cost as well as time effectiveness.

Das et al., (2017), made an attempt to delineate groundwater potential zones in Hingoli district, Maharashtra, India. The authors utilized remote sensing techniques and conventional datasets from various sources and analysed in GIS software to generate thematic maps of varied geo-environmental parameters affecting groundwater potential. The authors integrated various layers in GIS and evaluated them by applying the multi influence factor (MIF) method to determine the groundwater potential zones. The authors found that the method has remained successful in providing satisfactory results related to groundwater potential of the Hingoli region.

Das, 2019, carried out demarcation of groundwater potential zones in Vaitarna basin, Maharashtra using three approaches viz., influencing factor, frequency ratio and analytical hierarchy process in GIS environment. The nine geo-environmental parameters affecting groundwater potential were considered in the study and the thematic maps were generated and integrated in GIS software to determine the groundwater potential zones. Groundwater levels of 302 wells were used by author to validate results generated by above three approaches using area under curve (AUC) analysis. The author reported 75% AUC for frequency ratio, 71 % for influencing factor and 70 for AHP. The author concluded that all the three methods are having good performance as concerns the generation of groundwater potential model for any region.

6.4 Methodology

The thematic maps of various geo-environmental parameters (GEPs) generated and discussed in foregoing chapters are analysed through Multi Criteria Decision Analysis (MCDA) - Analytical Hierarchical Process – (AHP) approach to identify the groundwater potential zones in Khapri watershed (figure 6.1).

For determining the groundwater potential zones, the thematic maps are converted to raster format with the common geographic (WGS 1984) and projected coordinate system (UTM_WGS 1984_Zone 43). To synthesize the thematic layers, the sub-classes of each thematic layer is reclassified to a common preference scale from 1 to 5 using reclassify tool in Arc GIS 10.4, where 1 being the least favourable while 5

represent most favourable. The assigned preference indicates the importance of the sub-class in each thematic layer. For example, in case of slope layer, the areas with flat to gentle slope (0-3°) favours more infiltration and is assigned value of 5 compared to regions with moderate to steep slope (18-35°) with value of 1. The reclassified thematic layers of GEPs are superimposed on each other using weighted overlay analysis tool in Arc GIS 10.4. The weightages calculated as per the AHP method are assigned to each raster layer in the tool. The details of deriving weightages using AHP method is discussed in section 6.5. Ultimately, the weighted overlay analysis for each raster layers is carried out to generate the groundwater potential zone map.
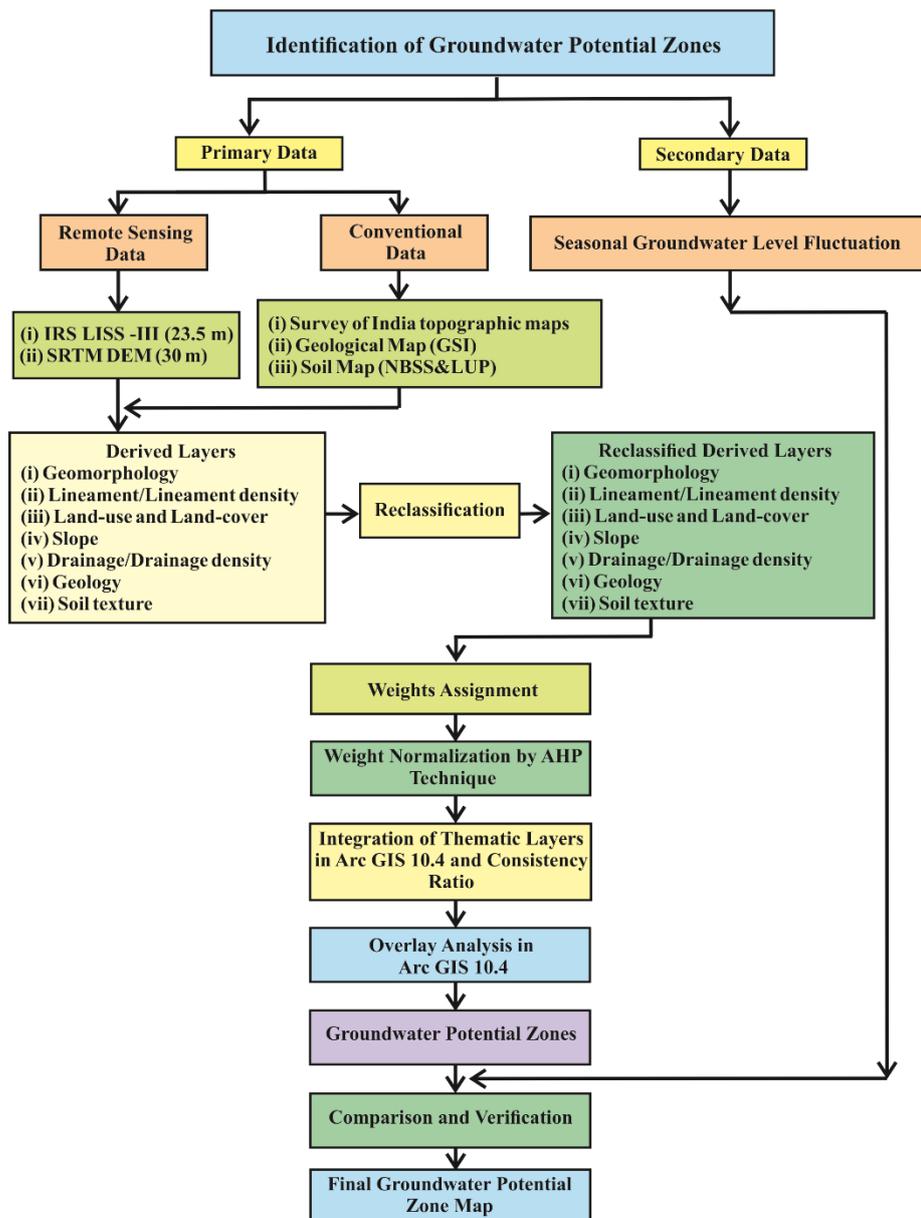

Figure 6.1 Schematic diagram of the methodology for identification of Groundwater Potential Zones.

6.5 Analytical Hierarchical Process (AHP)

Analytical Hierarchical Process (AHP) proposed by Saaty, (1987) helps decision-makers to solve the complicated environmental issues. This method simplifies the intricacy of multi-parametric problem to a single hierarchical structure, with judgements regarding the relative importance on the basis of pair wise comparison of multiple parameters and its sub-classes (Saaty, 1987). To identify groundwater potential zones, it is necessary to assign weightages to individual geo-environmental parameters (GEPs) as per its influence on groundwater potential. The methodology to derive weightages of various parameters and its sub-classes includes building a hierarchy, pair wise comparison matrix (PCM) and finally estimation of consistency ratio (CR) is as given below (Kannan, 2018).

In the present study, the goal is to demarcate the groundwater potential zones in the Khapri watershed. To achieve this goal seven GEPs controlling groundwater potential have been identified and are arranged in a hierarchy.

Saaty, (1987) proposed a pair wise comparison method to derive the weightages of parameters influencing the goal. In this method, the decision maker has to communicate expert opinion regarding the value of individual parameters in a single pair of the matrix. To communicate the expert opinions of the decision makers certain scale is used ((Kannan, 2018), Eastman et al. 1995). The scale indicates the relative importance or dominance of one parameter over the other (Saaty 1980, Zhang et al., 2009). The scale (1-9) used in the present study sets the relative preferences between any two GEPs as shown in the table 6.1.

Table 6.1 Saaty's fundamental scale (After Saaty, 1980).

