Application of remote sensing and GIS for groundwater potential zones identification in Bata river basin, Himachal Pradesh, India

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Abstract: Groundwater is not uniformly distributed all over and is limited in hard rock terrains. A case study was made to find out the groundwater potential zones in Bata river basin, in Himachal Pradesh, India. Thematic maps of geology, geomorphology, soil, land-use/land-cover and drainage were prepared for 288 km^2 study area. Digital Elevation Model (DEM) was generated from 20 m interval contour lines to obtain the slope of the study area. Ground water potential zones were obtained by overlaying all thematic maps in terms of the weighted index overlay method. Ranking was given for each individual parameter of each of the thematic maps and weights were assigned according to the influence such as land-use/land-cover (8%), slope (5%), geomorphology (6%), fault buffer (5%), aspect map (5%), lineament buffer (5%), drainage buffer (7%) and geology (7%) in terms of very poor, poor, moderate to good, good and very good within the study area. The GIS method output results were validated by conducting field survey by randomly selecting wells in different villages using GPS instruments. Coordinates of each of the well locations were obtained and plotted in the data base. The spatial variation of the potential zones indicates that groundwater occurrence is controlled by structures, landforms and slope.

Keywords: Open potential, GIS, Index overlay method, Remote sensing

1. Introduction

Ground water is one of the most important natural resources on which the survival and progress of mankind depends to a great extent. It is a renewable resource. In view of its wide distribution, low level of contamination and availability in the reach of the consumer, ground water development gets priority for meeting the ever-growing demand of water for domestic, agricultural and industrial purposes (Murthy, 2000; Sener et al., 2005; Ibrahim-Bathis and Ahmed, 2016). It is a critical resource in many parts of the world, especially in the arid and semiarid drought prone regions. It sets limits on the agricultural development *via-a-vis* the density of population and standard of living that can be sustained. In India, more than eighty percent of the population lives in villages. The overall development of the country would be meaningful only when the rural living conditions are improved (Dey and Naithani, 1988). In this context, ground water development is vital for rural upliftment. Though the replinishible groundwater resources in India is estimated to be around 42.3 million hectare meters (mhm) per year, at present only about 13.5 mhm is being exploited. This clearly shows that there is major scope for further ground water development. Ground water development does not require major investment, planning and government machinery. To meet the basic needs of rural population for portable water, national drinking water technology mission has been taken up using remote sensing technology for finding water sources. In India, 65% of the total geographical area is covered by hard rock formations with low porosity (less than 5%), and very low permeability (10^{-1} to 10^{-5} m/day) (Saraf and Choudhury, 1998). Therefore, efficient management and planning of groundwater is of utmost importance. Remote sensing provides multi-spectral, multi-temporal and multi-sensor data of the earth's surface (Krishnamurthy and Srinivas, 1995; Choudhury, 1999; Singh and Prakash., 2002; NRSA, 2008; Avtar et al., 2010; Chowdhury et al., 2010; Rashid et al., 2011; Ibrahim-Bathis and Ahmed, 2016). One of the avdvantages of using remote sensing and GIS for hydrological investigations and monitoring is its ability to generate information in spatial and temporal domin, which is very crucial for successful predication and validation (Burrough, 1986; Dar et al., 2010; Senthil Kumar and Shankar, 2014). Remote sensing is providing useful base-line information in conjunction with ground water truths on soils, land use, vegetation, surface and ground water, geology, landforms, topography and settlements in the regional prospectives. During the present investigation, ground water potential zones were studied in Bata river basin in Himachal Pradesh, India by integrating various thematic maps in GIS environment.

2. Materials and methodology

2.1 Study area

The Bata river basin, lying between latitude 30º 25′ 3.33′′−30º 35′ 13.71′′N and longitude 77º 22′ 34.75′′−77º 39′ 42.31′′E is spread over about 288 km^2 in the district of Srimaur in Himachal Pradesh (Fig. 1). It is bounded by the sinuous and meandering grip in the north-east by the Yamuna. The catchment is roughly elliptical in shape. The maximum east-west and north-south datum lengths are 36.4 km. The climate is sub-humid sub-tropical in lower part of the tract lying in Siwaliks and wet temperate in the upper part in central Himalaya. The region has distinct seasons of summer (April-June), monsoon (July-September), autumn

(October-November) and winter (December-March). Summer variation is very high; temperatures go up to about 42°C in the lower Siwaliks, but it is around 25°C in the upper part. The Bata river is characterized by highly dissected Siwalik hills merging into the valley on either side of the Bata river. The valley extension of Dun valley is called Kiarda dun. About 95 per cent of area falls under low hills of altitude <1,000 m. Half of the area is under moderately steeply sloping lands. Geomorphologically, the area can be divided into hills, piedmonts, terraces, flood plain and channel bars. A greater part of the Bata river lying in the middle Himalaya and Siwaliks is hilly with deep and narrow valleys separated by spurs and ridges. The altitude of the tract varies from 400 m at the mouth of Bata river at Sidhpurwala, northern ridge Baila (1020 m asl) and in south above Kolar (665 m asl). Large part of the study area falls under a variety of vegetation types with tropical and sub-tropical sal, khair and sissoo in Dun and lower Siwaliks, chir in the middle and upper Siwaliks and kail, deodar and oaks in the central Himalayan part. There is a good mixture of broad-leaved species in all the vegetation zones. Some part of the study area comes under the shrubland. Barren lands are also observed in some parts of the study area.

