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Assessment of Groundwater Potential in a Semi-Arid Region of India Using Remote Sensing, GIS and MCDM Techniques

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Abstract Remote sensing (RS) and geographic information system (GIS) are promising tools for efficient planning and management of vital groundwater resources, especially in data-scarce developing nations. In this study, a standard methodology is proposed to delineate groundwater potential zones using integrated RS, GIS and multi-criteria decision making (MCDM) techniques. The developed methodology is demonstrated by a case study in Udaipur district of Rajasthan, western India. Initially, ten thematic layers, viz., topographic elevation, land slope, geomorphology, geology, soil, pre- and post-monsoon groundwater depths, annual net recharge, annual rainfall, and proximity to surface water bodies were considered in this study. These thematic layers were scrutinized by principal component analysis technique to select influential layers for groundwater prospecting. Selected seven thematic layers and their features were assigned suitable weights on the Saaty's scale according to their relative importance in groundwater occurrence. The assigned weights of the thematic layers and their features were then normalized by using AHP (analytic hierarchy process) MCDM technique and eigenvector method. Finally, the selected thematic maps were integrated by weighted linear combination method in a GIS environment to generate a groundwater potential map. Thus, four groundwater potential zones were identified and demarcated in the study area, viz., 'good', 'moderate', 'poor' and 'very poor' based on groundwater potential index values. The area falling in the 'good' zone is about 2,113 km^2 (17% of the total study area), which encompasses major portions of Sarada, Salumber, Girwa, Dhariawad, and

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Mavli blocks of the study area. The northeast and southwest portions along with some scattered patches fall in the ‘moderate’ zone, which encompasses an area of 3,710 km^2 (about 29%). The ‘poor’ zone is dominant in the study area which covers an area of 4,599 km^2 (36% of the total area). The western portion and parts of eastern and southeast portions of the study area are characterized as having ‘very poor’ groundwater potential, and this zone covers an area of 2,273 km^2 (18%). Moreover, in the ‘good’ zone, the mean annually exploitable groundwater reserve is estimated at 0.026 million cubic metres per km^2 (MCM/km^2), whereas it is 0.024 MCM/km^2 in the ‘moderate’ zone, 0.018 MCM/km^2 in the ‘poor’ zone, and 0.013 MCM/km^2 in the ‘very poor’ zone. The groundwater potential map was finally verified using the well yield data of 39 pumping wells, and the result was found satisfactory.

Keywords Groundwater potential · Remote sensing · GIS · MCDM · Hard-rock aquifer system · Semi-arid region

1 Introduction

The remote sensing (RS) technique provides systematic, synoptic, rapid and repetitive coverage of the earth’s features in different windows of the electromagnetic spectrum. As a result, it offers a unique and powerful tool for obtaining spatio-temporal information of large areas in a short time. Remotely sensed data are usually cost-effective compared to the conventional methods of hydrological surveys and particularly are of great significance for remote as well as data-scarce regions. Satellite data provide quick and useful baseline information about various factors controlling directly or indirectly the occurrence and movement of groundwater such as geomorphology, soil types, land slope, land use/land cover, drainage patterns, lineaments, etc. (Waters et al. 1990; Engman and Gurney 1991; Meijerink 1996; Jha and Peiffer 2006; Jha et al. 2007). In addition, geographical information system (GIS) provides an excellent framework for efficiently handling large and complex spatial data for natural resources management. Thus, RS and GIS have been proved to be useful tools for groundwater studies (e.g., Krishnamurthy et al. 1996; Meijerink 1996; Nour 1996; Sander et al. 1996; Edet et al. 1998; Shahid and Nath 2002; Rao and Jugran 2003; Jha and Peiffer 2006; Jha et al. 2007, 2010; Madrucci et al. 2008; Chowdhury et al. 2009, 2010; Chenini et al. 2010).

In the past, several researchers have used RS and GIS techniques for the delineation of groundwater potential zones (Chi and Lee 1994; Krishnamurthy and Srinivas 1995; Kamaraju et al. 1995; Krishnamurthy et al. 1996, 2000; Sander et al. 1996; Edet et al. 1998; Saraf and Choudhury 1998; Shahid et al. 2000; Jaiswal et al. 2003; Rao and Jugran 2003; Sikdar et al. 2004; Sener et al. 2005; Ravi Shankar and Mohan 2006; Solomon and Quiel 2006; Madrucci et al. 2008; Chowdhury et al. 2009; Jha et al. 2010) with successful results. The type and number of thematic layers used for assessing groundwater potential by RS and GIS techniques vary considerably from one study to another and their selection is arbitrary. Also, in a majority of the studies, personal judgment has been used for assigning weights to different thematic layers and their features. Thus, the review of past literature revealed that a standard methodology for delineating groundwater potential zones using RS and GIS techniques is generally lacking.

In the recent past, many researchers have found that multi-criteria decision making (MCDM) provides an effective tool for water management by adding structure, auditability, transparency and rigor to decisions (e.g., Dunning et al. 2000; Flug et al. 2000; Joubert et al. 2003). Recently, Hajkowicz and Higgins (2008) suggested that while the selection of a MCDM technique is important for water resources management, more emphasis is required on the initial structuring of a decision problem which involves choosing criteria and decision options. Saaty's Analytic Hierarchy Process (AHP) is a widely used MCDM technique in the field of water resources engineering. The method was first developed by Professor Thomas L. Saaty in the 1977s. Since then, the method has received numerous applications in natural resources, and environmental planning and management (Saaty 1980; Pereira and Duckstein 1993; Chen et al. 2001; Eastman 2003; Thirumalaivasan et al. 2003; Kolat et al. 2006; Mendoza and Martins 2006; Madrucci et al. 2008; Chowdhury et al. 2009; Jha et al. 2010). AHP has been accepted by the international scientific community as a very useful tool for dealing with complex decision problems. Its major innovation was the introduction of pair-wise comparisons. It has been found that when quantitative ratings are unavailable, humans are still adept at recognizing whether one criterion is more important than another. AHP employs a consistent way of converting such pair-wise comparisons into a set of numbers representing the relative priority of each criterion (Saaty 1980). The pair-wise comparison technique represents a theoretically founded approach to compute weights representing the relative importance of criteria. Weights are not assigned directly, but represent a "best-fit" set of weights derived from the eigenvector of the square reciprocal matrix used to compare all possible pairs of criteria (Eastman 2003). The application of MCDM techniques in groundwater assessment using RS and GIS techniques is highly limited (Chowdhury et al. 2009; Jha et al. 2010).

The objective of this study was to propose a methodology for identifying and delineating groundwater potential zones in a basin/sub-basin using integrated RS, GIS and MCDM techniques and its demonstration by a case study.

2 Overview of Study Area

2.1 Location

Udaipur district was selected as a study area in this study, which is situated in southern part of the driest and largest state (Rajasthan) of India (Fig. 1). It lies between 23°45′ and 25°10′ North latitude and 73°0′ and 74°35′ East longitude encompassing a geographical area of about 12698 km^2. It consists of 11 blocks (viz., Badgaon, Bhinder, Dhariawad, Girwa, Gogunda, Jhadol, Kherwara, Kotra, Mavli, Salumber, and Sarada). It is worth mentioning that for the administration purpose, a state in India is divided into districts, districts into blocks and blocks into *Gram Panchayats*; each *Gram Panchayat* consists of several villages.

2.2 Hydrometeorology

The climate of Udaipur is tropical, semi-arid with mercury staying between a maximum of 42.3°C and a minimum of 28.8°C during summers. Winters are a little

