© IWA Publishing 2014 **Hydrology Research** | 45.4-5 | 2014

Identification of groundwater potential zone of Nawada district, Bihar (India) – a study based on remote sensing and GIS platform

Gouri Sankar Bhunia, Nandini Chatterjee and Dilip Kumar Pal

ABSTRACT

A study was conducted to delineate the groundwater potential zones of Nawada district of Southern Bihar using satellite-derived information layers, namely, elevation, slope, drainage density, land use, fractional impervious surface (FIS) and also using existing thematic maps (lithology, soil, pre- and post-monsoon water level) based on the weighted linear combination method. On the basis of the relative contribution of each datum towards groundwater potential, the weight of each thematic map has been computed. The normalized weights of the individual themes and their different features were obtained through Saaty's analytical hierarchy process. Results showed that zones of 'very high' and 'high' groundwater potential are present in the central and northeastern part of the study area. 'Very low' and 'low' groundwater potential zones are found in the southeastern and very small pockets of the eastern corner of the district. Thus surface investigation of groundwater has proved that an integrated approach involving remote sensing and geographic information system (GIS) technique can be successfully used in identifying potential groundwater zones in a short time and at low cost, while the yield could be ascertained with some sample ground truth 'test drillings'.

Key words | groundwater potential zone, Saaty's analytical hierarchy process, satellite data, weighted linear combination method

Gouri Sankar Bhunia
Department of Geography,
University of Calcutta,
Kolkata,
India

Nandini Chatterjee (corresponding author)
Department of Geography,
Presidency University,
86/1 College Street,
Kolkata-700073,
West Bengal,
India
E-mail: *nandini_chsl@rediffmail.com*

Dilip Kumar Pal
Department of Surveying and Land Studies,
The PNG University of Technology,
Lae,
Papua New Guinea

INTRODUCTION

Prudent exploitation of groundwater is an imperative source of water supply which can operate as a natural storage. Furthermore, groundwater can shield against deficiencies of surface water during periods of drought, which also can prove vital to irrigation planning in a worthwhile crop rotation suitable for the area. Surface runoff, minor streams and rivers are significant sources for replenishing groundwater downstream from mountain fronts and steep hill slopes in arid and semi-arid areas (Bhattacharya 2010). The increasing demand for water has increased awareness towards the availability of groundwater supplies. Groundwater is promising as a poverty reduction tool in developing countries and can be conveyed to poor communities far more than conventional canal irrigation water (IWMI 2001). Although groundwater cannot be openly observed on the Earth's surface, a diversity of techniques can provide information about its accessibility. The occurrence of groundwater is a consequence of the interaction of the climatic, geological, hydrological, physiographical and ecological factors (Antony Ravindran 2012).

The existence of groundwater is contingent on geological structures, lithology, physiography, physico-chemical properties of soil profile and precipitation pattern. Most of the diverse surface features are derived from remote sensing data which act as pointers of groundwater subsistence (Todd 1980; Jha & Peiffer 2006). Furthermore, spatial information systems have emerged as dominant tools for managing geospatial data and decision-making in numerous areas, including engineering and environmental fields, over the last two decades (Stafford 1991; Goodchild 1993). Several scientists and researchers have followed geoinformatics procedures for the demarcation of groundwater potential zones