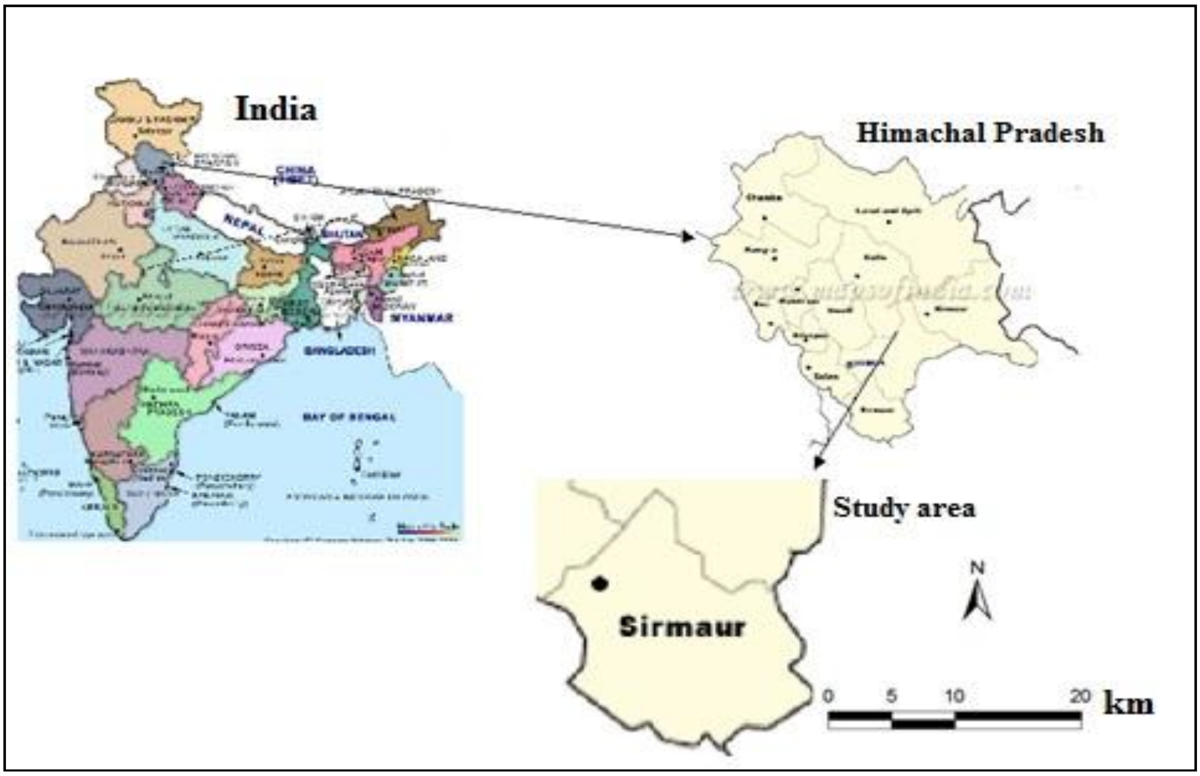

Figure 1: Location map of the study area

2.2 Method

2.2.1 Data acquisition and software: Topographical base of Bata River Basin area: The Survey of India (SOI) toposheets no. 53F/6, 53F/7, 53F/10 and 53F/11 on 1:50.000 scales formed the source of data for the study. The image data was a product of Indian Remote Sensing (IRS) 1D LISS III of December 2016 with spatial resolution of 23.5 m and the image has four bands and PAN data 5.8 m were merged using principal component analysis. Tube well data, dug well data, rainfall data of various locations in and around the Bata river were collected from the government offices. SOI toposheets and visual analysis of satellite data in conjunction with the available ancillary data were used as reference maps for the preparation of thematic maps. Considering seven factors *viz*., land-use/land-cover, slope, geology, geomorphology, fault buffer, lineament buffer and drainage buffer maps weightages were assigned to each of these factors according to their relative importance. These attributes were used to create database in ArcGIS and the groundwater potential map was derived. The flowchart (Fig. 2) shows the sequential steps involved in this study.

Software used: The GIS software used for digitization and overlay analysis in the present study area were the ArcGIS®10 software and ERDAS Imagine®2013. These were used for geo-referencing, creation of attributes table and digitization of the collected maps. ArcGIS®10 is vector based package and it is capable of accessing spatial data base, analysis and produce outputs for the present study.

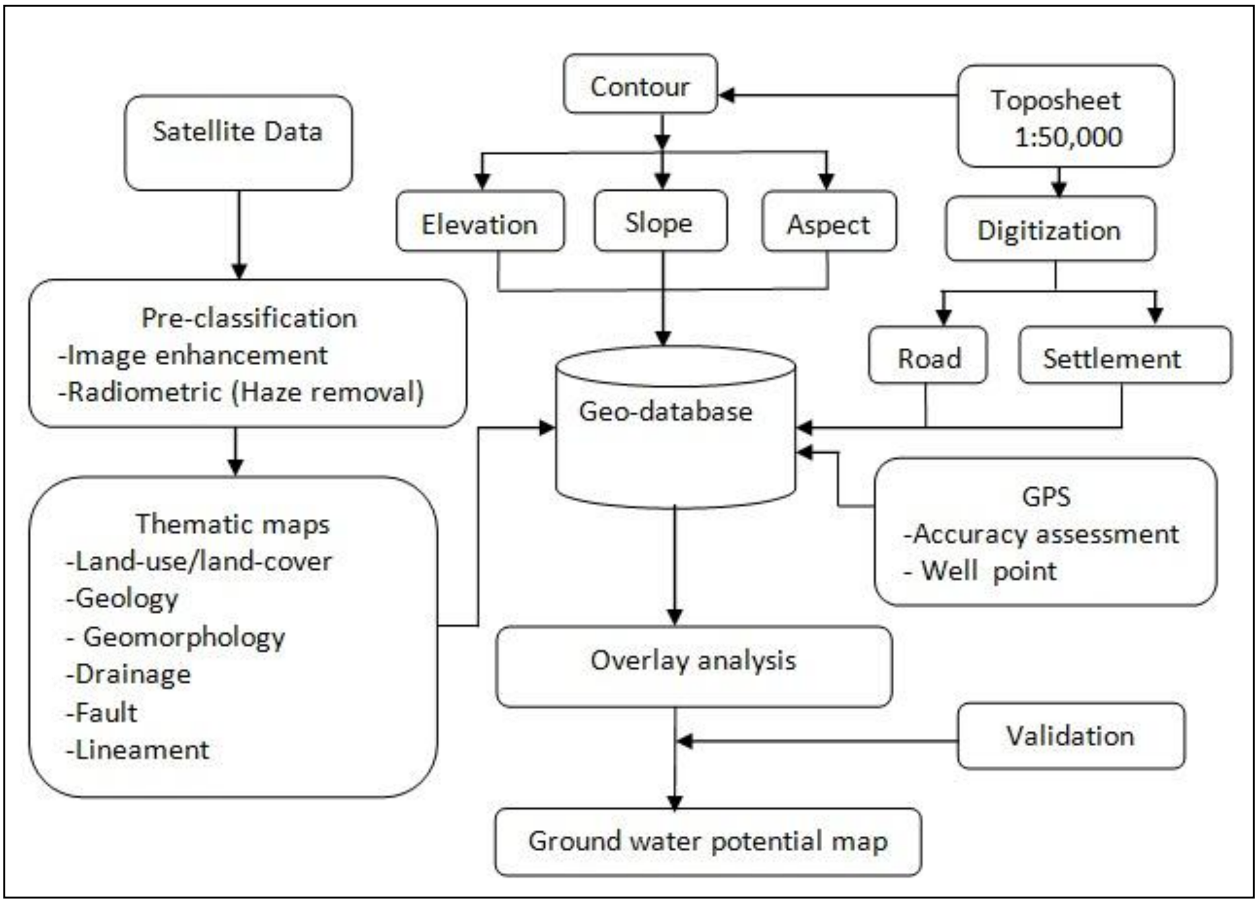

Figure 2: Methodology flow chart of the present study

2.2.2 Field data collection: A pre-field interpretation map was prepared and the bore well points were verified by ground truth. Ground truth information was collected by GPS survey. Recent satellite data were used during the field survey and the current land use classes and the field data of wells location points were collected. Geomorphic provinces and hydrological characters of various units were recorded. Major lineaments/faults affecting the area and mass movement activities were also studied during prefield interpretation. Visual interpretation of above satellite data of the study area was required for comparative study of geology, structure, geomorphology, hydrology, land-cover and land-use. Data were transfered on base map in order to prepare the overlays of geology, geomorphology, land use derived from imagery. Geotraverses were planned for the selected field check to finalize the pre-field map. The GPS points were downloaded and overlaid on the imagery and used for refinement of the pre-field interpretated land-use/land-cover and ground water potential map.