Intensity of importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgement slightly favour one element over another
5	Strong importance	Experience and judgement slightly favour one element over another
7	Very strong importance	One element is favoured very strongly over another, its dominance is demonstrated in practice
9	Extreme importance	The evidence favouring one element over another is of the highest possible order of affirmation
2,4,6,8		These values are used to express the intermediate values

To build a pair wise comparison matrix (PCM) for the present goal, the seven GEPs viz. geology, geomorphology, drainage, slope, lineament, land use/land cover and soil have been considered. These GEPs are structured in 7 by 7 sized square matrix in such a way that parameter listed in the first left column are one by one equated with parameter listed in the top most row of the matrix. Based on literature survey, detailed parametric assessments and ground truth verification, the relative importance to each parameter is assigned ranging from 1 to 9 as per the Saaty's scale (1987). These scores are assigned as inputs in specified matrix cells. In other words, if the judgement suggests that geomorphology possess strong importance than geology, the score of 5 is assigned in the matrix cell present at the intersection of the geomorphology (row) and geology (column). Likewise, considering the judgement from fieldwork and existing knowledge, the scores for all the GEP's are assigned in each matrix cell and a PCM is obtained. From the obtained PCM, the normalized weightages (Eigen vector) for each parameter are computed. To compute the normalized weights, each value in column cell is divided by the summation value of the same column, resulting into matrix, known as normalized PCM. The sum of individual columns of derived normalized PCM will be equal to 1. Individual row of the normalized PCM indicates the normalized values for each parameter and their summation divided by total number of parameters results into mean value. These mean values obtained for individual rows of normalized PCM are considered as the relative weightages for the corresponding GEPs. The PCM and normalized PCM for the present study is given in table 6.2 and 6.3 respectively. The whole exercise of generating PCM and normalized PCM, is also carried out for the sub-classes of the individual GEPs, to ensure throughout consistency in assigning the scores.

Calculation of the consistency ratio (CR) is the ultimate and crucial stage of AHP method which indicates the consistency of the judgement based scores. It is the ratio of consistency index (CI) and random index (RI) (Equation 6.1).

$$CR = CI/RI \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6.1)$$

The consistency index (CI) measures the deviation in consistency and is determined by the equation 6.2. The random index (RI) is the function of parameters under consideration and is given by Saaty, 1987 (table 6.4).

$$\text{Consistency index (CI)} = (\lambda_{max}-n)/(n-1) \ldots\ldots\ldots\ldots\ldots (6.2)$$

To compute λ_{max}, the different values in the first column of the original PCM is multiplied with the normalized weight (0.26) of a first GEP i.e. geomorphology. Similarly, the different values in the second column of original PCM is multiplied with the normalized weight (0.17) of second parameter i.e. slope and so on. The summation of the values derived for the first row from above process is divided by the normalized weight of first GEP to obtain consistency measures (Kannan, 2018). The λ_{max} is then obtained by averaging the values of consistency measures. In case of a consistent matrix, the value of λ_{max} is more or less similar to the number of parameters under consideration. For the present study, the value of λ_{max} is 7.6 and the CI is 0.117.

$$CI = (\lambda_{max} - n)/(n-1)$$
$$CI = (7.6 - 7) / (7-1) = 0.6/6$$
$$CI = 0.117$$

Finally, the calculation of consistency ratio (CR) is carried out to ensure the accuracy of the original PCM.

$$CR = CI / RI = 0.117/1.32$$
$$CR = 0.08$$

The consistency ratio (CR) obtained for the present investigation is 0.08. As per Saaty, 1987, CR < 0.1 is acceptable and suggests that the judgements are consistent and does not need any re-examination.

Table 6.2 Pair wise comparison matrix of geo-environmental parameters.

Parameters	Geomorphology	Slope	Lineament density	Drainage density	LULC	Soil	Geology
Geomorphology	1.00	3.00	0.33	3.00	7.00	5.00	6.00
Slope	0.33	1.00	0.50	3.00	3.00	3.00	7.00
Lineament density	3.00	2.00	1.00	1.00	3.00	7.00	9.00
Drainage density	0.33	0.33	0.50	1.00	5.00	3.00	3.00
Land use and land cover (LULC)	0.14	0.33	0.33	0.25	1.00	1.00	3.00
Soil	0.20	0.33	0.14	0.33	1.00	1.00	0.50
Geology	0.17	0.14	0.11	0.33	0.33	2.00	1.00
Sum	5.18	7.14	2.92	8.92	20.33	22.00	29.50

Table 6.3 Normalized pair wise comparison matrix of geo-environmental parameters.

Parameter	Geomorphology	Slope	Lineament density	Drainage density	LULC	Soil	Geology	Normalized vector/Relative weightage
Geomorphology	0.193	0.420	0.114	0.303	0.362	0.227	0.203	0.260
Slope	0.064	0.140	0.171	0.303	0.155	0.136	0.237	0.172
Lineament density	0.580	0.280	0.342	0.101	0.155	0.318	0.305	0.297
Drainage density	0.064	0.047	0.171	0.101	0.259	0.136	0.102	0.126
Land use and land cover (LULC)	0.028	0.047	0.114	0.025	0.052	0.045	0.102	0.059
Soil	0.039	0.047	0.049	0.034	0.052	0.045	0.017	0.040
Geology	0.032	0.020	0.038	0.034	0.017	0.091	0.034	0.038

Table 6.4 Saaty's random inconsistency indices for n = 10 parameters.

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.46	1.49

6.6 Geo-Environmental Parameters (GEPs) controlling groundwater potential

To determine the groundwater potential zones in the Khapri watershed seven GEPs viz. geology, geomorphology, drainage, slope, lineament, land use/land cover and soil are identified. The influence of GEPs and their sub-classes are discussed in following sub-sections.

6.6.1. Geology

The geological setup and hydraulic characteristics of rock types strongly govern the occurrence, distribution and movement of groundwater reflecting its recharge and potential. Geologically the Khapri watershed is completely underlined by Deccan basalts of Cretaceous-Eocene age. These Deccan basalts are unconformably overlain by weathered profile, in-situ residual soil, thin veneer of recent alluvium and alluvio-colluvial sediments of Quaternary age. These recent deposits consist of gravel, sand, silt and clay sized particles, which occur in discontinuous patches along the river sections and significantly found at the confluence of river Khapri with Ambica. Amongst the eleven basaltic flows identified in the Dangs district, the Khapri watershed possesses nine basaltic flows (GSI, 2005) (figure 2.2). These flows are intruded by east northeast – west southwest, west northwest-east southeast, northwest-southeast and northeast-southwest trending dykes and are transacted by numerous regional joints and fractures dominantly trending in north northeast-south southwest (figure 2.10). The geological succession of the Khapri watershed is referred in table 2.3. Depending upon the inherent hydrogeological characteristics, presence of weathered thickness and fracture framework, suitability ranks for groundwater potential zones are assigned to the different basaltic flows of the Khapri watershed (figure 6.2, table 6.5).

Table 6.5 Assigned ranks to lithology/flows of the Khapri watershed.

Lithology/flows	Hydraulic characteristics	Groundwater Potential	Rank
Alluvium	Porous and Permeable	Very good	5
Flow-X Mega phenocrysts basalt	--	Poor	2
Flow-IX Massive fine-grained basalt and Amygdular basalt	$S = 0.08\text{-}0.1$ $T=6\text{-}15m^2/day$	Moderate	3
Flow-VIII Porphyritic basalt	--	Moderate	3
Flow-VII Honey yellow coloured basalt, fine grained basalt with rib and furrow structure, vesicular basalt with blebs of green glass	$S = 0.08\text{-}0.1$ $T=6\text{-}15m^2/day$	Good	4
Flow-VI Mega phenocryst basalt	--	Poor	2
Flow-V Honey yellow coloured basalt and fine-grained basalt with spotted appearance	$S = 0.08\text{-}0.1$ $T=6\text{-}15m^2/day$	Very poor	1
Flow-IV Glomeroporphyritic basalt	--	Moderate	3
Flow-III Massive fine-grained basalt and amygdular basalt	$S = 0.08\text{-}0.1$ $T=6\text{-}15m^2/day$	Poor	2
Flow-II Porphyritic basalt	--	Moderate	3
S = Storativity and T= Transmissivity (After Deolankar, 1980)			