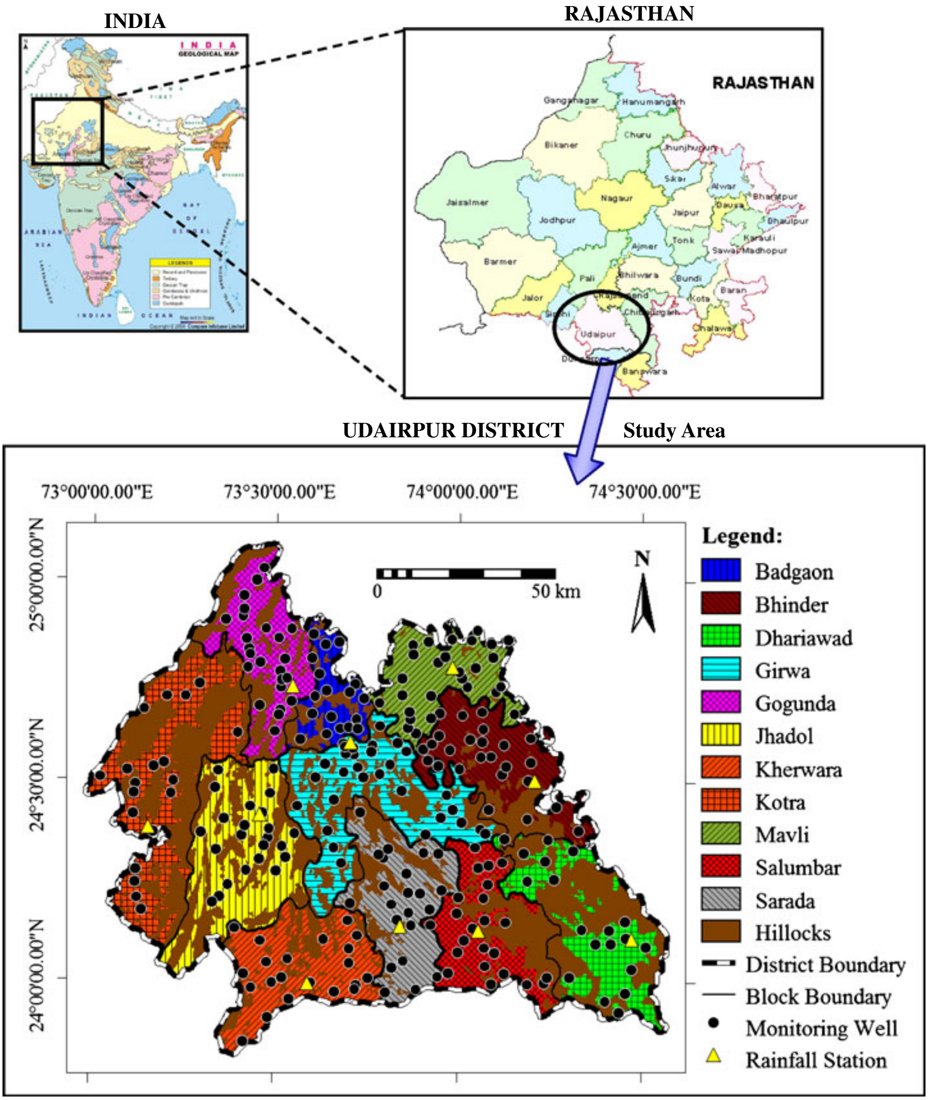


Fig. 1 Location map of the study area

cold with the maximum temperature rising to 28.8°C and the minimum dipping to 2.5°C. January is the coldest month and May is the hottest month. The mean annual rainfall is 625 mm, precipitating more than 80% during June through September. The rainy season (i.e., wet season) usually starts from mid-June and lasts for about 4 months up to the end of October. November to May can be characterized as the dry period.

The major sources of water supply in the study area for drinking and industrial uses are surface water bodies (lakes) and groundwater. In the past, the lakes were primarily used for irrigation, washing, recreational and religious activities, and social functions. However, with ever-increasing population in the area, domestic sector has become the largest consumer of the water stored in the lakes. Two large lakes, viz., Fatehsagar and Pichhola, contribute to the urban water supply in the study area. According to Ground Water Department (GWD), in Udaipur district, 51,147 wells and 2,117 tubewells are in use, of which 34,217 wells are fitted with pumps and the remaining 16,930 wells are operated by either *bullock mote* or *Persian wheel* (GWD 2008). Currently, groundwater (wells and handpumps) is the major source of irrigation contributing 69% of the total irrigated area, whereas surface water contributes only 31% of the total irrigated area.

2.3 Hydrogeologic Setting

Udaipur is located on meta-sedimentary rocks of ‘Aravalli’ Supergroup (~1,800 million years old) represented by phyllite, greywacke, quartzite, dolomite, intra-formational conglomerate that were deposited in Precambrian sea nearly 2,300 million years before present (BP). The suite of granitic and gneissic rocks, formed between 3,300 and 2,500 million years BP, constituted the floor of the ‘Aravalli’ Sea. The deposited sediments were intensely folded, mildly metamorphosed, and uplifted. Long period of erosion produced the present-day physiography (http://www.geologydata.info/udaipur_geology.htm, accessed on 5 April 2009).

The main hydrogeological units occurring in the study area are granite gneiss of Pre-‘Aravalli’; Banded Gneissic Complex (BGC), phyllite, schist, quartzite and limestone of ‘Aravalli’ Supergroup, granite of Post-‘Aravalli’ and biotite-schist, calc-schist and calc-gneiss of ‘Delhi’ Supergroup (Roy 1988). The BGC consists predominantly of granitic gneisses, unfoliated granites with minor components of pegmatite, and enclaves of amphibolites, fuchsite quartzite and calcareous rocks. The district is encircled by ‘Aravalli’ ranges from north to south. The northern part of the district generally consists of elevated plateau, while the eastern part has vast stretches of fertile plains. The southern part is covered with rock, hills, and dense forest, while the western portion known as the hilly tracks of ‘Mewar’ is composed of ‘Aravalli’ range. ‘Aravalli’ Supergroup covers the major portions of the district.

The major hydrogeologic formations in Udaipur are phyllite-schist, and greywacke of ‘Aravalli’ Supergroup. These rocks have very little primary porosity. The movement of groundwater through these rocks is mainly through secondary openings like joints and fractures, which are usually limited in extent. Such hydrogeologic formations are typically termed “hard-rock formations” (CGWB 1997). The geomorphic controls play an important role in the occurrence of groundwater in the study area. The foothills generally form the recharge zone. The shallow aquifers present in the study area are mainly unconfined in nature and currently constitute major groundwater resources. Deep aquifers are reported to exist at more than 100 m depth, but little is known about such aquifers (GWD 2008).

2.4 Groundwater Scenario of the Study Area

The study area (Udaipur district) is situated in the hilly terrains of ‘Aravalli’ Range in Rajasthan. Because of its geographical location and capricious nature of south-western monsoon, the study area lacks inadequate water resources as well as suffers from frequent droughts and abnormally high temperature during summer (Bhuiyan et al. 2006). Every year during summer, the groundwater level in the study area lowers beyond the economic lift of pumping and most dugwells, which constitute the main source of drinking water for rural communities, completely dry up. Thus, the study area is severely afflicted with water scarcity, and the sustainability of water supply is threatened. The water scarcity has a direct impact on the livelihood, health and sanitation of the local people, besides environmental consequences. The water supply situation is expected to be much more severe in the future because of continued unsustainable water use and projected climate change. Unfortunately, no scientific study has been conducted to date in the study area concerning groundwater development and management despite being located in the semi-arid region.

3 Methodology

3.1 Generation of Thematic Maps

In order to assess groundwater potential in the study area, 10 thematic maps, viz., geomorphology, geology, soil, slope, topographic elevation, net recharge, rainfall, pre-monsoon groundwater depth, and post-monsoon groundwater depth and surface water bodies, were generated using remote sensing and conventional data with the help of Integrated Land and Water Information System (ILWIS) GIS software (ILWIS 2001). Out of these thematic maps, topographic elevation and slope maps were generated from Shuttle Radar Topography Mission (SRTM) data, whereas the remaining maps were generated using conventional data such as geomorphology, geology, soil, surface water body maps, and groundwater level, rainfall, and specific yield data.

Topographical elevation map for the study area was developed by Digital Elevation Model (DEM) extracted from the Shuttle Radar Topography Mission (SRTM) data (USGS 2004). The DEM of the study area obtained from the US Geological Survey (USGS) website was unfilled and unfinished, and therefore, the DEM was cleaned up by filling sinks to remove local depressions. The slope map for the study area was prepared from the DEM. For this, the DEM was subjected to two directional gradient filters (one in x-direction and another in y-direction). The filtering was done by using in-built linear filters (dfdx and dfdy) available in the ILWIS software. Then, the resultant maps were used to generate a slope map of the study area by computing slope using following equation (ILWIS 2001):

$$Slope = 100 \times \sqrt{DX^2 + DY^2} / Pixel\ Size(DEM) \tag{1}$$

Where, DX = filtered DEM with x-gradient filter, DY = filtered DEM with y-gradient filter, and $Pixel\ Size(DEM)$ = pixel size of the DEM.

In the present study, the geomorphologic map (in the paper format) was collected from the State Remote Sensing Application Center, Jodhpur, Rajasthan (GOR 1999), and the geology map was collected from the Ground Water Department, Udaipur, Rajasthan. Both the maps were first scanned, rectified and then digitized using ILWIS software to prepare thematic layers of geomorphology and geology. The soil map of the study area was obtained from the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Nagpur at 1:250,000 scale. This map was also scanned, rectified and then digitized using ILWIS software to create a digital soil map.

Moreover, the 19-year (1988–2006) mean pre- and post-monsoon groundwater depth data at 251 sites over the study area were used for geostatistical modelling, which included computation of experimental semi-variogram, fitting of geostatistical models, and finally preparation of groundwater level spatial maps. The mean pre- and post-monsoon groundwater depth maps were generated by kriging technique using exponential semi-variogram model. The nugget, sill and range of the fitted exponential semi-variogram for the pre-monsoon season were 8 m^2, 37 m^2 and 48 km, respectively, while the model parameters for the post-monsoon season were 7 m^2, 23 m^2 and 41 km, respectively. Considering the data availability in the study area, the groundwater fluctuation method was used in this study to estimate mean annual net groundwater recharge. Point estimates of the mean annual net recharge at 140 sites were interpolated by kriging technique using exponential semi-variogram model to obtain a spatial map of mean annual net recharge. The nugget, sill and range of the fitted exponential semi-variogram for the mean annual net recharge were 0.65 m^2, 3.9 m^2 and 29 km, respectively. Further, point estimates of mean annual rainfall based on 43 years' (1965–2007) data at 10 rainfall stations were used to create a point rainfall map for the study area. This point map was converted into a raster map by Thiessen polygon method. The surface water bodies present in the study area were digitized from the map collected from Ground Water Department, Udaipur, Rajasthan.

3.2 Selection of Thematic Layers

In the past RS- and GIS-based groundwater studies concerning groundwater potential zoning, various thematic maps for delineating groundwater favorability zones were selected presuming that all the parameters have significant influence on the occurrence of groundwater (e.g., Rao and Jugran 2003; Solomon and Quiel 2006; Ettazarini 2007; Ganapuram et al. 2009); the number of thematic layers used depends on the availability of data in an area. Such a blind approach of thematic layers adoption for groundwater prospecting may yield erroneous results because it involves multi-criteria analysis. In contrast, in this study, it is proposed to scrutinize available thematic layers by applying a multivariate technique such as principal component analysis (PCA). PCA is a statistical tool to discriminate which variables (or thematic maps) are more important in a group of samples and to discriminate groups or families of statistical units that could have, potentially, a relationship (Dillon and Goldstein 1984). Only the first two principal components can be taken into account if they explain most of the variance. The acceptance level of variance should be higher than 60% (Andreo et al. 2008).