2.2.3 Index overlay method: Index overlay method was applied where maps were analysed together in a weighted combination. In this simplest type of weighted model, input maps are binary and each map carries a single weight factor (Saaty, 1980). However, multiclass maps are used, each class of every map is given a different rating score. In case the map classes occurring on each output map are assigned different score, as well as the map receiving different weights. It is convenient to define the score in attribute table for each input map. The average score can be defined as:

$$\mathbf{S = \sum S\ ij\ Wi / \sum Wi}$$

i = 1 to n (no. of thematic layers)
j = 1 to m (no. of classes in theme)

where S is the weighted score for this study area object (polygon, pixel), Wi is the weight of the input map, and S ij is the rating score for the j^{th} class of the i^{th} map. The value of j depending upon the class actually occurring at the current location. Each map must be associated with a list of scores, one per map class. Class scores can be put into an attribute table with an editor, for access by the modeling procedure. The attribute table can be modified without changing the procedure. If the score for some classes are set to negative value, area where such a class occurs are automatically set to class 0 (zero) in the output map.

2.2.4 Integration of thematic layers: In order to integrate various thematic maps, a rating was developed for the integration of these thematic maps. A numerical rating system ranging from 1 to 9 were assigned to various classes of individual themes, based on degree of influence of individual categories on ground water regime of the region (Table 1). All the thematic maps were assigned a “weightage factor, called equal weightage integration method” aimed at reducing subjectivity in rating of coding, completely from the analysis (Dinesh Kumar et al., 2007; Preeja et al., 2011).

Ground water potential zones were obtained by overlaying all thematic maps' output in raster format and classified in to user-defined classes, showing different ground water prospective area based on the selected parameter in ArcGIS®10 software.

Table 1: Rank and weightage of different parameters for groundwater potential zones

Parameter	Classes	Individual weights	Total Weight
Land-use	River bed Scrubland Degraded Forest Dense Forest Exposed Rock Water Standing Crop Fallow land	6 2 5 6 1 9 8 7	25
Slope (°)	0-15^0 15-30^0 30-45^0 45-60^0 60-90^0	8 7 5 4 1	15
Geomorphology	Structural hill Subdued hill Upper Piedmont River Terrace Middle Piedmont River bed	2 3 3 8 4 9	25
Fault	100 200 300	2 2 3	5
Lineament buffer (km/km2)	25 50 75	2 2 3	5
Drainage (km/km2)	5 8 12 16 20	2 3 5 6 7	10
Lithology	Lower Siwalik Upper Siwalik Alluvium Doon Gravel Subathu Dagshi formation Mandhali formation	3 3 8 5 2 2 4	10

3. Results and discussion

3.1 Lithology

In the present study, seven types of lithological characteristics were considerd to understand the distribution and occurrence of ground water (Table 1). The lithological map of the study area is shown in (Fig. 3). The upper Siwalik are exposed in the southern part of the basin and are overlaid by the Nahans (lower Siwalik) along the Markanda thrust. The pre-tertiary limestones, (Sataun formation) wherever exposed, occur as discontinuous outcrops along the fringe of Nahan thrust separating them with lower Siwaliks. The main boundary thrust demarcates the boundary between Siwalik and the older rocks and marks the boundary between the Nahan (lower Siwaliks) and the pre-Nahan (Sabathu and /or Sataun formation), (NRSA, 1999).

3.1.1 Upper Siwaliks: This formation is encountered in the southern part of Bata catchment separating its boundary with Haryana. It is composed of grey, soft friable sandstone with clay bands. These are interbedded with conglomerates (Dey and Naitnani, 1988). The upper Siwaliks are exposed in the south along the Bata and Markanda rivers and deposit more dissected topography in the area. The formation consist of coarse classic deposits such as boulder conglomerate, grit, sand and earthy clays. It generally starts with pebbles horizon at the base grading upward into thick. Some part of the band alternating with conglomerates is soft sand stone and in the upper part there are clays with same sandstone. The boulders and pebbles are ill sorted and composition is heterogeneous and they are of all shapes, sub rounded to rounded and sub angular. They are mostly formed of quartzite, schist, chert phyllite slates and granite gneisses. The upper Siwaliks are expressed in road section of Puruwala and Kolar.

3.1.2 Lower Siwaliks: The lowermost part of Siwalik formation has fine to medium grained relatively matured sediments with calcareous cementing material (Devi and Wankhede, 1995). These sediments are said to be from the rising mountains in the north and were laid down in alluvial plains of a series of rivers or a single river system named as "Indo-Brahma" river. In the Bata basin, Nahans are northerly dipping in general amounting to 20º-30º. Nahans in the area succeeded upwards by the older Subathu rocks. It is made up of alternating beds of sandstone and clay. The sandstone is micaceous and light gray in colour. It is mainly formed along both the sides of ridge dividing Giri catchment with Bata river.

3.1.3 Middle Siwaliks: These rocks are exposed in the northern part of Bata catchment overlaying the lower Siwalik along the ridge dividing Bata with Giri river. It consists of hard grey sandstone with small potion of orange clay and subordinate shale.

3.1.4 Alluvium: The central regions parallel to the NW-SE flowing Bata river and planking its sides are mostly covered with recent alluvium. It contains lenticular beds of sand and gravels.

3.1.5 Subathus: Subathu is named after the town Subathus of the Simla hills, which consists of thick succession of green, grey and red shales intercalated with thin lenticular bands of sandstone and impure limestone (Jugran, 2003). The red shale often contains gypseans, carbonaceous and pyretic layer. These rocks are exposed in the central part of the area just after Baila towards Birla village, extending upto the northwestern tip.

3.1.6 Dagshi formation: It consists of massive, very hard grey and purplish brown quartezitic sandstone, intercalated with seams of red clay. It covers major portion of Sarahan and Narg ranges and small part occurs in the study area.