6.6.2. Geomorphology

Geomorphology facilitates the characterization and analysis of environmental conditions responsible for water circulation vis-a-vis groundwater occurrence and potential (Verstappen 1983). The Khapri watershed is characterized by unique assemblages of nine landforms from south-east to north-west directions viz., escarpments, highly dissected plateaus, moderately dissected plateaus, low dissected plateaus, planation surfaces, pediments, pediplains, alluvial plains and valley fill deposits (figure 4.2). Each of this landform has varying capacity of runoff-infiltration and thereby groundwater occurrence-distribution and act as good indicators of groundwater potential (Dongare & Deota, 2023). Among different geomorphic features, the moderately

dissected plateau occupies the major part of the watershed (201.36 km^2), while the alluvial plain occupies very small area of 2 km^2. Depending upon the hydrological influence the ranks are assigned to each geomorphic feature (figure 6.3, table 6.6).
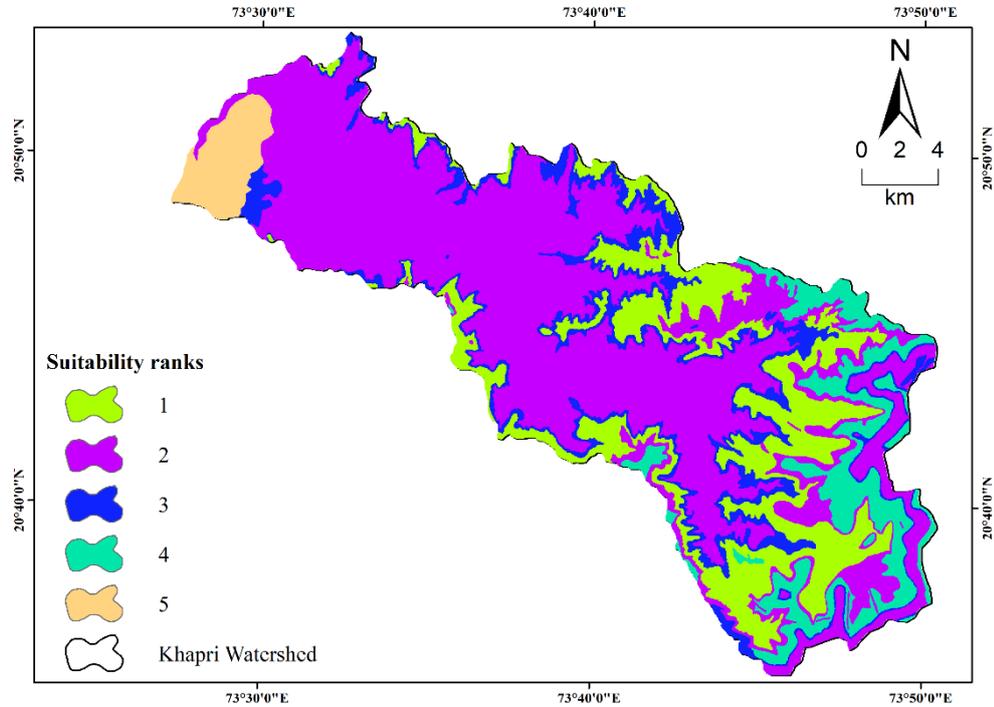

Figure 6.2 Reclassified geological map of the Khapri watershed based on suitability ranks.
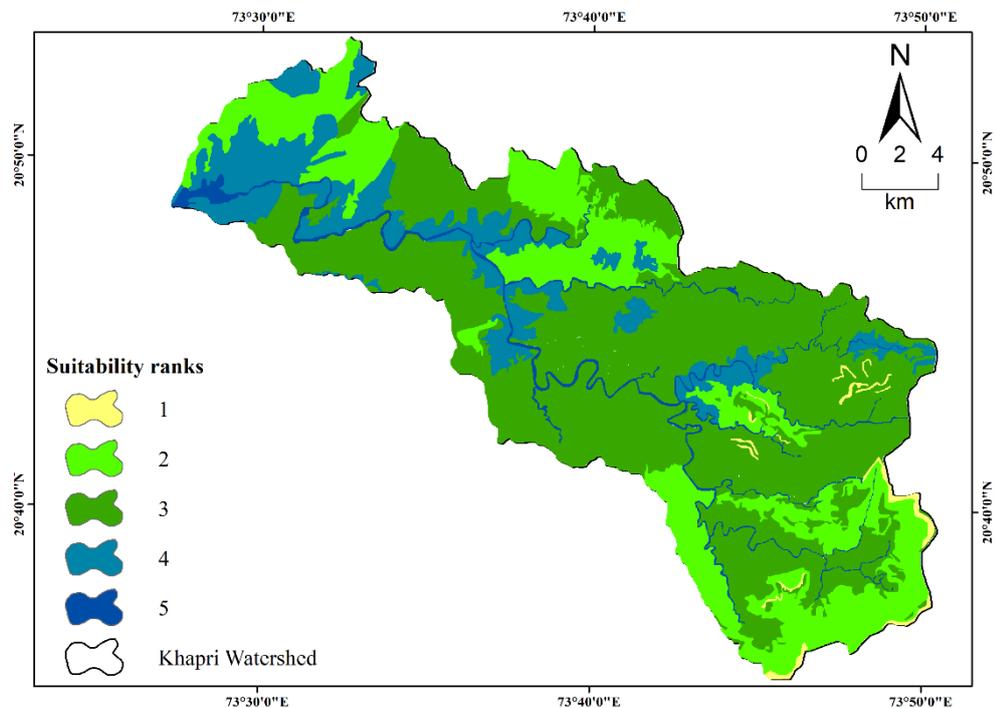

Figure 6.3 Reclassified geomorphology map of the Khapri watershed based on suitability ranks.

Table 6.6 Ranks assigned to geomorphic features of the Khapri watershed.

Landform	Description	Groundwater potential	Rank
Escarpment	Near vertical or almost vertically sloping faces formed on account of erosion or faulting	Very poor	1
Planation surfaces	Widespread and nearly level topographic surface having low slope gradient	Poor	3
Highly dissected plateau	Rugged terrain with development of serrated margins, mesa and butte hills, deep valleys and steep slopes	Poor	2
Moderately dissected plateau	Characterized by moderate drainage densities, relatively shallow valleys separated by moderate slopes and less rugged topography compared to HDP.	Moderate	3
Low dissected plateau	Characterized by moderate to low drainage densities, coarse drainage texture, gentle slopes, uniform topography and flat-topped ridges followed by shallow valleys.	Moderate	3
Pediment	gentle to moderately sloping surfaces developed at the base of steep uplands	Good	4
Pediplain	gently sloping undulating surfaces with large aerial extent formed because of continuous process of weathering and coalescence of pediments	Good	4
Valley fills	loose unconsolidated sediments deposited at the base of valley slopes under the action of gravity	Very good	5
Alluvial plain	gently sloping depositional surfaces, formed by river and consist of unconsolidated sediments characterized by high primary porosity and permeability.	Very good	5

6.6.3. Drainage density

Measure of channel lengths of all streams per unit area of drainage basin is defined as drainage density (D_d) (Horton 1945, Strahler 1957). It indicates the equipoise between the erosive potential of overland flow and transmissible nature of the surface soils and rocks (Dongare et al. 2022). Drainage density is directly related to the measure of stream lengths and governs the duration of concentration and magnitude of discharge. Low drainage density tends to reduce the flooding levels in the watershed; reflecting the permeable nature of underlying rocks that support infiltration and groundwater enrichment (Hajam et al. 2013; Horton, 1945; Selvan et al. 2011). The high drainage density value of Khapri watershed (3.07 km/km^2) is attributed to less transmissible nature of underlying rocks, hilly topography and steep slopes, leading to less infiltration and increased flood potential. In other words, the drainage density shows an inverse relation to infiltration. The drainage density of Khapri watershed ranges between 0.02 and 6.34 km/km^2, which is classified into 4 classes viz. very low (<1 km/km^2), low (1-2 km/km^2), moderate (2-3 km/km^2) and high (>3 km/km^2) (figure 3.3). Considering the influence of the drainage density on runoff-infiltration potential, the ranks are assigned to each class to assess the groundwater potential (figure 6.4, table 6.7).

Table 6.7 Ranks assigned to drainage density of the Khapri watershed.

Drainage density (km/km^2)	Category	Groundwater Potential	Rank
<1	Very low	Very good	5
1-2	Low	Good	4
2-3	Moderate	Moderate	3
>3	High	Very poor	1