In the present study, PCA was performed in two stages, firstly for the thematic maps of pre-monsoon and post-monsoon groundwater levels, and then for the eight thematic maps (i.e., geomorphology, geology, soil, rainfall, post-monsoon groundwater level, net recharge, topographic elevation and slope). The first stage PCA was carried out to evaluate the comparative significance of pre-monsoon and post-monsoon groundwater levels. In the second stage PCA, salient physical characteristics of the eight thematic maps were used.

3.3 Assignment of Weights and Weight Normalization

Unlike the past studies, in this study experts' opinions were sought for assigning suitable weights to the selected themes and their features. This approach has been strongly recommended by Saaty (1980), but it has been ignored in most of the earlier studies related to RS- and GIS-based groundwater prospecting. A total of ten international experts (geologists and hydrogeologists) in the field of hydrogeology were interviewed through a questionnaire specially prepared for this study to seek their opinions on relative importance of the hydrologic/hydrogeologic variables influencing groundwater occurrence. The local hydrogelogists were also consulted for their views/opinions about the relative importance of the themes and their features. The experts provided weights for the selected thematic maps and their features on the Saaty's scale (Saaty 1980). Thereafter, the final weights were decided based on the experts' opinions as well as local field experience. The weights thus assigned to different thematic maps and their individual features were normalized by eigenvector technique and Saaty's analytic hierarchy process (AHP). The normalization process reduces the subjectivity associated with the assigned weights of the thematic maps and their features. Furthermore, as the assigned weights are based on different experts' opinions, the normalized weights of the thematic layers and those of their features were examined for consistency as recommended by Saaty (1980). Saaty (1980) suggested to compute consistency ratio (CR) for this purpose. The following steps were followed to compute CR for each theme and feature:

Step 1: Principal eigenvalue ($\lambda_{\max}$) was computed by eigenvector technique.

Step 2: Consistency Index (CI) was calculated from the following equation (Saaty 1980):

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{2}$$

Where, n is the number of criteria or factors.

Step 3: Finally, consistency ratio (CR) was calculated as (Saaty 1980):

$$CR = \frac{CI}{RCI} \tag{3}$$

Where, RCI = random consistency index.

The value of RCI was obtained from the standard table given in Saaty (1980). The value of consistency ratio (CR) should be less than 10% (Saaty 1980) for consistent weights, otherwise the corresponding weights should be re-evaluated to avoid inconsistency.

3.4 Delineation of Groundwater Potential Zones

The methodology proposed in this study to identify and delineate groundwater potential zones using RS, GIS and MCDM techniques is illustrated in Fig. 2. The selected seven thematic maps were integrated in the GIS environment to generate

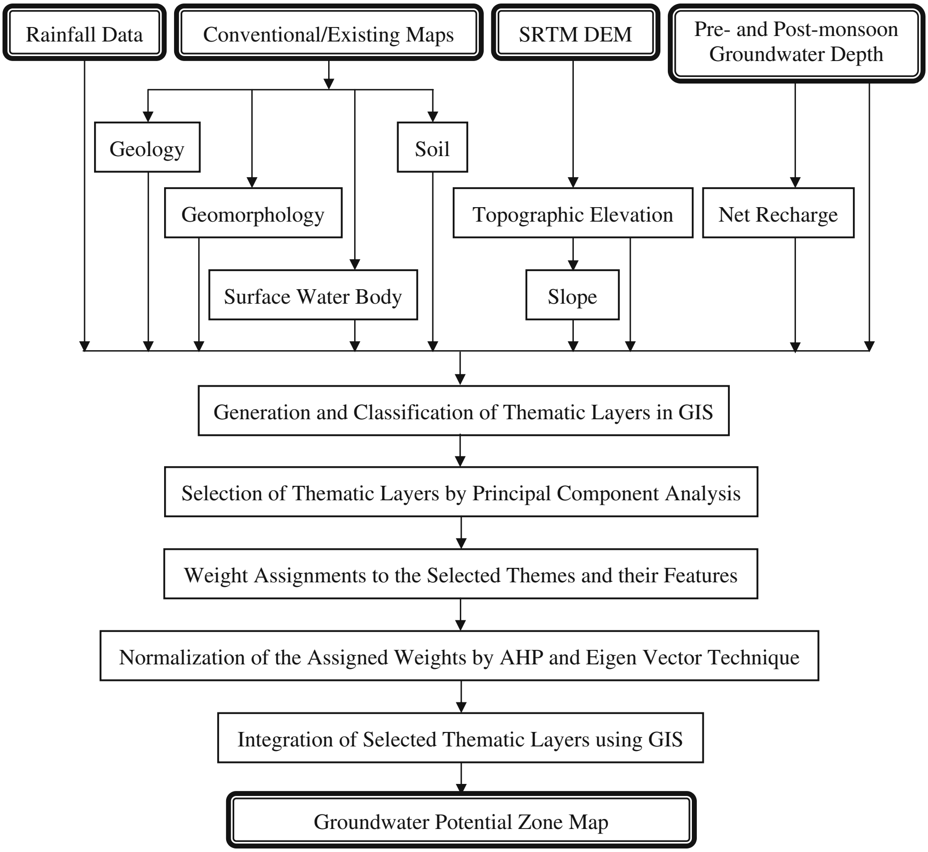


Fig. 2 Flowchart for groundwater potential assessment using RS, GIS and MCDM techniques

groundwater potential index (GWPI). The GWPI was computed by using the weighted linear combination method (Malczewski 1999) as follows:

$$GWPI = \sum_{w=1}^{m} \sum_{i=1}^{n} (w_j \times x_i) \tag{4}$$

Where, GWPI = groundwater potential index, x_i = normalized weight of the i^{th} class/feature of theme and w_j = normalized weight of the j^{th} theme, m = total number of themes, and n = total number of classes in a theme.

3.5 Quantification of Exploitable Groundwater Reserve

The Central Ground Water Board (CGWB), Government of India, New Delhi has suggested the concept of exploitable groundwater reserve to estimate the aquifer yield, which actually represents the long-term average annual recharge under conditions of maximum groundwater use (Karanth 1989). Using this concept, the mean annually exploitable groundwater reserves of different groundwater potential zones (as identified by RS, GIS and MCDM techniques) were estimated as (CGWB 1997):

$$GW_R = WL_d \times A \times S_y \tag{5}$$

Where, $GW_R =$ mean annually exploitable/utilizable groundwater reserve, $WL_d =$ mean groundwater level decline between November of the current year and May next year, $A =$ area of the groundwater potential zone, and $S_y =$ specific yield of the zone.

Generally, up to the end of October, soil is saturated with moisture and no additional groundwater for irrigation is required in the study area. Groundwater irrigation actually starts from the beginning of November until May of the next year. Therefore, the groundwater reserve can be exploited annually on a long-term basis without detrimental effects on the groundwater reservoir (CGWB 1997). Using Eq. 5, the mean annually exploitable/utilizable groundwater reserves for the identified groundwater potential zones were estimated.

3.6 Verification of the Groundwater Potential Zone Map

The groundwater potential zone map delineated in the present study was verified using the available well yield data of 39 pumping wells. Mean discharge of the existing pumping wells in individual groundwater potential zones was computed and compared. In addition, cumulative frequencies of the wells falling in individual groundwater potential zones were plotted against well yields, which provided further verification.

4 Results and Discussion

4.1 Thematic Layers of Udaipur District

4.1.1 Topographic Map

The topographic map prepared from SRTM data is shown in Fig. 3. On the basis of topographic elevation, the study area can be divided into six topographic elevation classes. The highest topographic elevations (about 1350 m MSL) exist in the western and northwestern portions of the area which induces highest runoff and hence less possibility of rainfall infiltration. The topographic elevation is usually low in the southeast and south portions of the area, including the western portion of the area in small extent. The study area is dominated by topographic elevations of 300–450 m in 3,533 km^2 area and 450–600 m in 4,080 km^2 area located in between northwest and southeast portions of the area.

4.1.2 Slope Map

The topographic slope of the area has its own importance in affecting the runoff, recharge and movement of surface water. The slope map of the study area, developed from DEM, is shown in Fig. 4 which reveals four slope classes: (1) 0–3%, (2) 3–10%, (3) 10–30%, and (4) >30%. It can be seen from Fig. 4 that the lowest slope (0–3%)