3.1.7 Mandhhali: Mandhali of the study area marked plane of structural discordace exits as a distinct linear feature between lower Siwalik and Pretertiary rock. Stromatolitic (algal shape) structure is the charctaristics feature of this rock unit. It occupies northern part just up of the lower Siwalik of the study area associated with green slate, phyllite and black shale and extend to further eastward across Yamuna river. Quartzite, carboniferous material is also found here. Strain in the rock indicates slikenside nature. This is the older rock. While carrying out detailed geological study the limestone belt of pre-Tertiary in the Bata basin marked plane of structural discordance exists as a distinct linear feature between Nahanas (lower Siwaliks) to its south and the older Tertiaries (Subathu) to its north. The carbnate rocks of the Basantpur formations extends in time to lower Palaeozoic, and there is no fossil records to support. The limestone is massive, thinly bedded, white grey in colour and are seen on road sections of Grinagar-Baila.

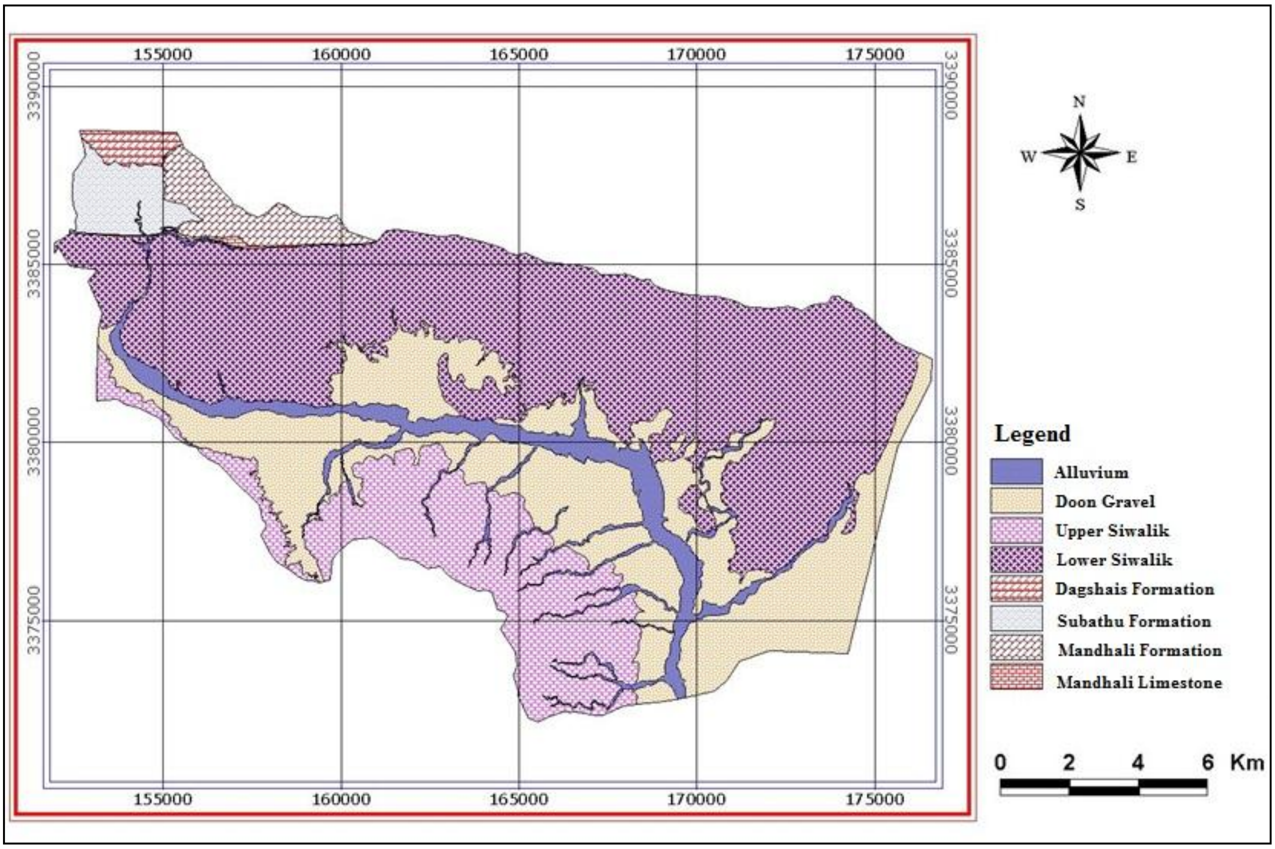

Figure 3: Lithology map

3.2 Geomorphology

It is well known fact that the geomorphological characteristics of an area affect its response to a considerable extent of groundwater occurrence (Nossin, 1971; Thomas et al., 2009). Thus, linking of geomorphological parameters with hydrological characteristics of a basin provides a simple way to understand their hydrological behavior (El-Gammal et al., 2013). The geomorphological characteristics were divided into six major groups. The geomorphological features such as river bed, river terrace, middle piedmont, upper piedmont, structural hills, subdued hills are the good sources of groundwater of the study area (Fig. 4). The alluvial plain of the Bata basin cover an area of 75.0 km^2, which is 27.55 percent of the total area of the Bata basin. The younger alluvium of the alluvial plain of the Bata basin covers only 17.1 km^2 area, which is 6.28 percent of the total basin. The older plains, which extend in an area of 57.9 km^2 or 21.27 percent of the total Bata basin, are in fact, relics of older flood plain. The piedmont zone of the Bata basin covers 133.3 km^2 area or 48.97% of the total area of the Bata basin. The upper piedmont zone or the denudational slopes cover an area of 41.4 km^2 or 15.21% of the total area, where as the middle piedmont zone or the fan-plain cover an area of 52.5 km^2 or 19.29% of the total area. The denudational sub-dued hills are found almost in all the three sections of the piedmont zone. These are mainly the highly eroded hills in the lower and upper Siwalik. Older and younger fan terraces are the most important landform found in the lower piedmont zone or fan-plain area of the Bata basin. The denudo-structuralhills of Bata basin cover an area of 63.9 km^2 or 23.48% of the total area of the basin. The ranks are given to geomorphological units considering their contribution to groundwater infiltration.