doi: 10.2166/nh.2013.258

with triumphant results (Krishnamurthy *et al.* 2000; Khan & Maharana 2002; Jaiswal *et al.* 2003; Sikdar *et al.* 2004; Sener *et al.* 2005; Ravi Shankar & Mohan 2006). However, the earlier studies commonly used thematic layers for the assessment of groundwater potential and local experience has been used for assigning weights to different thematic layers. Alternatively, several studies have integrated geoinformatics techniques to demarcate groundwater prospective zones (Sreedevi *et al.* 2001; Hadithi *et al.* 2003; Rao & Jugran 2003; Israil *et al.* 2006; Srivastava & Bhattacharya 2006; Bhunia *et al.* 2012a, b). In this study, commonly used thematic layers, remotely sensed environmental variables and high resolution digital elevation model (DEM) data were used. We also used Saaty's analytical hierarchy process (AHP) for normalizing the assigned weights for each variable to demarcate the groundwater potential zone. Conversely, insufficient information about the groundwater availability, due to its concealed environment and its occurrence in multifaceted subsurface formation is still an immense hindrance to the competent management of this vital resource. The unstable nature of groundwater probability and agricultural drought is a persistent phenomenon in the southern part of Bihar (Bihar's Agriculture Development 2008). Every year in summer most surface water sources dry up, causing serious water shortages for both domestic and irrigation purposes. As such, due to the whimsical nature of monsoonal rainfall in India, the accessibility of surface water cannot be ensured precisely at the requisite time. Consequently, the preponderance of the irrigated area in the study area is being cultivated with the assistance of groundwater attained from dugwells and tubewells. Furthermore, to date, very limited numbers of studies using this geoinformatics technique have been conducted in this dry semi-arid hilly region, especially in southern Bihar, India.

Hence, the study of groundwater potential of the dry region in Bihar will reveal an apparent idea about the spatial allocation of groundwater and will help to devise and implement an appropriate plan to improve agriculture and other associated activities. In the present study, satellite-derived information and thematic maps, namely slope, relief, fractional impervious surface (FIS), land use/land cover, soil, drainage, lithology, pre-monsoon water level and post-monsoon water level are used to delineate groundwater potential zones. The information and maps were reclassified on the basis of 'weights' assigned based on their relative importance and brought into the 'Raster calculator' function of spatial analyst tool for integration. The Raster calculator is a powerful tool in ArcGIS 'Spatial Analyst' functions for performing mathematical calculations using operators and functions based on the set up selection queries, and/or type in 'Map Algebra Syntax' (ESRI 2001). However, the objective of the study was to demonstrate a remote sensing and geographic information system (GIS)-based procedure in determining various groundwater potential zones of Nawada district, Bihar (India).

STUDY AREA

The Nawada district is located in the southern segment of the province of Bihar, India. The district extends between 24°31′N and 25°08′N latitudes and 85°00′E and 86°03′E longitudes (Figure 1), with an area of 2,494 km^2 and occupying 1.43% of the total geographical area of Bihar province. The entire district is drained by the non-perennial rivers such as Tilaiya, Ghaghra, Khuri, Sakri and Dhanarjya (http://nawada.bih.nic.in/). Out of the total geographical area of Nawada, the net area under cultivation is 50.43%. The main agricultural practices in the district comprise paddy, wheat, pulses and different types of vegetables. The average annual rainfall in the district is 1,037 mm. The climate is generally hot and dry, while in the couple of winter months temperature dips down from 16 °C to as low as 4 °C. During the summer, the temperature sometimes shoots up to 46 °C (Central Ground Water Board 2008).

MATERIALS AND METHODS

Data acquisition and description

The Landsat5 – Thematic Mapper (TM) data (Path/Row – 140/043) was acquired on 6 November 2011 and downloaded from the USGS Earth Explorer Community (http://earthexplorer.usgs.gov/). The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM product was downloaded from the US ASTER website (http://asterweb.jpl.nasa.gov/). Secondary data such as lithology, depth of water level in