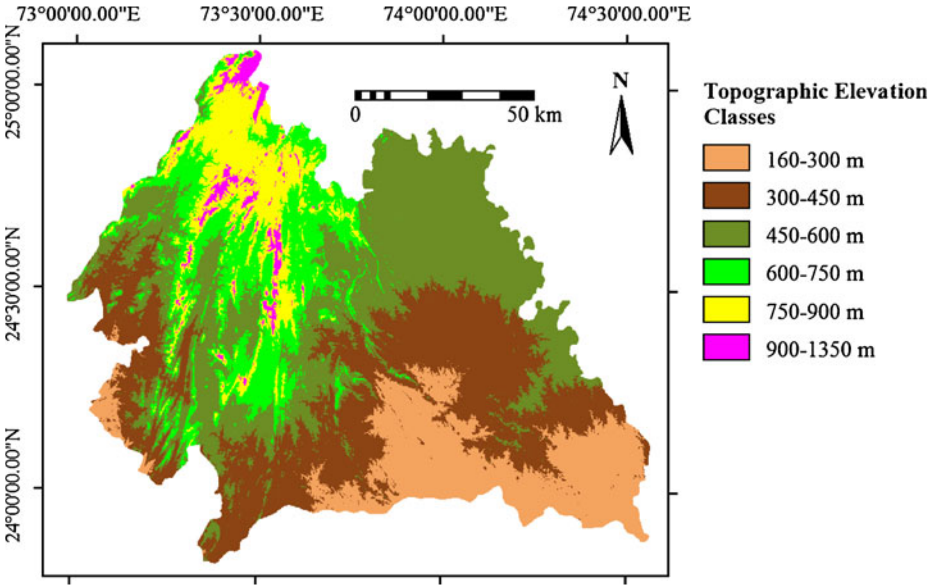


Fig. 3 Thematic layer of topographic elevation

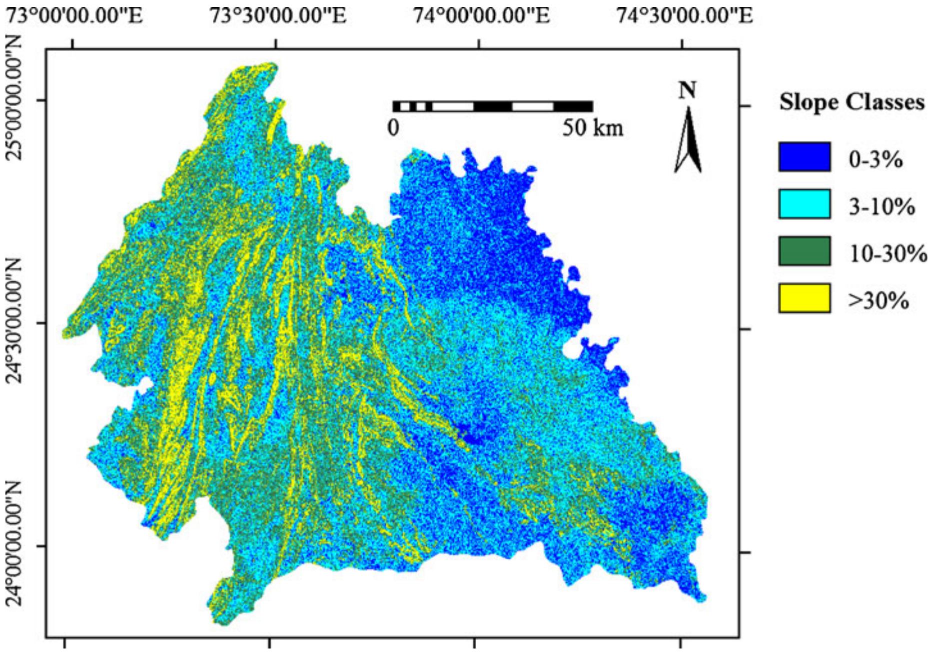


Fig. 4 Thematic layer of slope

exists in the northeast portion of the area, which indicate almost flat topography. The highest slope (>30%) exists in the form of stretched strips along the hillocks lying in the western portion of the area. The slope of 3–10% encompassing an area of 5,009 km^2 (about 40% of the total area) dominates in the study area.

4.1.3 Geomorphology Map

Geomorphologic map depicts important geomorphic units, landforms and underlying geology so as to provide an understanding of the processes, materials/lithology, structures, and geologic controls relating to groundwater occurrence as well as to groundwater prospects. Geomorphologically, the study area consists of pediment, buried pediment, valley fills, and structural hills as shown in Fig. 5. Pediment is mainly broad gently sloping rock flooring, erosional surface of low relief between hills and plains. It is comprised of varied lithology, crisscrossed by fractures and faults. A large part of the study area (2,409 km^2) is covered with pediment formation. Buried pediment is pediment covered essentially with relatively thicker alluvial, colluvial or weathered materials. A pediment is a gently inclined slope of transportation and/or erosion that truncates rock and connects eroding slopes or scarps to the areas of sediment deposition at lower levels (Oberlander 1989). The study area has buried pediment mainly in east and southeast portions encompassing an area of 1,684 km^2. It is moderate to good for groundwater occurrence. The study area has valley fills in small patches mostly along the river systems, encompassing an area of 457 km^2. The valley fills are formed by fluvial activity usually at lower topographic locations and comprised of boulders, cobbles, pebbles gravels, sand, silt, and clay. The unit has consolidated sediment deposits and is usually good for groundwater occurrence.

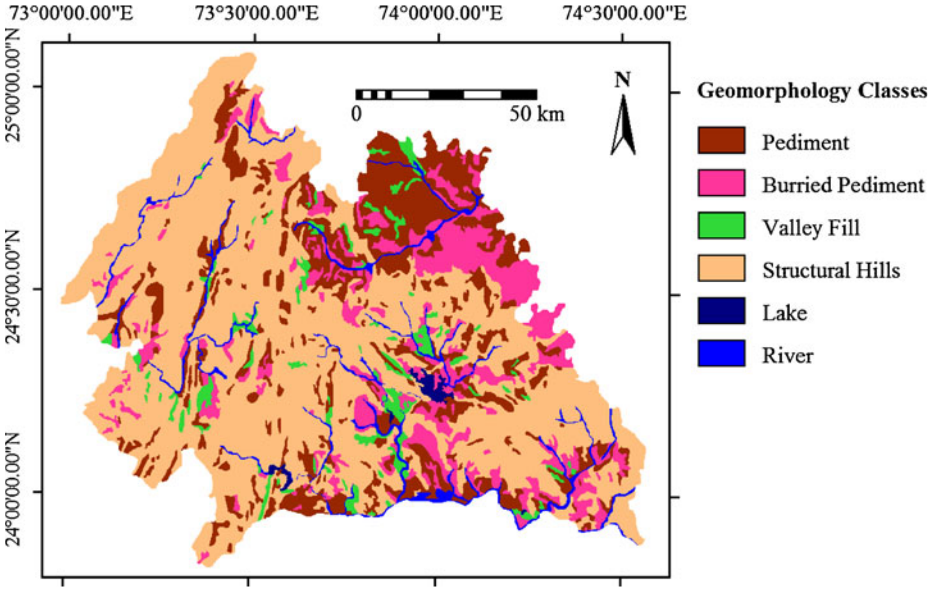


Fig. 5 Thematic layer of geomorphology

About 60% of the study area (i.e., 7,632 km^2) is falling under this geomorphologic feature. Structural hills are linear to arcuate hills showing definite trend-lines with varying lithology associated with folding, faulting, etc.

4.1.4 Geology Map

Six types of geologic lithology namely, phyllite-schist, gneiss, schist, granite, quartzite and hillocks are found in the study area (Fig. 6). Phyllite-schist represents argillaceous sediments and grades from shale, slate, phyllite to mica schist. These litho units are soft and friable. These formations are most wide spread and cover western half of the study area. A localized pocket occupied by the underlying aquifer is located near Mavli. Gneiss comprises porphyritic gneissic complex associated with aplite, amphibolite, schist and augen gneiss. Gneiss is grey to dark colored, medium to coarse grained rocks. Gneiss rocks occupy eastern part in Bhinder, Dhariawad, Girwa, Mavli, Salumber and Sarada blocks. Schist litho units are hard and compact, fine to medium grained and characterized by alternating bands of light and dark color ferromagnesian minerals. Schist covers small areas in parts of Gogunda and Kotra blocks. Granite is grey colored, medium to coarse grained rock mainly composed of quartz, feldspar with biotite and hornblende as minor constituents. Granite encompasses western peripheral part within the boundary of Kotra block. Quartzite represents Alwar group of sediments and is characterized by arenaceous facies comprising mainly quartzites of varied color. Quartzites are grey, pink, pale and light green. Quartzite occupies southwest part of the study area and is confined to Jhadol block.

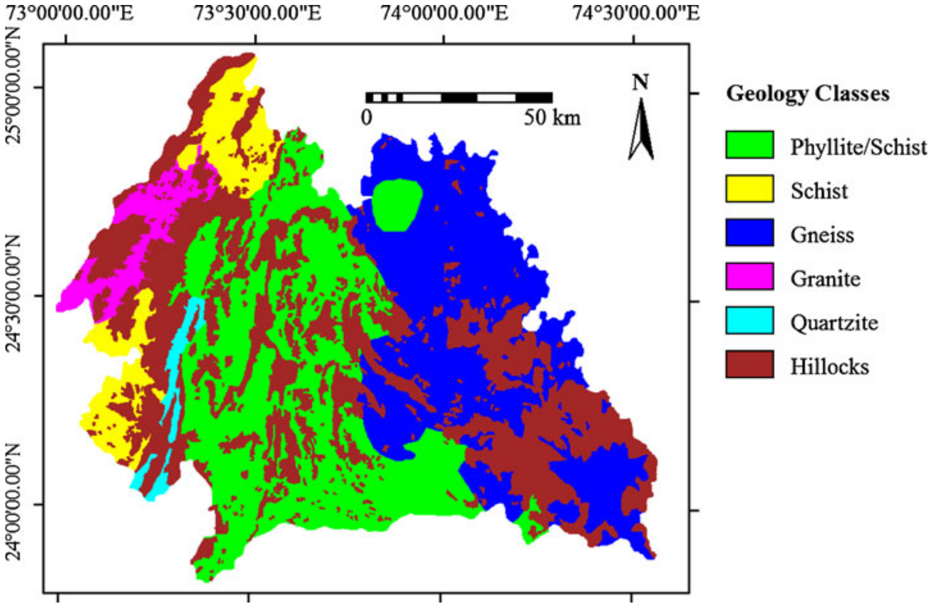


Fig. 6 Thematic layer of geology

4.1.5 Soil Map

The thematic layer on soil for the study area reveals six main soil categories (Fig. 7). It is apparent from Fig. 7 that the majority of the study area is dominated by hillocks (5,811 km^2) and fine loam (5,132 km^2) with other soil types present in relatively small areas (about 14%).