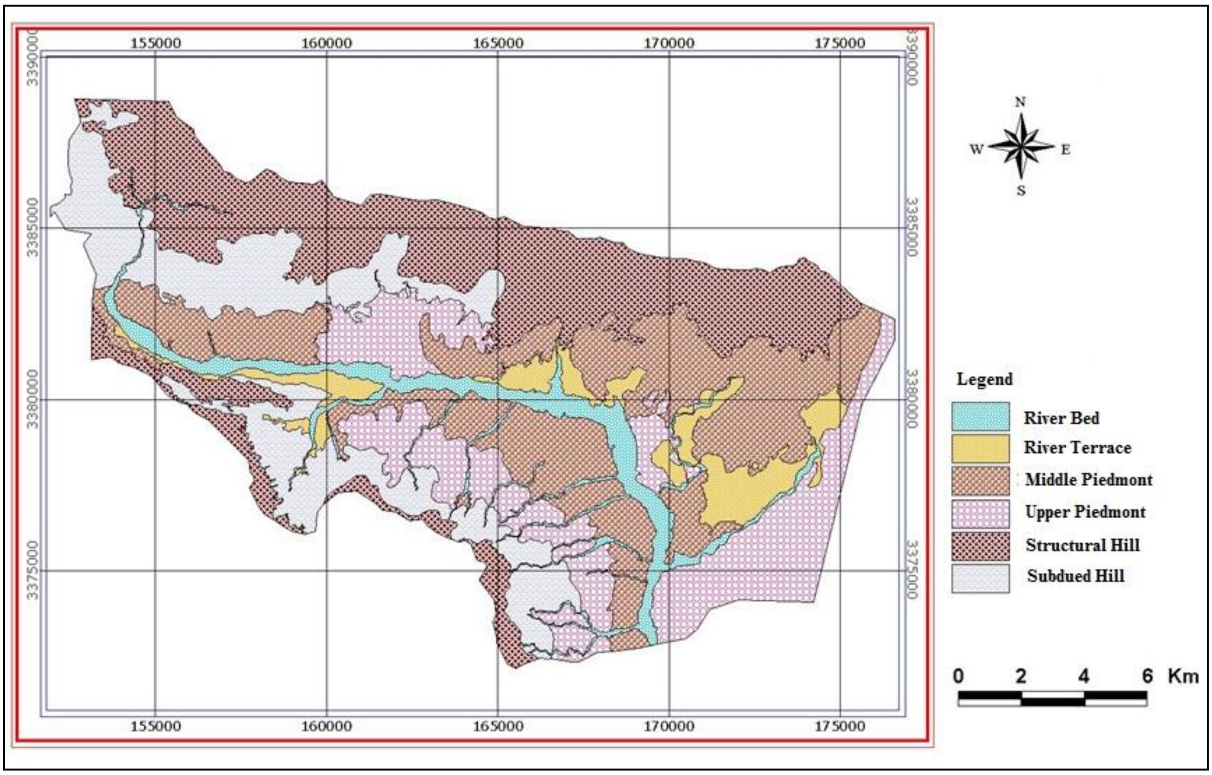

Figure 4: Geomorphological map

3.3 Slope

Slope of a surface refers to change in height across a region of surface. Slope is an important factor as it affects land stability. The slope of the study area ranged from 0º–>90º (Fig. 5) Steep slope was found mainly in North-south part of the province. In the central part the area has flat topography. Mostly, the hilly terrains are having steep slope. Slope steepness/gradient is important because it influences groundwater recharge (IMSD, 1995; Rokade et al., 2007). Flat areas are capable of holding the rainfall and facilitate groundwater replenishment in contrast to steep areas which instigate runoff. Low slope indicates the presence of high groundwater potential zones, high slope shows the presence of poor groundwater potential zones, as water drains rapidly off the surface.

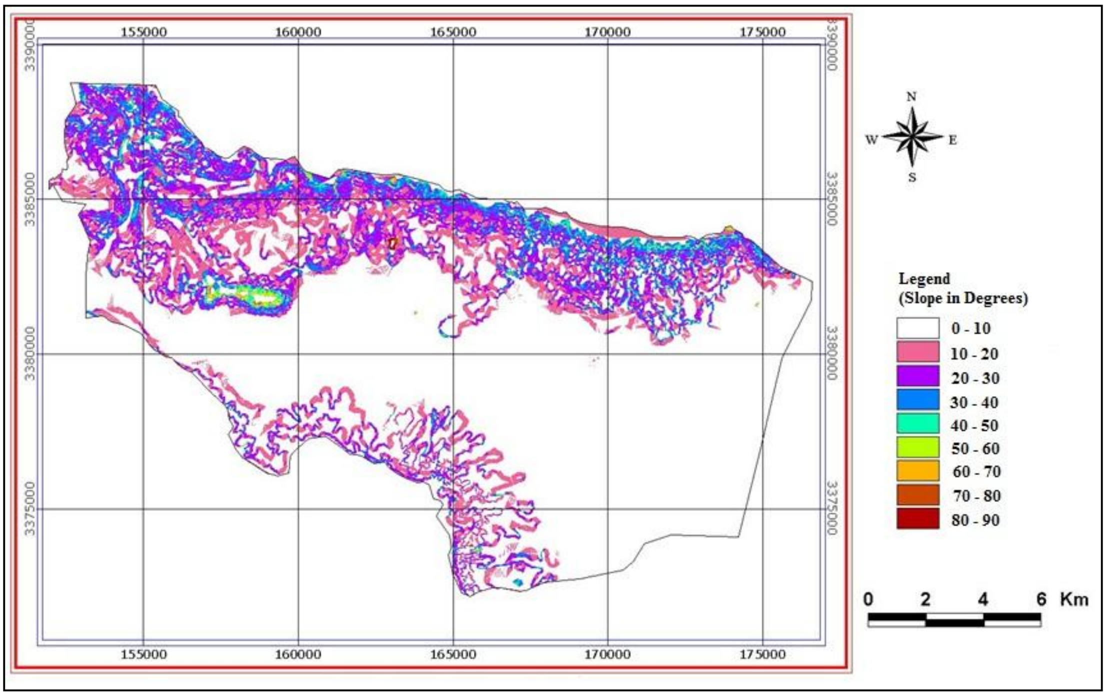

Figure 5: Slope map

3.4 Drainage density

Another input to evaluate the recharge property can be realized by detailed morphometric analysis of the drainage network. Drainage pattern of any terrain reflects the characteristics of surface as well as subsurface formations. In areas where the number of streams is more in a unit area, the largest proportion of the water coming from precipitation goes to runoff (Tribe, 1991; Shaban et al., 2006; Sreedevi et al., 2009). This is indicative of the subsurface condition of porosity. The drainage network order to a large extent depends on lithology, which provides an important indication of the percolation rate. Seventy three percent of the study area falls under low to moderate drainage density category. Thus, low drainage density was assigned for good ranking as high drainage density implies low groundwatwer potential in the study area.