6.6.4. Lineament

Lineaments are the discontinuous linear features on earth's surface, formed on account of natural processes. It includes faults, fractures, joints, dykes, ridge crests, bedding planes, foliation, streams, boundaries of litho-contacts between stratigraphic formations and volcanic flows ((Dasgupta & Mukherjee, 2019). The lineament density is one of the most significant geo-environmental inputs for mapping the groundwater potential zones. In general, the areas with high lineament density shows presence of prominent zones of localized weathering that give rise to secondary porosity and permeability and thus forming a good groundwater repository (Deota et al. 2005). To

assess the groundwater potential for Khapri watershed, the negative lineament density is considered (figure 2.13). The negative lineament density varies from 0.1 to 8.8 km/km^2 and is directly related to infiltration. It is classified into 5 categories viz., Very low (0.1 – 0.76 km/km^2), Low (0.77 – 1.73 km/km^2), Moderate (1.74 – 3.1 km/km^2), High (3.11 – 5.1 km/km^2) and Very high (5.11 – 8.81 km/km^2). The highest negative lineament density in upper reaches is observed near villages Sinbandh, Galkund, Pipalpada, and Isdar while, in the central part it is observed to the south of village Khapri. In lower reaches it is observed near villages Ghodi, Dhodhalpada, Kusmal, Koylipada and Raygadh. The ranks assigned to the categories of negative lineament density are shown in figure 6.5 and table 6.8.
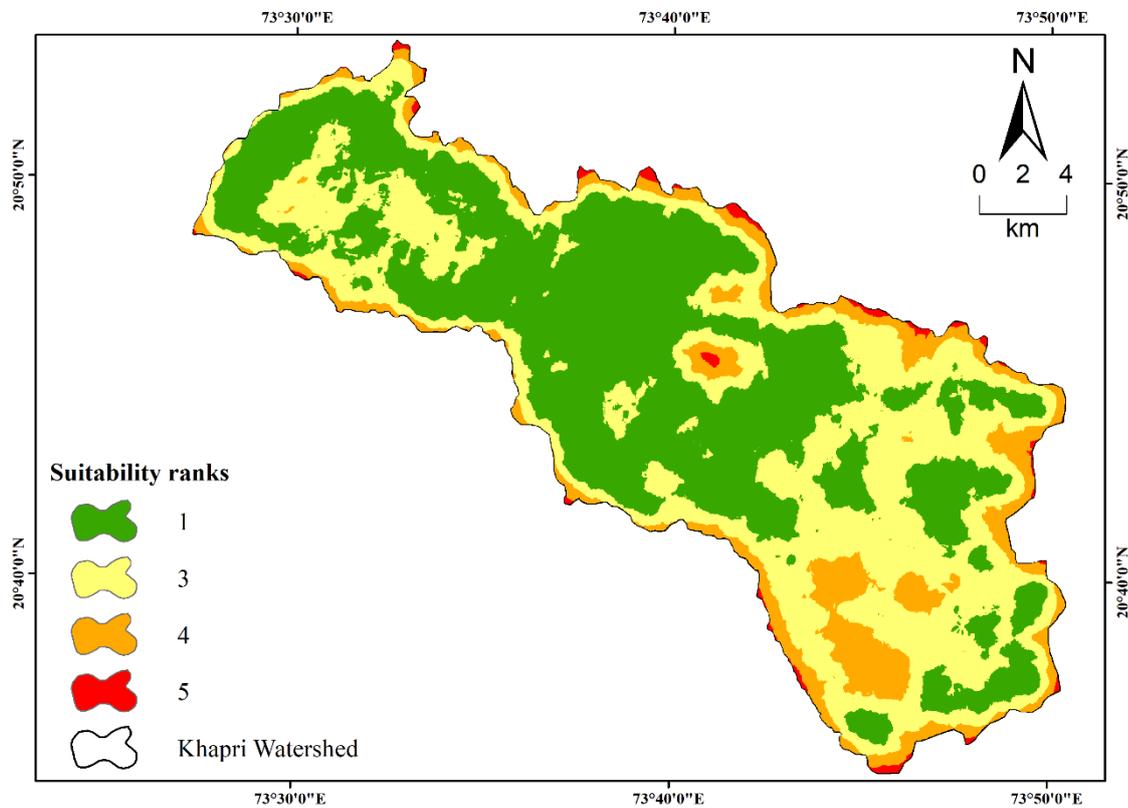

Figure 6.4 Reclassified drainage density map of the Khapri watershed based on suitability ranks.

Table 6.8 Ranks assigned to lineament density of the Khapri watershed.

Lineament density km/km^2	Category	Groundwater potential	Rank
0 – 0.76	Very low	Very poor	1
0.77 – 1.73	Low	Poor	2
1.74 – 3.1	Moderate	Moderate	3

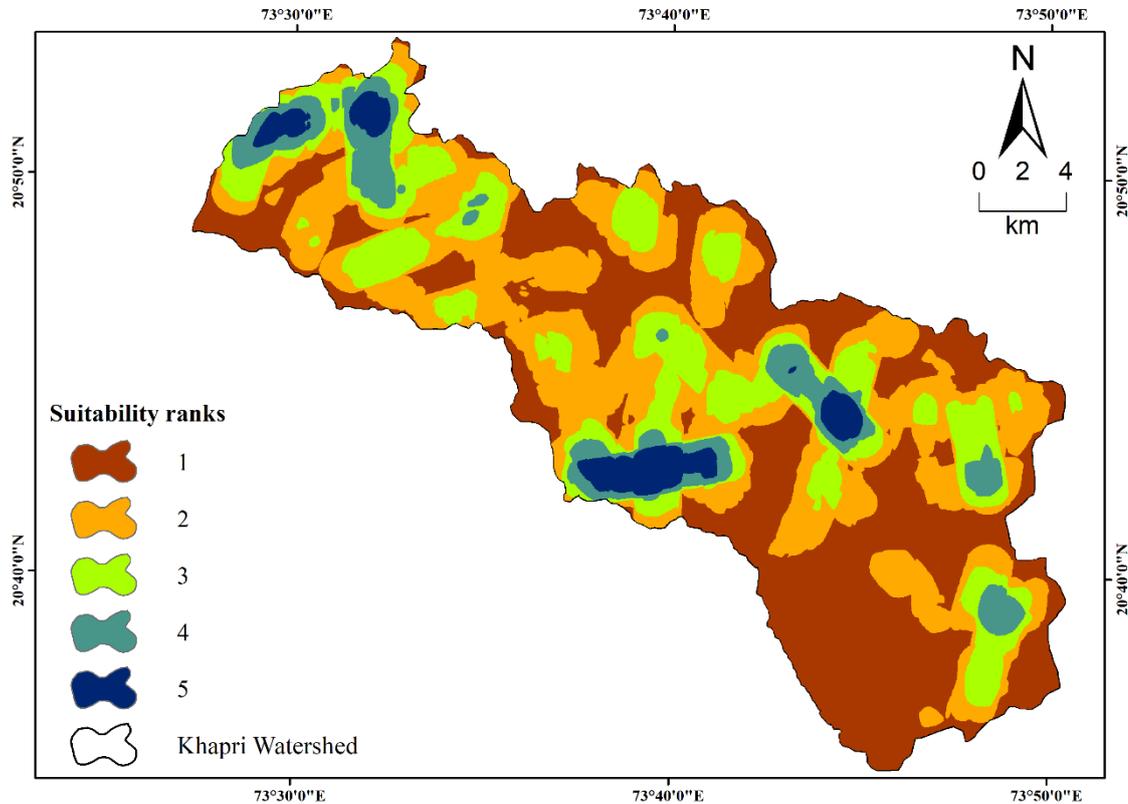| 3.11 – 5.1	High	Good	4
5.11 – 8.81	Very high	Very good	5

Figure 6.5 Reclassified negative lineament density map of the Khapri watershed based on suitability ranks.

6.6.5. Slope

Slope is one of the significant geomorphic indicators that remarkably governs runoff and infiltration capacity of the watershed (Nassif and Wilson, 1975, Deota and Desai, 1995). The gentle slopes allow water to remain in contact with the surface for longer duration and increase the probability of infiltration as compared to the moderate and steep slopes. However, the effect of slope may enhance or diminish with respect to other GEPs. The slope of Khapri watershed varies from 0° to 67° and classified into seven classes (Dongare et al. 2022 and Dongare and Deota, 2023) viz. flat to very gently sloping (0° - 3°), very gently sloping (3° - 6°), gently sloping (6° - 10°), moderately sloping (10° - 18°), moderately steep sloping (18° - 35°), steeply sloping (35° - 45°) and very steeply sloping (>45°) (figure 4.13). The slope is inversely related to the infiltration of water hence, the areas with flat to gently sloping categories generally possess good to excellent ability of water infiltration and thereby groundwater potential. On the other hand, moderate to steep slopes reduce the infiltration thereby leading to poor

groundwater potential. Accordingly, the ranks are assigned to each slope category of the Khapri watershed (figure 6.6, table 6.9).

Table 6.9 Ranks assigned to slope categories of the Khapri watershed.