4.1.6 Pre-monsoon and Post-monsoon Groundwater Depth Maps

The mean pre-monsoon groundwater level in the area generally varies from 4.8 to 23 m below ground surface (m bgs) with a major portion of the area having 4.5 to 8.5 m bgs depth (Fig. 8). In the northeast portion of the area, the mean pre-monsoon groundwater depth varies from 14.5 to 17.5 m. In contrast, in the western and central portions, and at some scatter places in the south, the mean pre-monsoon groundwater depth varies in the range of 8.5 to 11.5 m. On the other hand, the contour map of 16-year mean post-monsoon groundwater level (Fig. 9) reveals that the groundwater depth varies from 2.3 to 18 m with a majority of the area having mean post-monsoon groundwater depth of 4.5 to 7 m. The developed pre- and post-monsoon groundwater depth maps (Figs. 8 and 9) were divided into five classes.

4.1.7 Net Recharge Map

The mean annual net recharge map developed by kriging technique is shown in Fig. 10. The mean annual net groundwater recharge in the study area varies from 0.5 to 6 cm. Based on these recharge estimates, the area can be divided into five

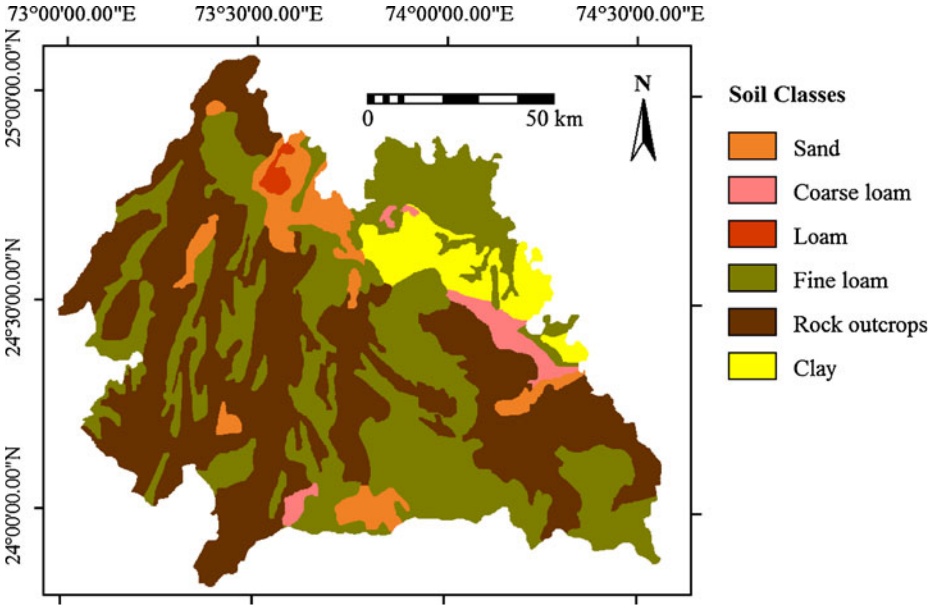


Fig. 7 Thematic layer of soil

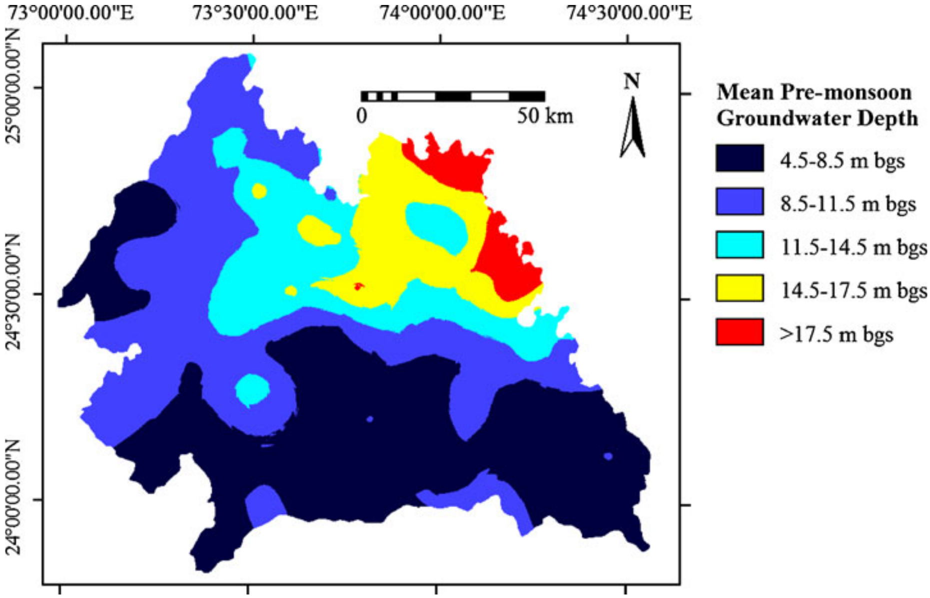


Fig. 8 Mean pre-monsoon groundwater level map of Udaipur district

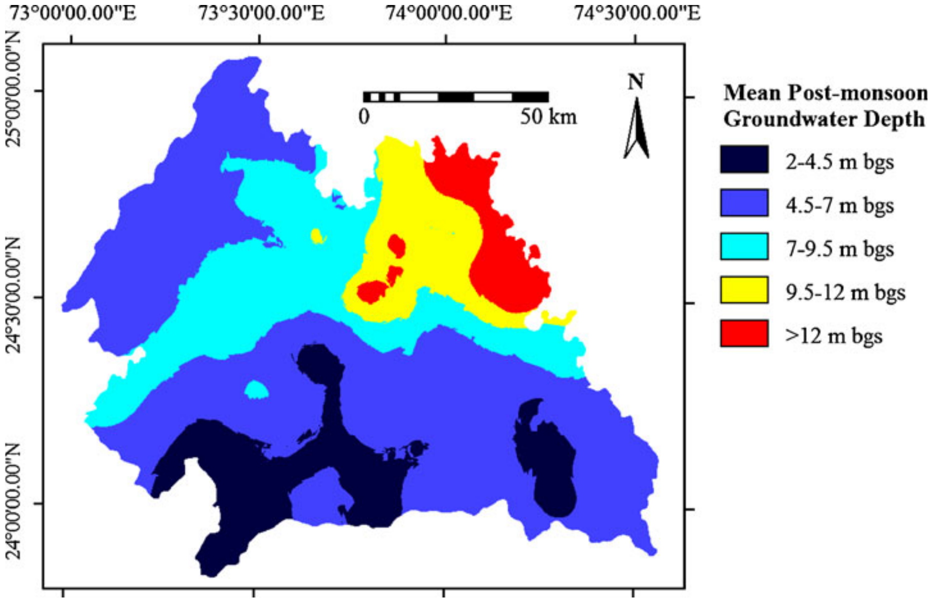


Fig. 9 Mean post-monsoon groundwater level map of Udaipur district

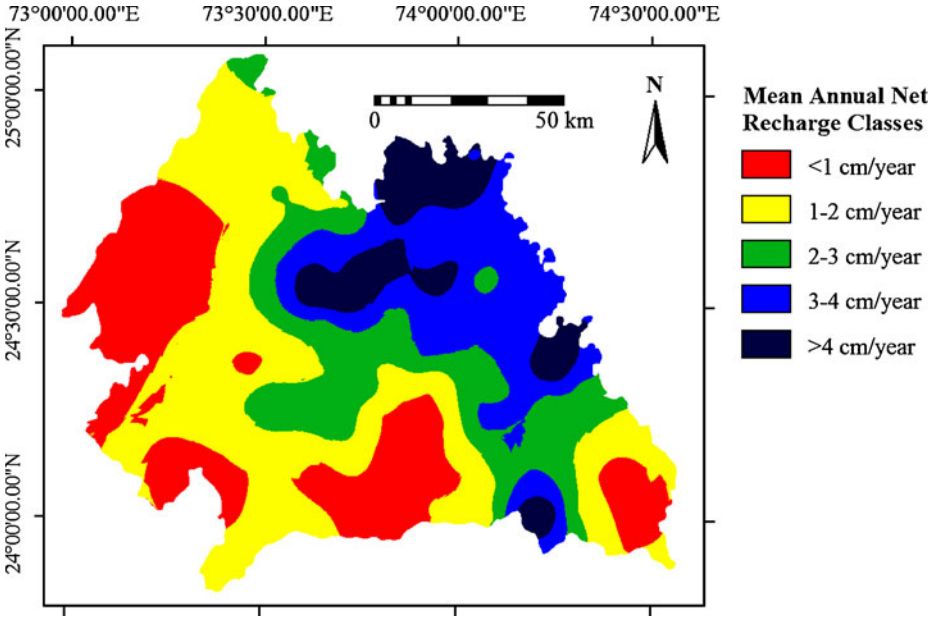


Fig. 10 Thematic layer of net recharge

recharge zones: (1) 0–1 cm/year, (2) 1–2 cm/year, (3) 2–3 cm/year, (4) 3–4 cm/year, and (5) >4 cm/year as shown in Fig. 10. It is apparent from this figure that a net recharge rate of 1–4 cm/year is dominant in the district. Four patches in the southeast, south, southwest, and west portions of the study area have very low recharge rate (<1 cm/year). A high recharge rate (>4 cm/year) is confined to four patches in the north, northeast, east and south portions of the area.

4.1.8 Rainfall Map

The thematic layer of rainfall (Fig. 11) developed by using Theissen polygon method divides the study area into five rainfall zones: (1) <55 cm/year, (2) 55–60 cm/year, (3) 60–65 cm/year, (4) 65–70 cm/year, and (5) >70 cm/year. Figure 11 depicts low rainfall in the south portion and high rainfall in the southeast and western portions of the area. Major portion of the study area has a mean annual rainfall of 65–70 cm/year.