3.5 Distance from structures

Linear structures, which are important for increasing the permeability of the bed rock are lineaments, faults, fractures, and joints (Fig. 6). O'Leary et al. (1976) defined a lineament as a mappable and simple or composite liner feature of a surface, whose parts are aligned in a rectilinear or slightly curvilinear relationship. These structural features are identified from the digital remote sensing data and distance to structure map is derived using the distance function. Areas close to structures develop a secondary porosity that will help them to percolate water better than those far from structures. Therefore, higher rank is given to areas proximal to geological structures. Generally, the folded structures in the form of synclines and anticlines are found in the study area. Syncline is found near Thana Panjahal in the western part, north of main boundary fault (Nag, 2005; Sander, 2007). This syncline is followed by anticlinal flexure exposing Dharmshala rocks within the core portion near Birla village. The synclinal axis is running nearly parallel to the main boundary fault.

The demarcation is more clear due to change in topography. This is also dipping towards north. Sudden changes in slope form saddle indication of thrust in the study area, which is clearly seen in remote sensing data as a deep trench extending E –W direction of the area. Roasted quartzite, crushing nature in upper Siwalik sand stone, depression in Sirmur tal (forming a big lake) also indicate thrust passing through the area. The lower Siwaliks are thrusted over the upper Siwaliks (Markanda fault) along Markanda and Bata river (flowing in a same line but both are 180^{o} apart to each other). This fault marks the southern boundary between lower Siwaliks. It runs eastwards and disappears over the alluvium deposits along Bata river in east and Marjanda in west. The differences in the levels as well as different geological unit on the both the banks of river are indication of fault. Near Dakpathar, the Bin river course follows the Markanda fault, which separates lower Siwaliks from middle Siwalik formation and joins with Main Boundary Fault (MBF). Number of transverse and cross faults is picked up from image interpretation of the study area. These faults are occurring the Pre Tertiaries and Tertiaries formation. Number of informational faults are observed in Siwalik group of rock. Major break in slope and variation dipping attitude were seen in lower Siwalik. Road section from Dhola Kuwan to Baila and other places show number of break in slope and sagging. Malgi village is a good example of these phenomena. Thrust is low angle reverse fault forming a wide zone known as Thrust Zone. One important thrust is available in the study area as follow: MBT also a low angle NW-SE to EW trending reverse fault, dipping towards N and NE. The Pre Tertiary rock like slate, phyllite and quartzite are moderately fractured and jointed. The lower Siwalik sndstone is also moderately fractured and shows criss cross jointing. The NS joint is prominent. The rocks of middle Siwaliks are poorly jointed.

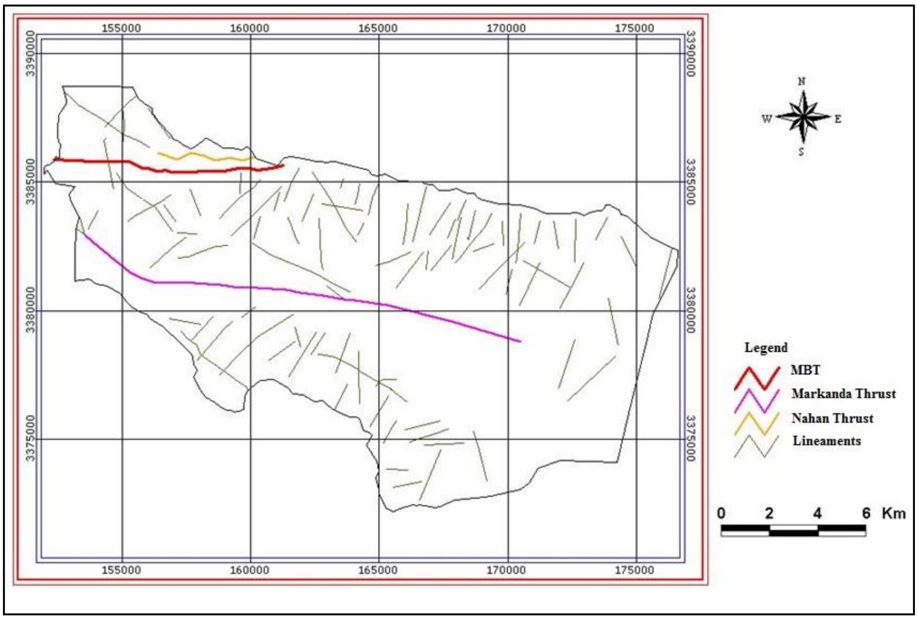

Figure 6: Lineament map

3.6 Land-use/land-cover

The land-use/land-cover map of the entire Bata basin was generated (Fig. 7) and derived classes is presented in Table 1. The effect of land cover to groundwater recharge is both negative and positive (Todd and Mays, 2005; Shaban et al., 2006; Chowdhury et al., 2009; Rawat and Manish, 2015). Trees may increase water loss by evapotranspitation or they may facilitate recharge by reducing runoff and by intercepting water and infiltrating its droplet slowly. For the identification and interpretation of the landuse pattern of area through image interpretation of remote sensing data, landcover classes were delineated. It includes standing crop, fallow land, dense forest, degraded forest, grass land, exposed rock, barren land and water body.