Slope category	Category	Groundwater potential	Rank
0-3°	Flat to very gently sloping	Very good	5
3-6°	Very gently sloping	Good	4
6-10°	Gently sloping	Moderate	3
10-18°	Moderately sloping	Poor	2
18-35°	Moderately steep sloping	Poor	2
35-45°	Steeply sloping	Very poor	1
>45°	Very steeply sloping	Very poor	1

6.6.6. Land-use and Land cover

The term land use indicates the utilization of land parcel for different human activities, while the land cover specifies the entities that shelter the land parcel. Definite land uses such as natural vegetation, forest, and barren lands characterizes the infiltration capacity and eventually influence the groundwater potential (Valdiya, 2013). Thus, it is important to link the land-use and groundwater potential. The land use and land cover of Khapri watershed has been classified into seven classes viz. dense forest, scattered forest, agriculture, mixed built-up, built-up land and barren land (figure 6.10). Among the different land uses, the dense forest occupies the highest aerial coverage (51.08%), followed by agriculture (36.11%), scattered forest (5.12%), water bodies (4.76%), mixed built-up (1.67%), barren lands (0.88%) and built-up land occupies the lowest aerial coverage (0.38%) (figure 6.7). Depending upon the infiltration capacity and aerial coverage of the land-use parcels appropriate ranks have been assigned (figure 6.7, table 6.10).
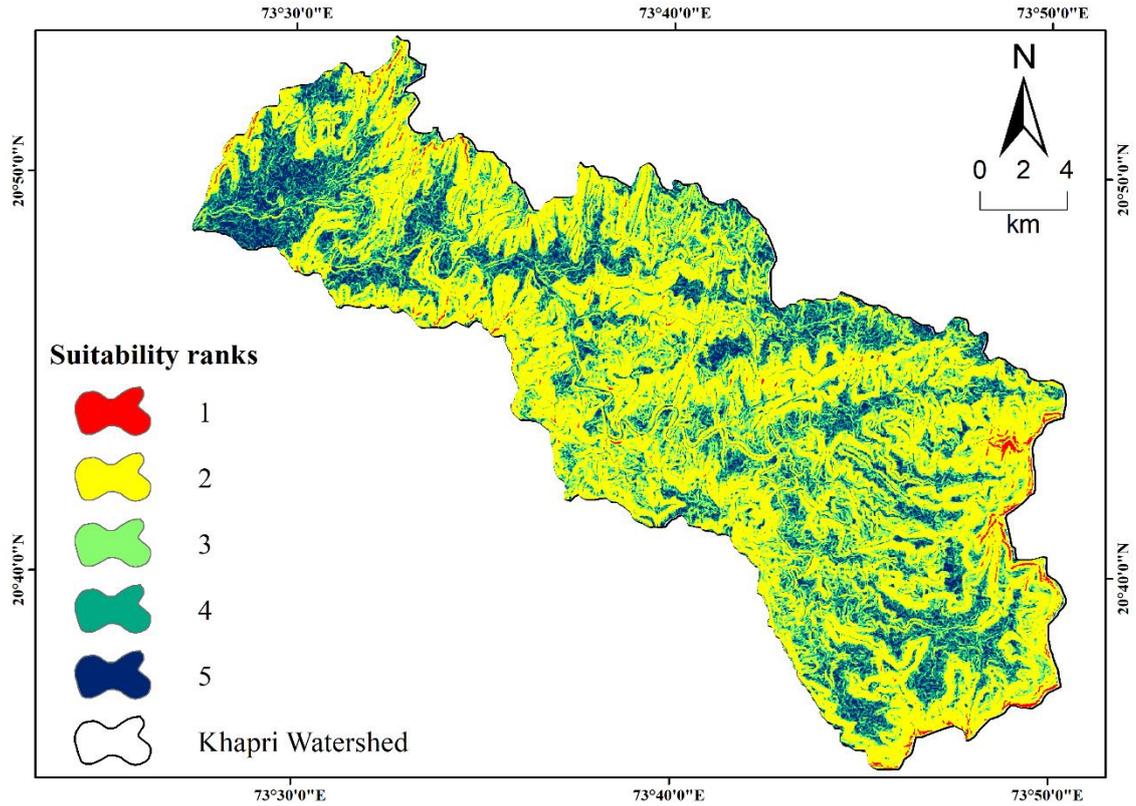
Figure 6.6 Reclassified slope map of the Khapri watershed based on suitability ranks.

Table 6.10 Ranks assigned to Land-use/Land cover categories of the Khapri watershed.

Land use	Infiltration capacity	Aerial Coverage (%)	Rank
Water body	Very good	4.76	5
Dense forest	Good	51.08	4
Scattered forest	Poor	5.12	2
Agriculture	Moderate	36.11	3
Mixed Built-up	Poor	1.67	2
Built-up	Very poor	0.38	1
Barren land	Very Poor	0.88	1

Suitability ranks

1
2
3
4
5
Khapri Watershed

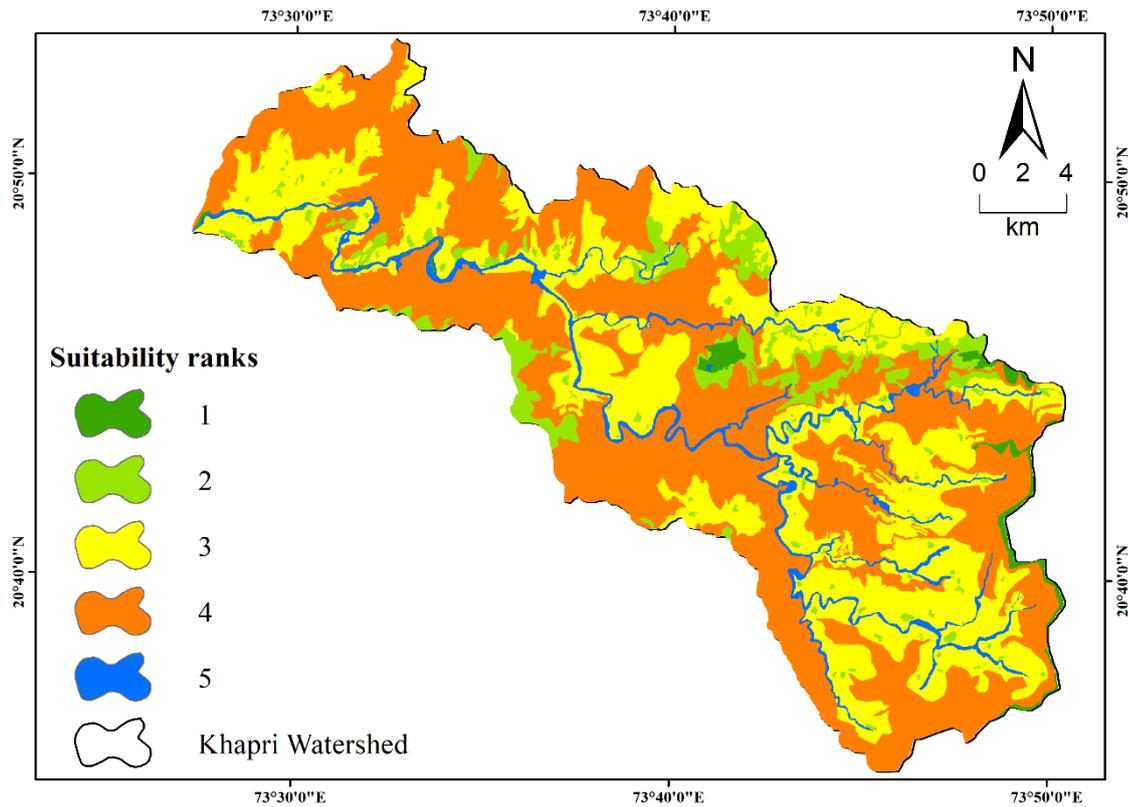*Figure 6.7 Reclassified land use map of the Khapri watershed based on suitability ranks.*

6.6.7. Soil

Soil is defined as natural part of the earth's surface, being characterized by layers parallel to the surface resulting from modification of the parent materials by physical, chemical and biological processes operating under varying conditions during varying period of time (Bushnell, 1944). Texture of soil refers to relative proportion of sand, silt and clay sized particles which constitutes the mineral fraction of the soil. Soil texture reflects the porosity and permeability of the soil and affects the ability of water to infiltrate and recharge the underlying aquifers. Clayey soils, characterized by smaller particles and smaller pore spaces, typically have a low infiltration rate compared to sandy soils, which have large particles and larger pore spaces (Brady and Weil 2008 pp.152-156). This suggests that the water can easily infiltrate in sandy soils, giving rise to faster groundwater recharge. The Khapri watershed is characterized by three soil series viz. 140-Ahwa series, 142-Bedmal series and 144-Vadhvania series (figure 6.8). Among these soil series present in Khapri watershed, the Ahwa series covers the maximum aerial extent (455.7 km^2), while the Bedmal series occupies the minimum area (23.58 km^2) and Vadhvania series occupies area of 43.45 km^2 of the watershed. The soil

of Ahwa series is very shallow and hardly reaches the depth of 0-90 cm (Sharma et al. 2006). The soil is excessively drained and is not able to hold the moisture. Mostly these soils are found on gently to moderately sloping surfaces and shows severe erosion characteristics. In comparison to Ahwa series, the Bedmal series is very shallow and reach only up to the depth of 0-50 cm (Sharma et al. 2006). The soil is excessively drained and possesses loamy skeletal texture on account of which it is not able to hold the water. This soil series occupies a small portion of the watershed in the upper reaches on steep slopes near Saputara. The soil of Vadhvania series also shows characteristics similar to Ahwa series and occupies a small area around villages Amsarpada and Mahal. Depending upon the porosity and permeability appropriate ranks are assigned to the sub-classes of the soil layer (figure 6.8, table 6.11).