4.2 Map on Proximity to Surface Water Bodies

The prepared map on surface water bodies was divided into three classes: (1) <75 m, (2) 75–150 m, and (3) >150 m (Fig. 12) considering suitable buffer distances for proximity to the surface water bodies. It is discernible from Fig. 12 that the water bodies are small in aerial extent and are distributed sporadically all over the area. It can also be seen that the proximity to surface water bodies' class of 75–150 m has negligible aerial extent (about 1%).

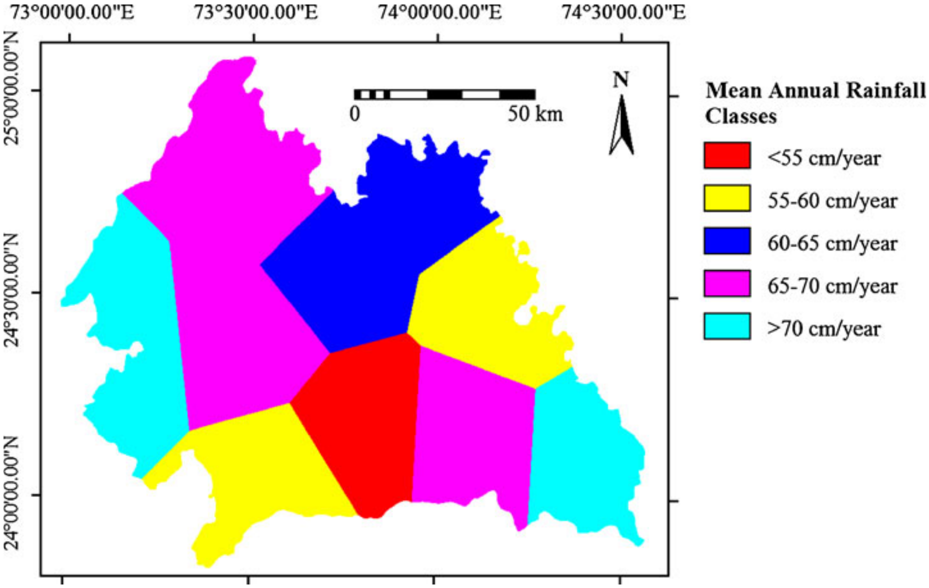


Fig. 11 Thematic layer of mean annual rainfall

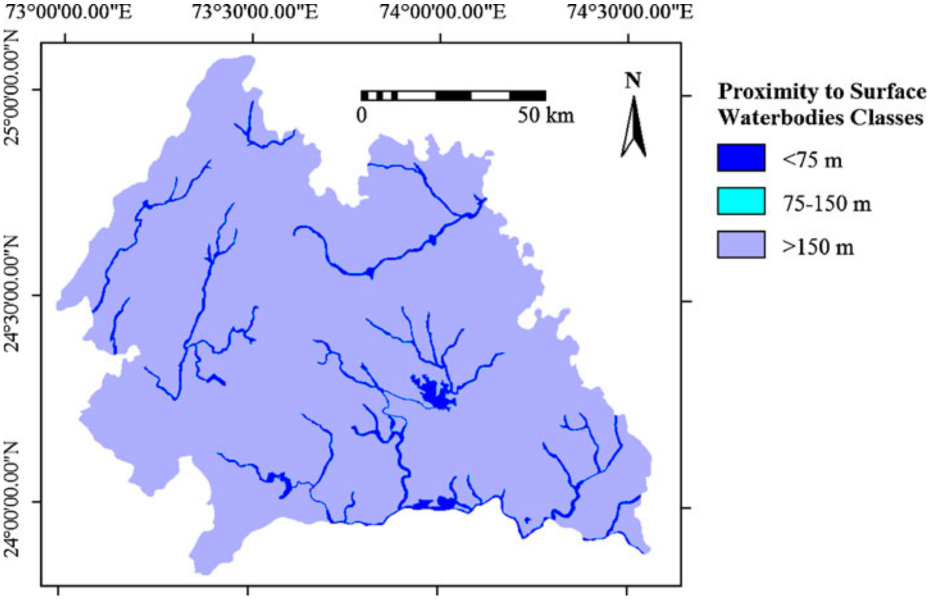


Fig. 12 Thematic layer of proximity to surface water bodies

4.3 Identifying Influential Thematic Layers for Groundwater Assessment

The results of first stage principal component analysis (PCA) are presented in Table 1 for 15 significant principal components (eigenvalue > 1). First principal component (PC) explains 51 and 57% of the total variance in pre- and post-monsoon groundwater depths. However, the first two PCs explain 61% and 64% of the cumulative variances in pre- and post-monsoon depths, respectively. Loading of the first PC versus that of second PC is shown in Fig. 13. Monitoring wells in pre- and post-monsoon were grouped based on the PC loadings into three categories: strong, moderate, and weak. It is discernible from Fig. 13 that relatively large numbers of wells (about 64% of the total wells) are characterized by the first PC within relatively less extent in the post-monsoon season compared to that (about 49%) in the pre-monsoon season. This is most likely due to high hydraulic connectivity of the aquifer during post-monsoon season. Therefore, the post-monsoon groundwater depth data were selected for groundwater assessment.

The results of the second stage PCA including loadings of ten PCs, eigenvalues, and cumulative variances are summarized in Table 2. It is apparent from Table 2 that first two PCs explain about 71% of the total variance of the system. The plot of loading of first PC versus that of second PC (Fig. 14a) reveals that the set of variables favoring groundwater occurrence fall on the positive axis of first PC. These loadings are opposed by another set of variables which are less important from groundwater occurrence viewpoint and fall on the negative axis of first PC.

The second PC (Fig. 14a) can be characterized as a topographic factor. In this PCA, some variables do not seem to play a significant role in groundwater assessment. Therefore, PCA was carried out second time by eliminating less important

Table 1 Percentage variance explained by significant principal components for pre- and post-monsoon groundwater depths (first stage PCA)

Principal component	Pre-monsoon groundwater depth			Post-monsoon groundwater depth		
	Eigenvalue	Percentage of total variance (%)	Cumulative variance (%)	Eigenvalue	Percentage of total variance (%)	Cumulative variance (%)
1	72.00	51.43	51.4	80.33	57.38	57.4
2	13.74	9.82	61.2	9.23	6.59	64.0
3	10.31	7.36	68.6	8.37	5.98	69.9
4	7.35	5.25	73.9	6.97	4.98	74.9
5	6.07	4.34	78.2	6.39	4.57	79.5
6	4.84	3.46	81.7	5.53	3.95	83.4
7	4.01	2.86	84.5	4.22	3.01	86.5
8	3.72	2.66	87.2	3.89	2.78	89.2
9	3.40	2.43	89.6	3.00	2.14	91.4
10	3.07	2.20	91.8	2.86	2.04	93.4
11	2.94	2.10	93.9	2.52	1.80	95.2
12	2.80	2.00	95.9	2.28	1.63	96.8
13	2.15	1.54	97.4	1.81	1.29	98.1
14	2.01	1.44	98.9	1.45	1.04	99.2
15	1.57	1.12	100.0	1.16	0.83	100.0

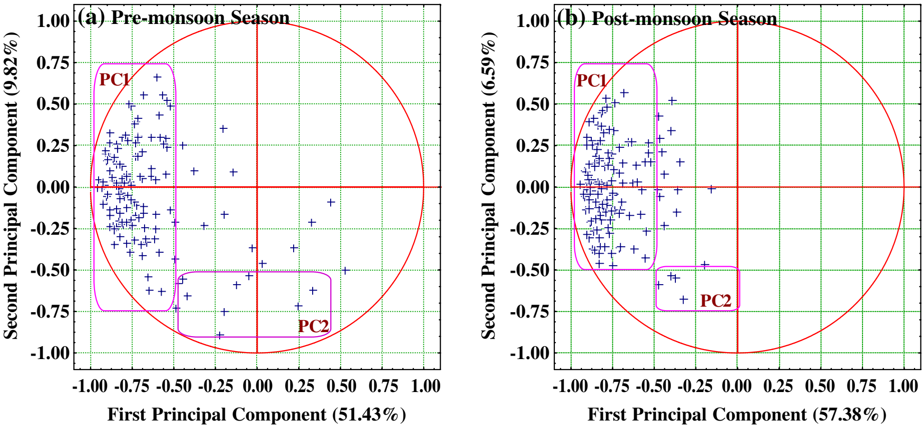


Fig. 13 Loadings of first principal component versus second principal component for pre- and post-monsoon groundwater depths

variables. Results of this PCA indicate that the first two PCs account for 70% of the variance (Fig. 14b). The first PC axis represents groundwater potential favored by the variables: gradient < 3%, gneiss, net recharge, pediment, buried pediment, post-monsoon groundwater depth, fine loam, and gradient ranging from 3–10%, and opposed by the variables: gradient ranging from 10–30%, structural hills, and gradient > 30%. The positive axis of the second principal component contains mean altitude, valley fills, phyllite-schist, whereas the mean annual rainfall falls on the negative axis.

Based on the results of second stage PCA discussed above, it can be inferred that six themes, namely slope, net recharge, geology, geomorphology, soil, and post-monsoon groundwater depth have more importance from the groundwater occurrence point of view than the rainfall and topographic elevation (altitude). Therefore, the thematic layers of mean rainfall and topographic elevation were not considered for groundwater potential zoning in this study. The exclusion of these two maps is technically reasonable also as far as multi-criteria analysis is concerned.