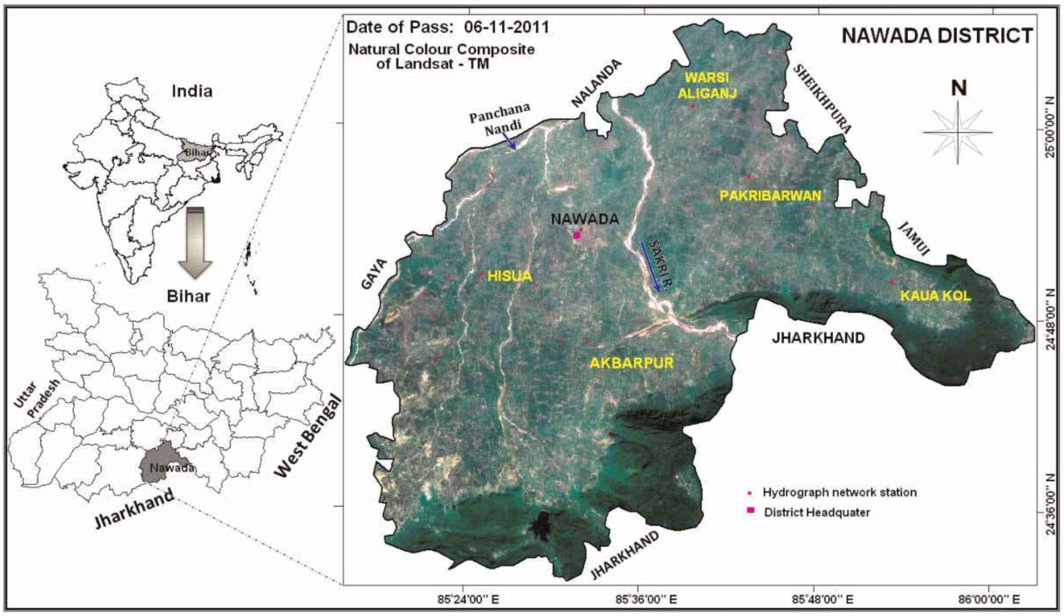

Figure 1 | Location map of the study area.

pre-monsoon and post-monsoon seasons were collected from the Central Ground Water Board, Bihar and the soil data were collected from the District Agricultural office of Nawada and are also available on an online database (http://ebookbrowse.com/bi5-nawada-28-08-12-pdf-d401842448). All these data were geo-referenced to the Universal Transverse Mercator (UTM) projection with World Geodetic System 84 (WGS-84) spheroid and 45N Datum. The detailed description of the data is given in Table 1.

Satellite data analysis and information extraction

Based on the district boundary layer the satellite data were extracted through clipping/subsetting in ERDAS Imagine software v9.0 (Atlanta, GA, USA). The supervised classification procedure based on maximum likelihood algorithm was adopted with the available true ground information of the study sites (Perumal & Bhaskaran 2010). Using the algorithm the study area was delineated into different types of land use/land cover (LULC) classes in the ERDAS Imagine software v9.0. For each LULC class, a minimum of five training sites were selected. After selectively combining classes, classified image was sieved, clumed and filtered before producing the final output. The following land use/land cover classes were considered in image classification, namely cropland, wet land, barren/waste land, lateritic land, dense forest, degraded forests, agricultural fallow, urban and built up, plantation with settlement, surface water body and sand, etc. This classified result was also verified with the district land use/land cover map of the National Remote Sensing Centre (NRSC) Open Earth Observation (EO) data archive (http://bhuvan-noeda.nrsc.gov.in/download/download/download.php). To perform accurate classification assessments, an error matrix table was derived that represented a square array of numbers laid out in rows and columns. The table evinces the number of sample units (e.g., clusters of pixel) assigned to a particular category relative to the actual category as verified in the field (Congalton & Green 1999). An overall accuracy, producer accuracy and user accuracy were calculated from the error matrix table (also known as confusion matrix). Producer accuracies result from dividing the number of correctly classified pixels in each category (on the major diagonal) by the number of training set pixels used for that category (the column total). User accuracies are computed by dividing the number of correctly classified pixels in each category by the total number of pixels that were classified in that category (the row total). Kappa statistics were used to measure agreement or map accuracy (Congalton 1991).