Table 6.11 Ranks assigned to soil textural classes of the Khapri watershed.

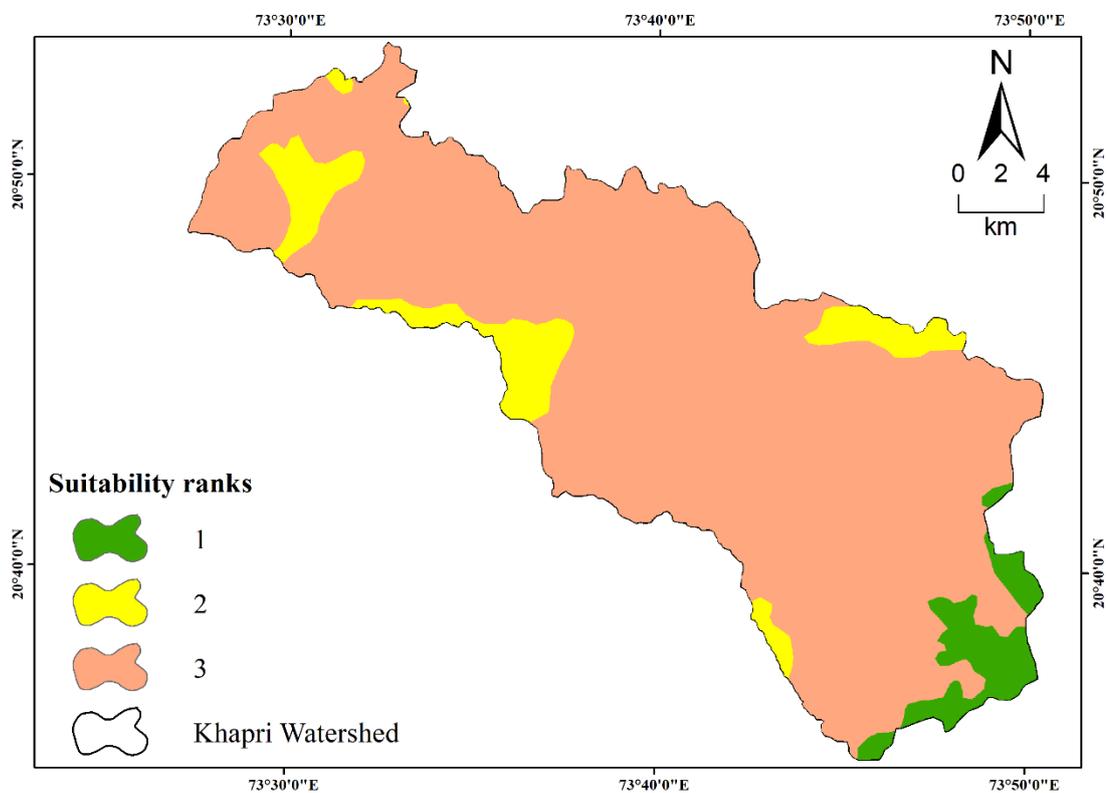| Soil Type	Textural class	Groundwater potential	Rank
144-Vadhvania series (14)	Loamy soil	Poor	2
142-Bedmal series (15)	Loamy skeletal soil	Very poor	1
140-Ahwa series (19)	Loamy soil	Moderate	3

Figure 6.8 Reclassified soil map of the Khapri watershed based on suitability ranks.

6.7 Overlay analysis and Groundwater Potential Zones

Overlay analysis involve two or more thematic maps, where each map can be thought of as a layer containing information on a particular theme such as geology, geomorphology, and slope. All thematic layers prior to overlay analysis are brought to a raster format with common scale, datum and projection system. The various thematic maps are integrated to generate an output map by applying either logical or arithmetic operations. To generate groundwater potential maps or site suitability maps, generally the arithmetic overlays are preferred. In such overlay analysis, each thematic map is assigned arbitrary weights on the basis of its role towards the ultimate goal. Further, the thematic maps are combined and the output map (suitability or index map) is classified to contain the ultimate meaningful classes of interest.

In the present research, the arithmetic overlay is employed where thematic maps of seven GEPs are overlaid using index overlay analysis to determine the groundwater potential zones in the Khapri watershed. Arithmetic overlay analysis can be used for binary as well as multi-class thematic maps. When overlay analysis is performed in case of the binary thematic maps a single weight factor is assigned whereas, in case of thematic maps with multiple sub-classes, there is a flexible system of assigning arbitrary weightage to each thematic map and its sub-classes. However, in the present investigation instead of arbitrary assignment of weightages, a statistically and arithmetically sound MCDA-AHP technique is employed. The AHP method is used to derive the normalized weightages of thematic maps and its sub-classes using pair wise comparison matrix analysis. The overlay analysis to determine the groundwater potential zones is carried out using AHP derived weightages in Arc GIS 10.4. The advantage of using AHP method, is that it emphasizes the importance of dominantly controlling GEP.

The groundwater potential zone map that resulted from the overlay analysis is classified into five categories viz. Very poor, Poor, Moderate, Good and Very good (figure 6.9) with their aerial coverage in table 6.12. The Moderate category of groundwater potential zone covers the maximum area of the watershed followed by Poor, Good, Very poor and the minimum is occupied by the Very good groundwater potential zones.

The groundwater potential zone map shows distribution of very good groundwater potential zones in upper reaches (near villages Sinband, Ukhatiya, Chavadvel and Rawchond), middle reaches (to the south of village Sunda) and lower

reaches (villages Chichigaontha, Dhodhalpada, Koylipada and Amania). The very good groundwater potential zone is the comprehensive result of parameters like alluvial plain, valley fills, low dissected plateau, high to very high lineament density, gentle slope and land uses such as dense forest or agriculture. The existence of good to moderate groundwater potential zones throughout the watershed reflect the interplay of geomorphic features like pediments and pediplains, moderate lineament density, gentle to moderate slope and agriculture land-use. The poor and very poor categories of groundwater potential zones are characterized by escarpments, highly dissected plateaus, very low lineament density and very steep slopes (> 45°), which are unfavourable for the occurrence of groundwater. The poor category of groundwater potential zones show ubiquitous distribution, while the very poor category is restricted to the south western and central part of the watershed near villages Vanar, Wanki, Chirapada, Gaurya, Bhavandagadh and Mulchond. The critical analysis of the groundwater potential zones of Khapri watershed suggests dominance of geomorphology, lineament density and slope characteristics over the other GEPs.
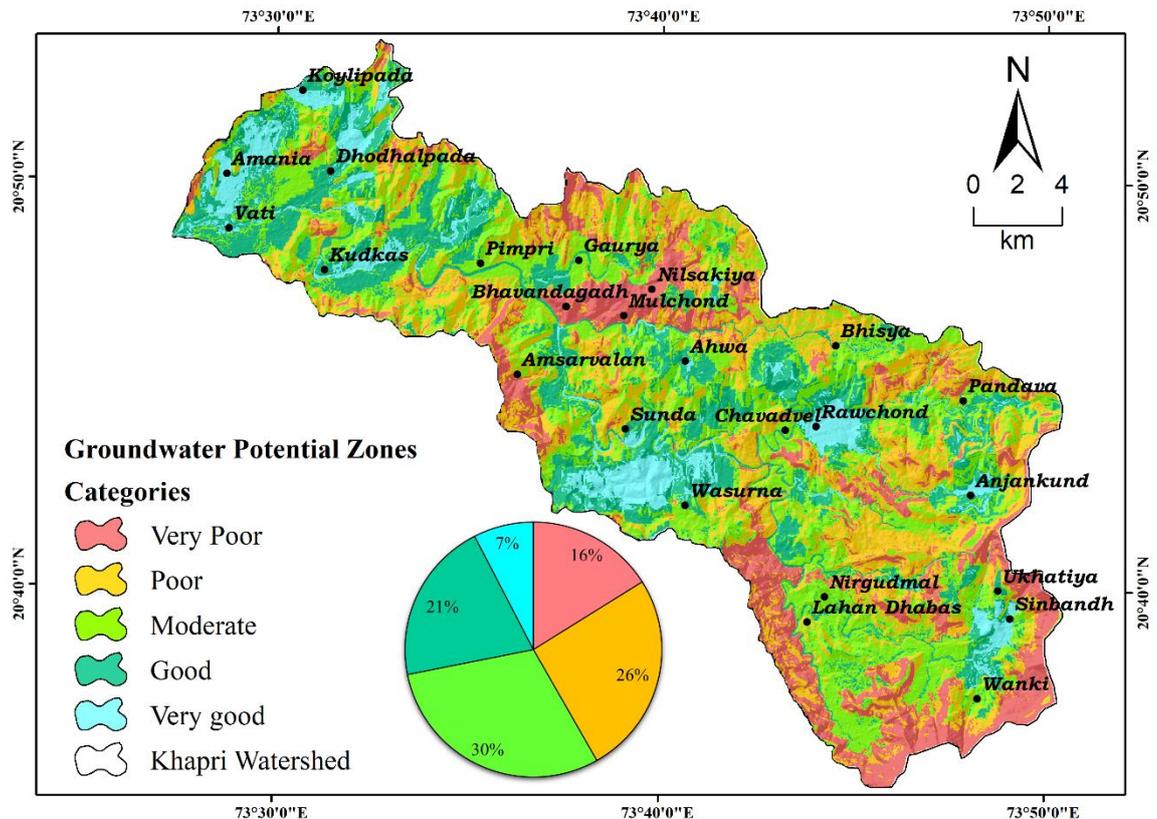