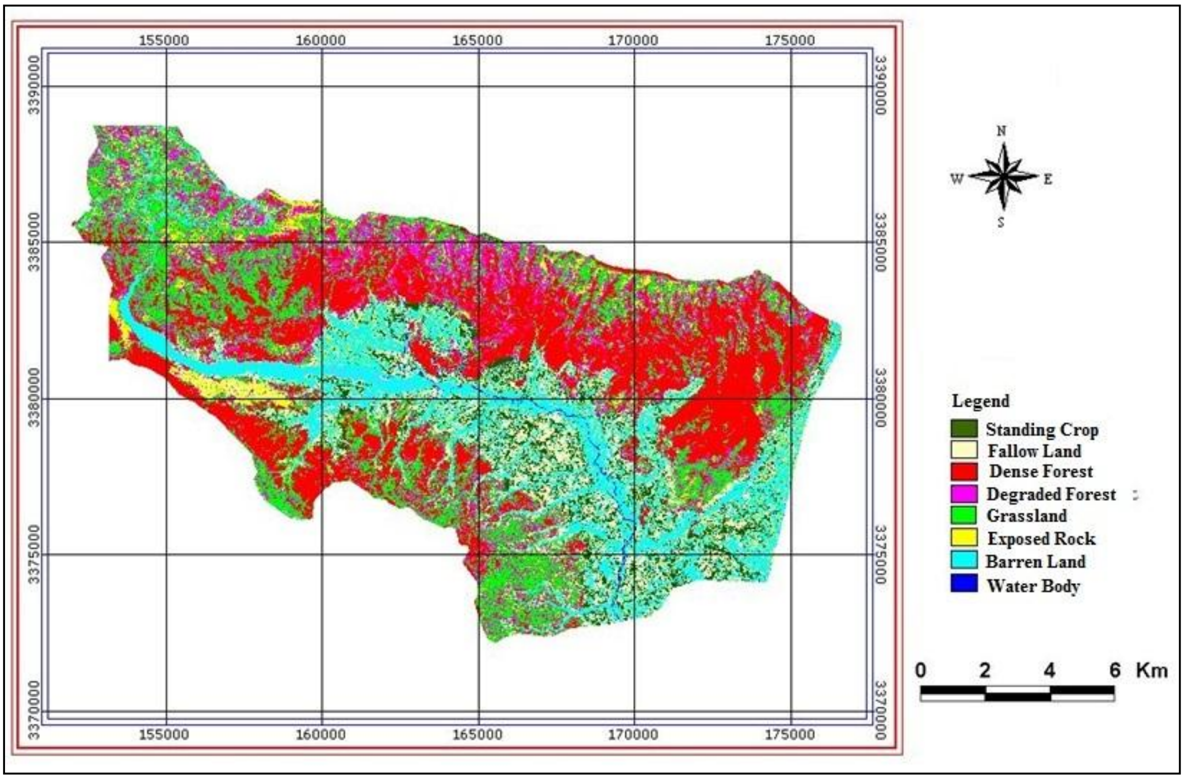

Figure 7: Land-use/land-cover map

3.7 Model validation

The groundwater potential map (Fig. 8) was generated on the basis of weights and ranks assigned to different parameters of the thematic layers in GIS, which was classified into groundwater potential zones based on the decision as very good (10.7% of the area), good (13.4% of the area), moderate (18.6% of the area), poor (32.4% of the area) and very poor (24.9% of the area). The validation of the model developed was done against the well inventory data, which reflects the actual groundwater potential zones prepared by the model to check the validity of the proposed model (Table 2).

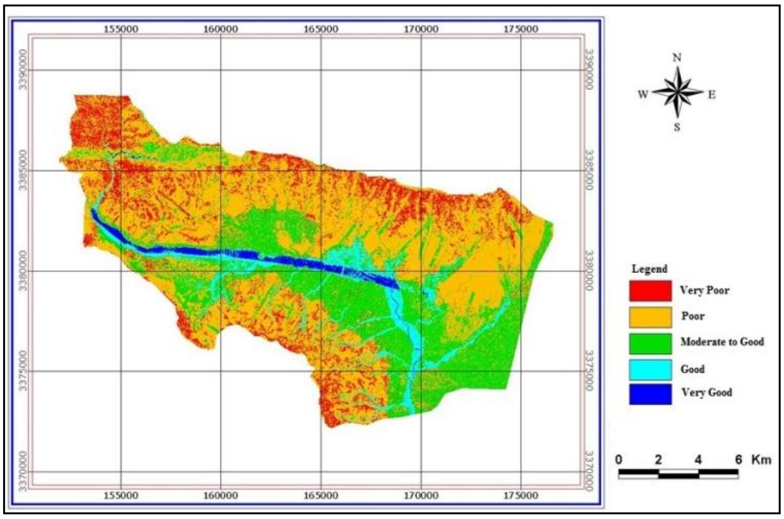

Figure 8: Groundwater potential zones of the study area

Table 2: Well inventory data of the study area

Sr. No.	Location (Village Name)	Depth of well (m)	Dia	Use
1	Teruwala	9.44	1.65	Domestic
2	Gondpur	9.16	2.39	Domestic
3	Jwalapur	25.96	2.9	Domestic
4	Naraingarh	36.1	2.84	Domestic
5	Kishankot	42.05	3	Domestic
6	Badrinagar	10.17	1.65	Domestic
7	Bhadripur	8.72	1.75	Domestic
8	Bain kuan	2.5	2.47	Domestic
9	Ganguwala	2.37	2.18	Domestic
10	Jamunawala	4.06	1.83	Domestic
11	Dhoka	1.89	1.85	Domestic
12	Gulabgarh	2.37	1.18	Irrigation
13	Ajiwala	4.67	1.89	Domestic
14	Khara	9.24	1.67	Domestic
15	Bhuppur	12.02	2.12	Domestic
16	Ganguwala	14.64	1.69	Domestic
17	Samsherpur	9.97	2.75	Domestic
18	Patiliyan	10.91	1.28	Domestic
19	Surajpur	7.83	1.76	Irrigation
20	Santokhgarh	4.22	1.31	Irrigation
21	Puuruwala	1.53	2	Irrigation
22	Johron	8.84	1.06	Domestic
23	Kiarda	7.19	2.12	Domestic
24	Misarwala	4.18	2.08	Domestic
25	Pipliwala	3.97	1.8	Domestic
26	Jagatpur	2.85	0.95	Domestic
27	Matak Majri	2.5	1.42	Domestic
28	Fatepur	2.38	1.97	Domestic
29	Kiratpur	1.56	1.62	Domestic
30	Nayagaon	9.7	2.08	Domestic
31	Sainwala	3.31	1.83	Irrigation
32	Tokion	4.69	1.7	Domestic
33	Dhaula Kuan	3.97	1.85	Irrigation
34	Bharapur	17.21	2.23	Irrigation
35	Rampur	10.48	2.1	Domestic
36	Majri	10.48	1.69	Domestic
37	Gunglo	3.5	1.44	Irrigation
38	Kolar	22.69	2.85	Domestic

4. Conclusion

Satellite imagery proved to be highly useful in terrain characterization i.e. in mapping of different groundwater potential zones. The groundwater potential zone map was validated by the coordinates of each well location, which were obtained by GPS and plotted in the data base. It was clearly shown that the well coordinates exactly match with the classified potential zones in the GIS environment. Excellent and good groundwater prospects zones mainly fall in the upper piedomant. The denudational hills, structural hills and residual hills mainly act as runoff zones. The final map prepared in the form of a prospect map would provide firsthand information to local authorities and planners about the areas to look for groundwater, followed by its suitable exploration. Based on the results of the study, concerned decision makers can formulate an efficient groundwater utilization plan for the study area so as to ensure long term sustainability of this vital resource.

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References

Avtar, R., C.K. Singh, S. Shashtri, A. Singh and S. Mukherjee (2010). Identification and analysis of groundwater potential zones in Ken-Betwa river linking area using remote sensing and geographic information system. Geocarto Int., 25: 379−396.

Burrough, P.A. (1986). Principles of geographic information system for land resources development. Oxford University Press, New York.

Choudhury, P.R. (1999). Integrated remote sensing and GIS techniques for groundwater studies in part of Betwa basin. Ph.D. Thesis (unpublished), Department of Earth Sciences, University of Roorkee, India.

Chowdhury, A., M.K. Jha, V.M. Chowdary and B.C. Mal (2009). Integrated remote sensing and GIS-based approach for assessing groundwater potential in West Medinipur district, West Bengal, India. Int. Jour. Remote Sensing, 30: 231−250.