4.4 Normalized Weights for Thematic Maps

The weights assigned to different thematic layers are summarized in Table 3. As mentioned in the methodology, the normalized weights of the seven themes and their individual features were obtained using the Saaty's analytical hierarchy process (AHP) and eigenvector technique. The derivation of the normalized weights for individual themes using AHP and eigenvector technique is shown in Table 4 as an example. Similarly, the assigned weights of different features of individual themes were normalized by AHP and eigenvector technique, which are summarized in Table 5 along with the assigned weights. Consistency ratios of the assigned weights for the seven thematic layers and their features were found to be less than 10% and thereby suggesting that the assigned weights are consistent.

Table 2 Principal component loadings of the 22 variables used in second stage PCA

Variable	Unit	Principal component									
		I	II	III	IV	V	VI	VII	VIII	IX	X
Surface area	km^2	−0.588	−0.543	0.372	0.410	−0.120	0.007	0.049	−0.177	−0.030	0.058
Weighted precipitated volume	10^6 m^3	−0.611	−0.551	0.464	0.275	0.069	−0.024	−0.058	−0.131	−0.030	0.068
Weighted precipitated depth	mm	−0.492	−0.434	0.489	−0.181	0.503	−0.032	−0.194	0.011	−0.062	−0.050
Gradient $< 3\%$	%	0.948	−0.250	0.134	0.058	0.010	−0.064	−0.103	0.035	0.036	−0.011
Area with $3\% <$ Gradient $< 10\%$	%	0.425	−0.598	−0.350	−0.406	0.220	0.088	0.330	−0.057	0.077	−0.020
Area with $10\% <$ Gradient $< 30\%$	%	−0.931	0.316	−0.053	0.030	−0.073	0.131	−0.004	−0.031	0.008	0.083
Area under Gradient $> 30\%$	%	−0.807	0.495	0.091	0.156	−0.077	−0.165	−0.042	0.024	−0.157	−0.106
Area under Phyllite-Schist	%	−0.225	0.541	−0.745	0.002	−0.033	0.097	−0.109	−0.265	−0.091	−0.041
Area under Gneiss	%	0.890	−0.380	0.173	0.061	−0.043	−0.127	0.059	−0.019	0.093	−0.017
Area under Hillocks	%	−0.823	−0.317	0.239	−0.271	0.221	−0.121	0.150	−0.024	−0.059	−0.035
Area under Pediment	%	0.838	0.312	0.077	0.224	0.245	0.167	−0.224	−0.053	0.058	−0.005
Area under Buried Pediment	%	0.695	−0.425	0.145	−0.348	−0.366	−0.106	−0.012	0.074	−0.208	−0.007
Area under Valley Fill	%	0.276	0.249	−0.458	0.676	0.154	−0.394	0.109	−0.023	0.053	−0.020
Area under Structural Hill	%	−0.980	−0.008	0.004	−0.108	−0.044	0.009	0.142	−0.036	0.073	−0.004
Area under Sand	%	−0.122	0.687	−0.113	−0.574	0.244	−0.302	−0.059	−0.062	−0.019	0.110
Area under Fine Loam	%	0.702	−0.063	−0.236	0.472	0.340	0.156	0.126	0.148	−0.210	0.056
Area under Rocky Outcrop	%	−0.922	−0.302	−0.013	0.191	0.055	0.075	0.012	−0.004	0.076	−0.090
Minimum altitude	m	0.276	0.873	0.274	−0.258	0.074	0.097	0.007	0.030	0.064	−0.021
Maximum altitude	m	−0.537	0.706	0.347	0.214	−0.008	0.034	0.185	0.104	−0.018	0.017
Mean altitude	m	−0.295	0.871	0.352	0.051	0.020	0.063	0.142	0.061	−0.008	−0.006
Mean post-monsoon GW level	m bgs	0.777	0.292	0.515	0.120	−0.066	−0.091	0.065	−0.113	0.035	0.018
Weighted net recharge	cm	0.879	0.203	0.229	−0.098	0.064	0.084	0.184	−0.236	−0.151	−0.034
Eigenvalue	–	10.99	5.33	2.62	1.92	0.80	0.44	0.40	0.25	0.19	0.06
Cumulative variance	%	47.79	70.98	82.35	90.69	94.15	96.08	97.80	98.89	99.74	100.00

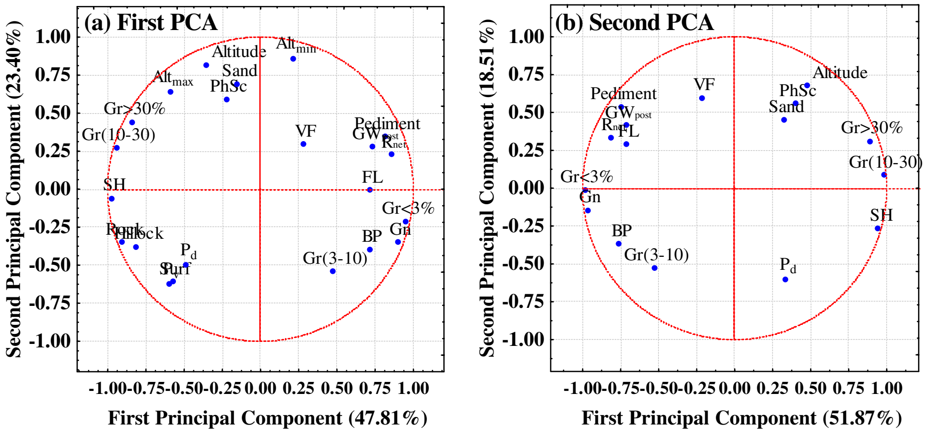


Fig. 14 Loadings of first principal component versus that of second principal component for **a** 22 and **b** 16 thematic variables (*Surf* surface area; *Pv* weighted precipitated volume; *Pd* weighted precipitated depth; *Gr* < *30* gradient < 3%; *Gr(3–10)* 3% < Gradient < 10%; *Gr(10–30)* 10% < Gradient < 30%; *Gr* > *30* Gradient > 30%; *PhSc* Phyllite-Schist; *Gn* Gneiss; *BP* buried pediment; *VF* valley fill; *SH* structural hill; *FL* fine loam; *Rock* rock outcrop; Alt_{min} minimum altitude; Alt_{max} maximum altitude; *Altitude* mean altitude; GW_{post} mean post-monsoon groundwater level; R_{net} weighted net recharge)

Table 3 Weights assigned to the seven thematic layers

Theme	Weight
Geomorphology	5.5
Geology	4.5
Soil	4
Post-monsoon groundwater depth	5
Net recharge	6.5
Slope	4
Proximity to surface water bodies	2

Table 4 Pairwise comparison matrix and normalized weights of the seven themes

Themes	Themes							Normalized weight
	GM	GG	Soil	GD	NR	Slope	SW	
GM	5.5/5.5	5.5/4.5	5.5/4	5.5/5	5.5/6.5	5.5/4	5.5/2	0.17
GG	4.5/5.5	4.5/4.5	4.5/4	4.5/5	4.5/6.5	4.5/4	4.5/2	0.14
Soil	4/5.5	4/4.5	4/4	4/5	4/6.5	4/4	4/2	0.13
GD	5/5.5	5/4.5	5/4	5/5	5/6.5	5/4	5/2	0.16
NR	6.5/5.5	6.5/4.5	6.5/4	6.5/5	6.5/6.5	6.5/4	6.5/2	0.21
Slope	4/5.5	4/4.5	4/4	4/5	4/6.5	4/4	4/2	0.13
SW	2/5.5	2/4.5	2/4	2/5	2/6.5	2/4	2/2	0.06
Column total								1.00

GM geomorphology; *GG* geology; *GD* post-monsoon groundwater depth; *NR* net recharge; *SW* proximity to surface water body

Table 5 Assigned and normalized weights of different features of seven thematic layers for groundwater potential zoning

Features	Groundwater prospect	Area (km^2)	Assigned weight	Normalized weight
Geomorphology				
Lake	Very good	67	8.0	0.26
River	Very good	446	8.0	0.26
Valley fill	Good	457	7.0	0.23
Buried pediment	Moderate	1684	4.0	0.13
Pediment	Poor	2409	3.0	0.10
Structural hill	Very poor	7632	1.0	0.03
Geology				
Gneiss	Very good	3157	8.0	0.29
Granite	Good	418	7.0	0.25
Phyllite-Schist	Moderate	3567	5.0	0.18
Quartzite	Poor	174	3.5	0.13
Schist	Poor	808	3.0	0.11
Hillocks	Very poor	4574	1.0	0.04
Soil				
Sand	Very good	762	8.0	0.30
Coarse loam	Good	264	7.0	0.26
Loam	Moderate	59	6.0	0.22
Fine Loam	Poor	5132	3.0	0.11
Clay	Poor	671	2.0	0.07
Rock outcrops	Very poor	5811	1.0	0.04
Post-monsoon groundwater depth				
2–4.5 m	Very good	1793	8.5	0.35
4.5–7 m	Good	6466	7.0	0.29
7–9.5 m	Moderate	2610	5.0	0.20
9.5–12 m	Poor	1142	3.0	0.12
>12 m	Very poor	686	1.0	0.04
Net recharge				
<1 cm/year	Very poor	2938	4.0	0.12
1–2 cm/year	Poor	4274	6.0	0.18
2–3 cm/year	Moderate	2206	7.0	0.21
3–4 cm/year	Good	2185	7.5	0.23
>4 cm/year	Very good	1095	8.5	0.26
Slope				
0–3%	Very good	2645	7.0	0.39
3–10%	Good	5009	6.0	0.33
10–30%	Poor	3586	4.0	0.22
>30%	Very poor	1458	1.0	0.06
Proximity to surface water bodies				
<75 m	Good	637	8.0	0.50
75–150 m	Moderate	132	6.0	0.38
>150 m	Poor	11929	2.0	0.13