Figure 6.9 Groundwater Potential Zone map of the Khapri watershed. Inset pie diagram shows percent aerial coverage of Groundwater Potential Zones.

Table 6.12 Aerial coverage of Groundwater Potential Zones in the Khapri watershed.

Groundwater Potential Zones	Area (km²)	Aerial Coverage (%)
Very Poor	82.50	16.08
Poor	131.73	25.68
Moderate	154.28	30.08
Good	105.49	20.57
Very Good	38.81	7.56

6.8 Accuracy assessment of Groundwater Potential Zones

The groundwater potential zones in the Khapri watershed are validated with the help of the groundwater depth data recorded during pre- and post-monsoon seasons (Nov-2021, May-2022, Nov-2022 and May-2023) (Annexure I). The groundwater potential zones are correlated with the data of seasonal groundwater fluctuation from 64 dug wells. The low groundwater fluctuation is indicative of good to very good groundwater potential, whereas high groundwater fluctuation suggests moderate to poor groundwater potential (Kumar & Pandey, 2016; Varni et al., 2013, (Dongare & Deota, 2023). The groundwater potential zones and the corresponding groundwater fluctuations are given in table 6.14. The accuracy assessment of groundwater potential zones is carried out through equation 6.3 (table 6.13).

Accuracy assessment = Wells in agreement/ Total wells * 100………. (6.3)

➤ Total number of dug wells (observation wells) = **64**
➤ Number of Dug wells that are in agreement with groundwater potential zone on map and groundwater potential zone obtained through seasonal groundwater fluctuation = **48**
➤ Number of Dug wells that are in disagreement with groundwater potential zone on map and groundwater potential zone obtained through seasonal groundwater fluctuation = **16**

Accuracy assessment = 48/64 * 100 = **75 %**

Table 6.13 Seasonal groundwater fluctuation in 64 dug wells.

Well no.	Well Co-ordinates		Groundwater Fluctuation (m)		Classification as per fluctuation	Expected potential from GWPZ map	Agreement/Disagreement
	Lat.	Long.	21-22	22-23			
1	20.84	73.58	7.3	8.1	Poor	Poor	**Agreement**
2	20.83	73.59	1.3	1.1	Very good	Mod	Disagreement
3	20.80	73.55	2.1	2.4	Good	Good	**Agreement**
4	20.81	73.55	5.5	5.0	Moderate	Mod	**Agreement**
5	20.80	73.58	7.3	1.5	Poor	Good	Disagreement
6	20.79	73.60	5	6.3	Moderate	Moderate	**Agreement**
7	20.76	73.62	3.3	2.3	Good	Good	**Agreement**
8	20.74	73.64	2.2	2.5	Good	Good	**Agreement**
9	20.73	73.64	4.1	2.1	Good	Good	**Agreement**
10	20.74	73.62	3.9	4.4	Good	Good	**Agreement**
11	20.76	73.57	7.9	7.7	Poor	Poor	**Agreement**
12	20.76	73.57	6.3	6.5	Moderate	Moderate	**Agreement**
13	20.75	73.59	9	7.5	Poor	Poor	**Agreement**
14	20.73	73.60	7.6	8	Poor	Poor	**Agreement**
15	20.76	73.60	2.6	12.1	Good	Poor	Disagreement
16	20.78	73.61	5.3	6	Moderate	Moderate	**Agreement**
17	20.80	73.66	6.2	5.3	Moderate	Moderate	**Agreement**

18	20.79	73.64	2.4	2.1	Good	Good	**Agreement**
19	20.7	73.65	3.8	2.7	Good	Good	**Agreement**
20	20.76	73.67	1.6	0.4	Very good	Moderate	Disagreement
21	20.75	73.7	1.8	0.6	Very good	Very good	**Agreement**
22	20.76	73.72	4.1	4	Good	Poor	Disagreement
23	20.76	73.75	10.2	10.3	Very poor	Moderate	Disagreement
24	20.77	73.75	6.5	5.2	Moderate	Moderate	**Agreement**
25	20.75	73.68	2.3	2	Good	Good	**Agreement**
26	20.70	73.72	1.2	1.8	Very good	Very good	**Agreement**
27	20.69	73.71	3	3.8	Good	Good	**Agreement**
28	20.67	73.72	4	3.5	Good	Good	**Agreement**
29	20.67	73.73	8.6	10	Poor	Good	Disagreement
30	20.66	73.73	10.8	1.3	Very poor	Moderate	Disagreement
31	20.67	73.74	14.7	5	Very poor	Moderate	Disagreement
33	20.65	73.77	4	1.3	Good	Poor	Disagreement
34	20.64	73.77	5.5	6	Moderate	Moderate	**Agreement**
35	20.64	73.76	6.7	6.4	Moderate	Moderate	**Agreement**
36	20.63	73.74	2	0.5	Good	Moderate	Disagreement
37	20.61	73.74	6.8	6.1	Moderate	Moderate	**Agreement**
38	20.63	73.80	1.4	0.8	Very good	very good	**Agreement**

39	20.63	73.80	2.5	2.6	Good	Good	**Agreement**
40	20.63	73.81	1.1	0.1	Very good	Very good	**Agreement**
41	20.63	73.81	0.8	1.6	Very good	Very good	**Agreement**
42	20.63	73.782	4	4.7	Good	Good	**Agreement**
43	20.66	73.79	9	7	Poor	Poor	**Agreement**
44	20.69	73.77	2.1	2.6	Good	Moderate	Disagreement
45	20.70	73.77	4	6.9	Good	poor	Disagreement
46	20.69	73.68	6.6	5.2	Moderate	Moderate	**Agreement**
47	20.80	73.53	1.5	1.8	Very good	Very good	**Agreement**
48	20.79	73.52	1.7	0.3	Very good	Very good	**Agreement**
49	20.81	73.52	3.2	2	Good	Poor	Disagreement
50	20.82	73.50	2.5	3.5	Good	Moderate	Disagreement
51	20.83	73.49	4.6	4.8	Good	Good	**Agreement**
52	20.83	73.47	2	2	Good	Good	**Agreement**
53	20.82	73.49	3	2.2	Good	Good	**Agreement**
54	20.81	73.50	3.5	2.1	Good	Good	**Agreement**
55	20.81	73.47	4	3	Good	Good	**Agreement**
56	20.79	73.48	2.1	2.4	Good	Good	**Agreement**
57	20.70	73.80	6.9	5.8	Moderate	very good	Disagreement
58	20.82	73.69	5.8	6	Moderate	Moderate	**Agreement**

59	20.79	73.65	5.2	5.8	Moderate	Moderate	**Agreement**
60	20.80	73.69	6.6	6.8	Moderate	Moderate	**Agreement**
61	20.74	73.80	6.9	5.9	Moderate	Moderate	**Agreement**
62	20.74	73.84	3.5	2.4	Good	Good	**Agreement**
63	20.65	73.79	18.3	17.3	Very poor	Very poor	**Agreement**
64	20.65	73.79	16.5	16.5	Very poor	Very poor	**Agreement**
65	20.66	73.81	1.5	1.8	Very good	Very good	**Agreement**

* No data was collected from well 32 in pre-&post-monsoon 2022 and pre-monsoon 2023.