Chowdhury, A., M.K. Jha and V.M. Chowdary (2010). Delineation of groundwater recharge zones and identification of artificial recharge sites in West Medinipur district, West Bengal, using RS, GIS and MCDM techniques. Env. Earth Sci., 59: 1209−1222.

Dar, I.A., K. Sankar and A. Dar Mithas (2010). Remote sensing technology and geographic information system modeling: An integrated approach towards the mapping of groundwater potential zones in Hardrock terrain, Mamundiyar basin. J. Hydrol., 394: 285– 295.

Dey, A.K. and A.C. Naithani (1988). Geological studies using remote sensing application in parts of Siwalik belt between Narayangarh and Paonta Sahib. Himachal Pradesh. Project Report, IIRS, Dehradun.

Devi and Wankhede (1995). Landform analysis related to environmental appraisal, slope stability and hydromorphogeological studies in part of Giri and Bata valley (Himachal Pradesh and Haryana). Project report, IIRS, Dehradun.

Dinesh Kumar, P.K., G. Gopinath and P. Seralathan (2007). Application of remote sensing and GIS for the demarcation of groundwater potential zones of a river basin in Kerala, southwest coast of India. Int. Jour. Remote Sensing, 28: 5583−5601.

El-Gammal, E.A., S.M. Salem and R.O. Greiling (2013). Applications of geomorphology, tectonics, geology and geophysical interpretation of, East Kom Ombo depression, Egypt, using Landsat images. Egyptian Journal of Remote Sensing and Space Sciences, 16:171–187.

Ibrahim-Bathis, K. and S.A. Ahmed (2016). Geospatial technology for delineating groundwater potential zones in Doddahalla watershed of Chitradurga district, India. The Egyptian Journal of Remote Sensing and Space Sciences, http://dx.doi.org/10.1016/j.ejrs.2016.06.002.

IMSD (1995). Integrated mission for sustainable development technical guidelines. National Remote Sensing Agency, Department of Space, Govt. of India.

Jugran, D.K. (2003). Geomorphic parameter for past Himalayan crustal deformation leading to geodynamic evolution and its effect on present instability in Trans Yamuna- Giri sector Paonta (H.P.) - A remote sensing and GIS based study. Dehradun. Report, IIRS, Dehradun.

Krishnamurthy, J. and G. Srinivas (1995). Role of geological and geomorphological factors in groundwater exploration – A study through remote sensing techniques. International Journal of Remote Sensing, 16: 2925−2618.

Murthy, K.S.R. (2000). Groundwater potential in a semi-arid region of Andhra Pradesh - A geographical information system approach. International Journal of Remote Sensing,21: 1867–1884.

Nag, S.K (2005). Application of lineament density and hydrogeomorphology to delineate groundwater potential zones of Baghmundi block in Prulia district, West Bengal. Jour. Indian Soc. Remote Sensing, 33: 521−529.

Nossin, J.J (1971). Outline of the geomorphology of the Doon valley, Northern U.P. India. Zeitschrift Fur Geomorphologie, Neue Folge, 12:18-50.

NRSA (1999). National rural drinking water mission methodology manual for preparation of groundwater prospects maps. National Remote Sensing Agency, Govt. of India, Hyderabad.

NRSA (2008). Groundwater prospect mapping using remote sensing and GIS, Rajiv Gandhi national drinking water mission project manual. National Remote Sensing Agency, Hyderabad.

O'Leary, D.W., J.D. Friedman and H.A. Poh (1976). Lineaments, linear, lineations: Some standards for old terms. Geol. Soc. Am. Bull., 87: 1463–1469.

Preeja, K.R., S. Joseph, J. Thomas and H. Vijith (2011). Identification of groundwater potential zones of a tropical river basin (Kerala, India) using remote sensing and GIS techniques. Jour. Indian Soc. Remote Sensing, 39: 83−94.

Rashid, M., M. Lone and S. Ahmed (2011). Integrating geospatial and ground geophysical information as guidelines for groundwater potential zones in hard rock terrains of south India. Environ. Monit. Assess., 184: 4829–4839.

Rawat, J.S. and Manish Kumar (2015). Monitoring land use/cover change using remote sensing and GIS techniques: A case study of Hawalbagh block, district Almora, Uttarakhand. India. Egypt. J. Remote Sens. Space Sci., 18: 77–84.

Rokade, V.M., P. Kundal and A.K. Joshi (2007). Groundwater potential modeling through remote sensing and GIS: A case study of Rajura taluka, Chandrapur district, Maharashtra. J Geol Soc India, 69: 943–948.

Saaty, T.L. (1980). Analytic hierarchy process; Planning, priority setting, resource caluculation. McGrow-Hill International Book company, New York. 1−287.

Sander, P. (2007). Lineaments in groundwater exploration: A review of applications and limitations. Hydrogeol. Jour., 15: 71−74.

Saraf, A.K. and P.R. Choudhury (1998). Integrated remote sensing and GIS for groundwater exploration and identification of artificial recharge sites. International Journal of Remote Sensing, 19, 1825–1841.

Sener, E., A. Davraz and M. Ozcelik (2005). An integration of GIS and remote Sensing in ground water Investigation: A case study in Burdur, Turkey. Hydrogeology Journal, 13: 826−834.

Senthil Kumar, G.R. and K. Shankar (2014). Assessment of groundwater potential zones using GIS. Front. Geosci., 2 (1):1–10.

Shaban, A., M. Khawlie and C. Abdallah (2006). Use of remote sensing and GIS to determine recharge potential zone: The case of Occidental Lebanon. Hydrogeology Journal, 14: 433–443.

Singh, A.K. and S.R. Prakash (2002). An integrated approach of remote sensing, geophysics and GIS to evaluation of groundwater potentiality of Ojhala sub-watershed, Mirjapur district, UP, India. In: Asian Conference on GIS, GPS, Aerial Photography and Remote Sensing, Bangkok-Thailand.

Sreedevi, P.D., S. Owais, H.H. Khan and S. Ahmed (2009). Morphometric analysis of a watershed of south India using SRTM data and GIS. Journal of Geological Society of India, 73:543–552.

Thomas, B.C., S.L. Kuriakose and S.K. Jaydev (2009). A method for groundwater prospect zonation in data poor areas using remote sensing and GIS: A case study in Kalikavu Panchayath of Malappuram district, Kerala, India. Int. Jour. Digital Earth, 2:155−170.

Todd, D.K (1980). Groundwater hydrology. 2nd ed., John Wiley & Sons. New York.

Todd, D.K. and L.W. Mays (2005). Groundwater hydrology. 3rd ed., Hoboken: John Wiley & Sons.

Tribe, A. (1991). Automated recognition of valley heads from digital elevation models. Earth Surf Process Landf., 16: 33–49.