To quantify water quality and channel stability the FIS area has been delineated in the study area. Impervious

Table 1 | Details of the data used in the present study

Data type	Description of data	Acquisition date	Data characteristics		Source of data
Satellite data	Landsat5 – TM (Path/Row – 140/043)	6 November 2011	Spatial resolution except TIR band 6	30 m	http://earthexplorer.usgs.gov/
			Radiometric resolution	8 bit	
			Temporal resolution	16 days	
			Spectral bands	7 bands	
	ASTER GDEM (ASTGTM2_N24E085, ASTGTM2_N24E086, ASTGTM2_N25E085)	17 October 2011	Spatial resolution 30 m		http://asterweb.jpl.nasa.gov/
Thematic map	Lithology	2008	Scale 1:50,000		Central Ground Water Board, Mid-Eastern region, Patna Bihar (India) Ground Water Board, Bihar
	Pre-monsoon water level	2008	Scale 1:50,000		Central Ground Water Board, Mid-Eastern region, Patna Bihar (India)
	Post-monsoon water level	2008	Scale 1:50,000		Central Ground Water Board, Mid-Eastern region, Patna Bihar (India)
	Soil	2008	Scale 1:50,000		District Agricultural office, Nawada, Bihar (India); available at: http://ebookbrowse.com/bi5-nawada-28-08-12-pdf-d401842448

surfaces amplify the occurrence and intensity of downstream runoff events, resulting in modifications of channel structure and the timing and volume of peak runoff. Runoff from impervious surfaces has higher velocities, bigger volumes and shorter times of consideration (Brun & Band 2000; Yasuda *et al.* 2013). Impermeable surface effects upon water superiority and channel constancy have been shown to arise when 10–15% of the watershed surface is impervious (Shaver & Maxted 1995). Ridd (1995) and Owen *et al.* (1998) showed the relation between the fractional vegetation cover (FVC) and FIS for developed areas (Equation (1)) as:

$$\mathrm{FIS} = 1 - \mathrm{FVC} \tag{1}$$

where $\mathrm{FVC} = (\mathrm{NDVI}_i - \mathrm{NDVI}_{\mathrm{low}}/\mathrm{NDVI}_{\mathrm{high}} - \mathrm{NDVI}_{\mathrm{low}})^2$; and the normalized difference vegetation index $(\mathrm{NDVI})_{\mathrm{low}}$ and $\mathrm{NDVI}_{\mathrm{high}}$ are values for bare soil and dense vegetation, respectively, as proposed by Carlson & Ripley (1997).

The slope and relief maps were derived from the ASTER DEM data using the ArcGIS software. The drainage layer was extracted from the DEM data automatically through hydrologic analysis tools of ArcGIS software v9.3.

Spatial database generation

All the obtainable spatial data were amassed in the digital form and properly registered to ensure that the spatial components overlapped correctly. The spatial database was generated by digitizing all the maps and other GIS processes were undertaken. We produced new layers of lithology, soil, pre-monsoon and post-monsoon water levels. Zonal statistics such as area, perimeter, and thickness of all these thematic layers were calculated in the ArcGIS software v9.3 (ESRI Inc., Redlands, CA, USA) to estimate the zonal geometry.

Data integration and spatial analysis for delineating groundwater potential zone

The weights of the different themes were assigned on a scale of 1 to 5 based on their influence on the groundwater development. To approximate precedence factor/criteria ranking value, Saaty's AHP was applied (Saaty 1980). A reliable couple comparison matrix was generated in which each factor was weighted against each other by demarcating a relative leading value varying between 1 and 9 and to quantify the consistency ratio (CR) of the matrix. The AHP captured the idea of uncertainty in judgements through the principal eigenvalue and the consistency ratio (Saaty 2004). The paired comparison matrix was prepared for each criterion using Saaty's nine-point scale. A consistency ratio of 0.10 or less was considered acceptable. Similarly, sub-parameters of various thematic maps were also compared and weightages were assigned on the basis of their influence on groundwater recharge. Consistency ratio was checked for each one of them and thus the ratings were arrived at.