Table 6.14 Groundwater Potential Zones and corresponding groundwater fluctuation.

Groundwater Potential Zones	Groundwater fluctuation (m)
Very Good	<2
Good	2-5
Moderate	5-7
Poor	7-10
Very poor	>10

6.9 Quantitative validation of AHP through Receiver Operating Characteristic (ROC) curve

Quantitative validation of mathematical or statistical models is the process of comparing the derived results with the actual field data to evaluate dependency or predictive power of the model. Model validation allows us to establish the degree of confidence of the obtained results before transferring it to the final users. Model validation is essential prior to substitution/elimination of parameters or predictor variables and its comparison with other mathematical/statistical models (Beguería, 2006).

In case of determining groundwater potential zones, its development and management variety of datasets related to GEPs are analysed. In the present investigation, the groundwater potential zones of Khapri watershed are validated through correlation of seasonal groundwater fluctuation data. In addition, the quantitative validation of AHP derived groundwater potential zone map is carried out using Receiver Operating Characteristic Curve (ROC) – Area Under Curve (AUC) method.

ROC-AUC is a significant evaluation metric to check and evaluate the performance of the model involving multi-parametric classifications. Often, this is also referred as Area Under the Receiver Operating Characteristic Curve (AUROC). AUROC is a measurement of performance of the classification problems at different threshold settings. ROC is a probability curve, whereas the AUC indicates the extent or index of separation. In other words, it specifies the capability of the model to distinguish between different GEP's and its sub-classes. If the value of AUC is high (1), then the performance of the model is excellent in distinguishing among the different sub-classes and/or parameters. The classification for different AUC values is given in table 6.15. The AUROC curve is generated by plotting the graph of True Positive Rate (TPR) versus False Positive Rate (FPR). These values are derived with the help of confusion matrix. The confusion matrix is a two-dimensional matrix that encapsulates the classification performance of the classifier with respect to specific test data (Sammut and Webb, 2011). The TPR is plotted on y-axis and FPR is plotted on x-axis. To plot the AUROC curve for the present study a python-based ArcGIS toolbox for spatial studies named Arc-SDM (Brown, 2017) is employed. The input data required for the toolbox is true positive rate (field data) which is tested on the AHP derived groundwater potential zone map. The toolbox evaluates the AHP derived groundwater potential zone map at all

thresholds of groundwater fluctuations and provides the final AUROC curve in the form of graph and table. In the present investigation, the AUC value is 0.755 (figure 6.10), indicates the good performance of AHP model.
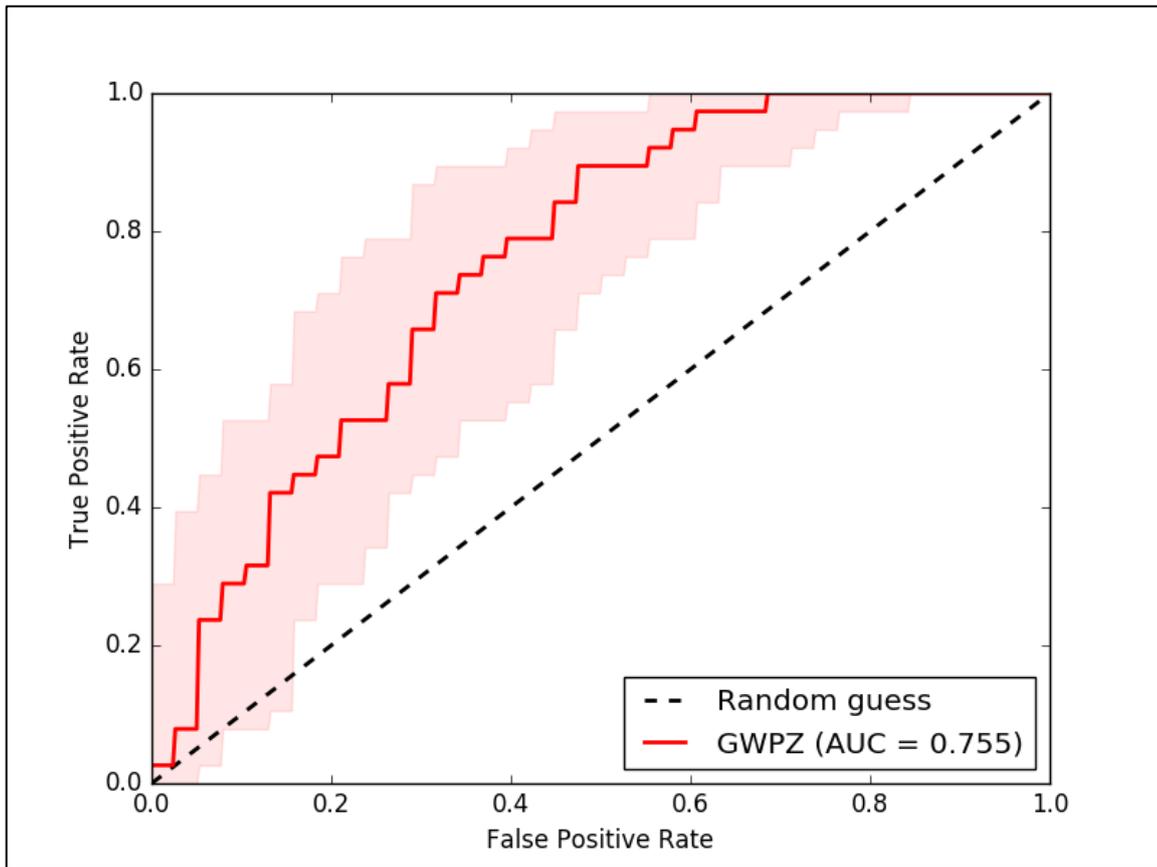

Figure 6.10 Receiver Operating Characteristic (ROC) curve.

Table 6.15 AUC classification (Sammut and Webb, 2011).

AUC	Classification
0.5-0.6	Poor
0.6-0.7	Average
0.7-0.8	Good
0.8-0.9	Very good
0.9-1.0	Excellent

6.10 Epilogue

The overlay analysis in Arc-GIS based on AHP derived weightages has proved to be an effective tool to demarcate the groundwater potential zones of Khapri watershed. The PCM in AHP-MCDA has provided a robust statistical framework to derive weightages of the individual GEPs instead of arbitrary weightage and thereby reduce the

human bias. Based on the AHP, groundwater potential zones in the Khapri watershed are classified into five categories viz. Very good, Good, Moderate, Poor and Very poor. The maximum area (154.28 km^2) of Khapri watershed is occupied by the moderate category of groundwater potential zone, while the category of very good groundwater potential zone covers the minimum area of 38.81 km^2. It is observed that the very good to moderate categories of groundwater potential zones mainly exists in the regions with favourable combinations of GEPs viz., geomorphology, slope and lineament density near villages Sinband, Ukhatiya, Chavadvel, Rawchond, Sunda, Chichigaontha, Dhodhalpada, Koylipada, Amania, Pimpri, Kudkas, Chikar, Gaurya, Borkhal, Moti and Lahan Dabhas, Nirgudmal etc. This fact indicates the dominant control of above GEPs on the groundwater potential zones over the others. The thematic layers of GEPs and the resultant groundwater potential zones are validated by ground truth verification as well as pre-monsoon (2022, 2023) and post-monsoon (2021, 2022) groundwater fluctuation data. The total accuracy of AHP derived groundwater potential zones comes to be 75%. Moreover, the quantitative validation of AHP derived groundwater potential zone map is carried out through ROC curve method to indicate the performance of the model. The ROC value of 0.75, indicate the good predictions and performance of the AHP model for mapping of groundwater potential zones.

The suggested method used for categorization of groundwater potential zones in the Khapri watershed in the Dangs district, forming a part of the Deccan Volcanic Province, proved to be promising and may be extrapolated to other parts of DVP with suitable modifications. The map of groundwater potential zones will be helpful for decision makers for proposing suitable sites for making groundwater extraction structures with greater accuracy.