4.5 Groundwater Potential Map

The groundwater potential map of the study area (Fig. 15) reveals four distinct zones representing ‘good’, ‘moderate’, ‘poor’ and ‘very poor’ groundwater potential

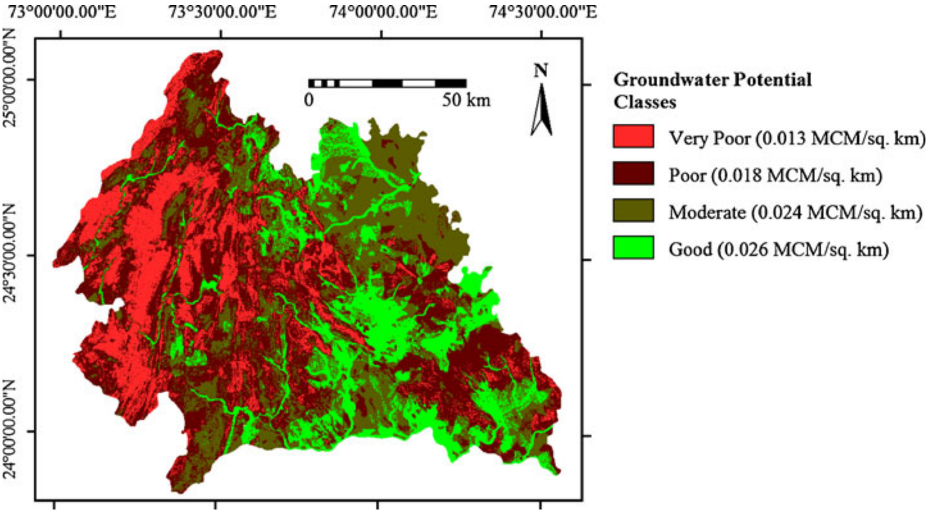


Fig. 15 Groundwater potential zone map of the study area

in the area. The 'good' groundwater potential zone mainly encompasses gneiss and buried pediment areas around the river systems. It demarcates the areas where the terrain is most suitable for groundwater storage, and also indicates the availability of water below the ground. The area covered by 'good' groundwater potential zone is about 2,113 km^2 (17%). Parts of almost all the blocks mainly Sarada, Salumber, Girwa, Dhariawad, Bhinder, Mavli, Badgaon, and Kherwara fall under this zone. The northeast portion and some small patches in the north, south, central, and southeast portions of the study area fall under 'moderate' groundwater potential zone. It encompasses an area of 3,710 km^2, which is about 29% of the total study area. The 'poor' groundwater potential zone mainly covers the area where rock outcrops cut the land surface and is dominant in the area encompassing an area of 4,599 km^2, which is 36% of the total area. The groundwater potential in the western portion and parts of northeast, central, eastern and southeast portions of the study area is very poor covering an area of 2,273 km^2, which is 18% of the total area. The 'very poor' groundwater potential in the study area is most likely due to the presence of hillocks, rock outcrops, and steep slopes.

4.6 Zone-wise Exploitable Groundwater Reserve

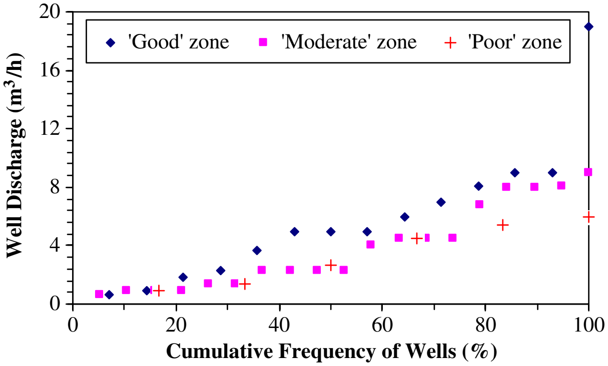
The mean annually exploitable groundwater reserve in the 'good' zone is estimated to be 54 million cubic metre (MCM) (0.026 MCM/km^2), whereas it is 89 MCM (0.024 MCM/km^2) in the 'moderate' zone, 85 MCM (0.018 MCM/km^2) in the 'poor' zone, and 31 MCM (0.013 MCM/km^2) in the 'very poor' zone. Thus, the total amount of mean annually exploitable groundwater reserve is more for the 'moderate' and 'poor' zones compared to that for the 'good' zone, which is due to larger areas falling under 'moderate' and 'poor' zones. It should be noted that these estimates of annually exploitable groundwater reserve for each potential zone are conservative because they represent the amounts of groundwater replenished annually. Therefore, these groundwater reserves can be considered as safe annual withdrawal from individual zones, which can be fully utilized to meet the water demands of different sectors. However, it is necessary to carry out step-drawdown pumping tests in the study area to determine sustainable yields of individual well sites within a zone.

4.7 Verifying Groundwater Potential Zone Map

The delineated groundwater potential zone map was finally verified using the available measured discharges of 39 pumping wells. The verification of the groundwater potential map with the well yield data reveals that nine of the 16 'high discharge' wells (discharge ≥ 5 m^3/h) exist in the 'good' zone, whereas five and two 'high discharge' wells exist in the 'moderate' and 'poor' zones, respectively. The majority of the 'medium discharge' (1–5 m^3/h) and 'low discharge' (<1 m^3/h) wells (i.e., 10 of 16 'medium discharge' and four of seven 'low discharge' wells) fall in the 'moderate' zone. It should be noted that no pumping well exists in the 'very poor' zone. Thus, the mean discharges of the wells falling in the 'good', 'moderate' and 'poor' zones are 5.88, 3.81, and 3.48 m^3/h, respectively.

Furthermore, the cumulative frequency of the wells falling in the 'good' zone is higher than that of the wells in the 'moderate' zone (Fig. 16). Similarly, the cumulative frequency of the wells lying in the 'poor' zone is lower than that of the wells in the 'moderate' zone. Based on these findings, it can be inferred that the groundwater potential zones identified by RS, GIS and MCDM techniques are reliable. The developed groundwater potential map can serve as useful guidelines for the cost-effective selection of suitable well-sites and thereby help efficient planning of scarce groundwater exploitation in the semi-arid study area so as to ensure sustainable groundwater development.

Fig. 16 Cumulative frequency of pumping wells in the delineated potential zones



5 Conclusions

In this study, a standard methodology for delineating groundwater potential zones using RS, GIS and multi-criteria decision making (MCDM) techniques has been proposed. The proposed methodology has been demonstrated by evaluating the groundwater potential of a hard-rock aquifer system in semi-arid Rajasthan, western India. Satellite data (SRTM data), conventional maps, groundwater level and specific yield data were used to prepare the thematic layers of ten hydrologic/hydrogeologic parameters namely topographic elevation, land slope, geomorphology, geology, soil, pre- and post-monsoon groundwater depths, annual net recharge, annual rainfall and proximity to surface water body. These thematic layers were scrutinized by principal component analysis (PCA) technique to select influential layers for groundwater assessment. The selected seven thematic layers and their features were assigned suitable weights on the Saaty's scale according to their relative importance in groundwater occurrence. The assigned weights of the thematic layers and their features were then normalized by using AHP (analytic hierarchy process) MCDM technique and eigenvector method. These layers were integrated in the GIS environment by weighted linear combination method with the help of ILWIS software to delineate groundwater potential zones in the study area. In addition, the mean annually exploitable groundwater reserves for each identified groundwater potential zone were estimated by groundwater-level fluctuation method. Finally, the developed groundwater potential map was verified using the well yield data of 39 pumping wells.

Based on the methodology presented in this study, the study area was demarcated into four groundwater potential zones, namely 'good', 'moderate', 'poor', and 'very poor', which cover 17%, 29%, 36%, and 18% of the study area, respectively. In the 'good' zone, the mean annually exploitable groundwater reserve is estimated to be 0.026 MCM/km^2, whereas it is 0.024 MCM/km^2 in the 'moderate' zone, 0.018 MCM/km^2 in the 'poor' zone, and 0.013 MCM/km^2 in the 'very poor' zone. Since the major portion (more than 80%) of the study area exhibits 'very poor' to 'moderate' groundwater potential, it can be inferred that groundwater resource is somewhat limited in the semi-arid study area. Therefore, judicious utilization of groundwater resources coupled with proper water management is essential for ensuring groundwater sustainability in the face of climate change. The verification of the groundwater potential map using well yield data was found to be reasonable. However, there is a need for a rigorous verification of groundwater potential map obtained by RS, GIS and MCDM techniques in order to properly evaluate the efficacy of these modern techniques. The groundwater potential zone map could be properly verified by conducting step-drawdown pumping tests at different locations within each groundwater potential zone, thereby determining site-specific sustainable groundwater withdrawals. Nevertheless, in the absence of such a rigorous validation, the proposed methodology can be used as a first estimate of the groundwater prospect and the identified favourable zones should be preferred for drilling water supply wells. Thus, the groundwater potential map developed in this study is very useful to the concerned decision makers and water managers. It can help formulate effective groundwater exploitation strategies for the study area so as to ensure long-term sustainability of this vital resource.

Overall, it can be concluded that RS, GIS and MCDM techniques are powerful tools for evaluating groundwater potential which can help prepare a suitable and cost-effective groundwater exploration plan for a basin or sub-basin. The proposed methodology, which is generic in nature and based on logical conditions and reasoning, can be useful for the other regions of the world as well. More interestingly, the methodology is less expensive and more suitable for developing and low-income countries where adequate and good-quality hydrogeologic data are often lacking for groundwater evaluation by data-intensive techniques.

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