The groundwater potential zones were explored by amalgamating all the entire information in a weighted linear combination analysis model (Equation (2)) via the spatial analyst tool in ArcGIS 9.2. During the overlay analysis the ranking values were consigned for each class of each thematic map based on the weight of the singular parameters on groundwater prospective. The weighted linear combination was adopted that allowed a linear combination of probability weights of each thematic map and different categories of derived thematic maps were assigned scores depending upon their suitability to hold groundwater (Machiwal *et al.* 2011). The maximum value was given to the feature with highest groundwater potentiality and the minimum given to the lowest potential feature. The procedure of weighted linear combination dominates in the raster-based GIS software system (ArcGIS v9.3). The formula (Equation (2)) of the groundwater potential (GP) model was computed by the weighted linear combination method as shown below:

$$\begin{aligned}\mathrm{GP} = {} & 0.79 \times \text{elevation} + 1.11 \times \text{slope steepness} \\ & + 0.95 \times \text{soil type} + 0.92 \times x\,\text{drainage density} \\ & + 1.24 \times \text{fractional impervious surface} \\ & + 1.58 \times \text{land use/land cover} + 1.43 \times \text{lithology} \\ & + 0.63 \times \text{pre-monsoon water level} + 0.48 \\ & \times \text{post-monsoon water level} \end{aligned} \tag{2}$$

where GP refers to groundwater potentiality; '×' refers to evaluation of weights shown in weight assignment and groundwater potential zoning. The output was then reclassified into five groups: very high, high, moderate, low and very low using the geometric interval classification method.

RESULTS AND DISCUSSION

Relief and groundwater potentiality

The altitudinal range of the study area varies from 9 to 630 m (mean ± standard deviation 121.84 ± 76.72). The extreme eastern, southern and southeastern part of the study area has the highest elevation, while the lowest elevation is found in the extreme northern part of the study site. The entire district was categorized into five divisions: (i) <50 m, (ii) 51–150 mm, (iii) 151–250 m, (iv) 251–500 m, (v) >500 (Figure 2(a)). The zonal characteristics of each division were calculated (Table 2). The result of the analysis shows that the maximum area (1,285.66 km^2) is covered with an elevation of 251–500 m and the minimum area with an elevation of >500 m (35.56 km^2).

Slope steepness and groundwater potentiality

The northern and northeastern parts of the study area with gentle slopes (<3°) constitute good to excellent groundwater potentiality. The maximum slope is found on small pockets of the southeastern and eastern parts of the district (Figure 2(b)). The western and central parts register moderate to good groundwater potentiality. The whole district is classified into five zones: (i) very gentle slope (<3°) constitutes 'excellent' groundwater potential zone due to the nearly flat terrain with relatively high infiltration rate; (ii) gentle slope (3–5°) ranks 'good' for groundwater potential due to slightly undulating topography with some runoff; (iii) moderate slope (5–10°) causes relatively high runoff and low infiltration with 'moderate to poor' groundwater potentiality; (iv) steep slope (10–20°); and (v) extreme slope (>20°) are considered as 'poor' groundwater potential due to higher runoff. The zonal characteristics of each sub-division were calculated and are shown in Table 3.

Land use/land cover characteristics and groundwater potentiality

The land use/land cover characteristics of Nawada district were classified into 12 land use categories, i.e., lateritic land, barren rocky surface, open forest, dense forest, urban and built up, sand, surface water body, agricultural fallow, wet fallow, dry fallow, plantation with settlement and crop land (Table 4). The maximum area of the study site is dominated by agricultural fallow land. The extreme eastern, southern and southeastern part of the study site is basically dominated by the dense forest and hilly region (Figure 2(c)). The northwestern and northern part of the study site is covered with agricultural fallow and crop land. A very small portion of the study site is dominated by the urban and built up regions. The southwestern part of the study site is characterized by a diversified land use pattern. In accordance with the groundwater hydrology, crop land, wet land, surface water body, open forest are associated with good to excellent groundwater potentiality. In contrast, lateritic land, barren rocky surface, urban and built up, dense forest are closely associated with moderate to poor groundwater potentiality. Producer accuracy and user accuracy have been delineated to assess the accuracy of land use classes. However, the overall classification accuracy shows 85.26%, and the overall kappa statistics shows 0.84.

FIS and groundwater potentiality

Impervious surfaces impede infiltration, percolation and subsurface water availability, involve decreases in natural

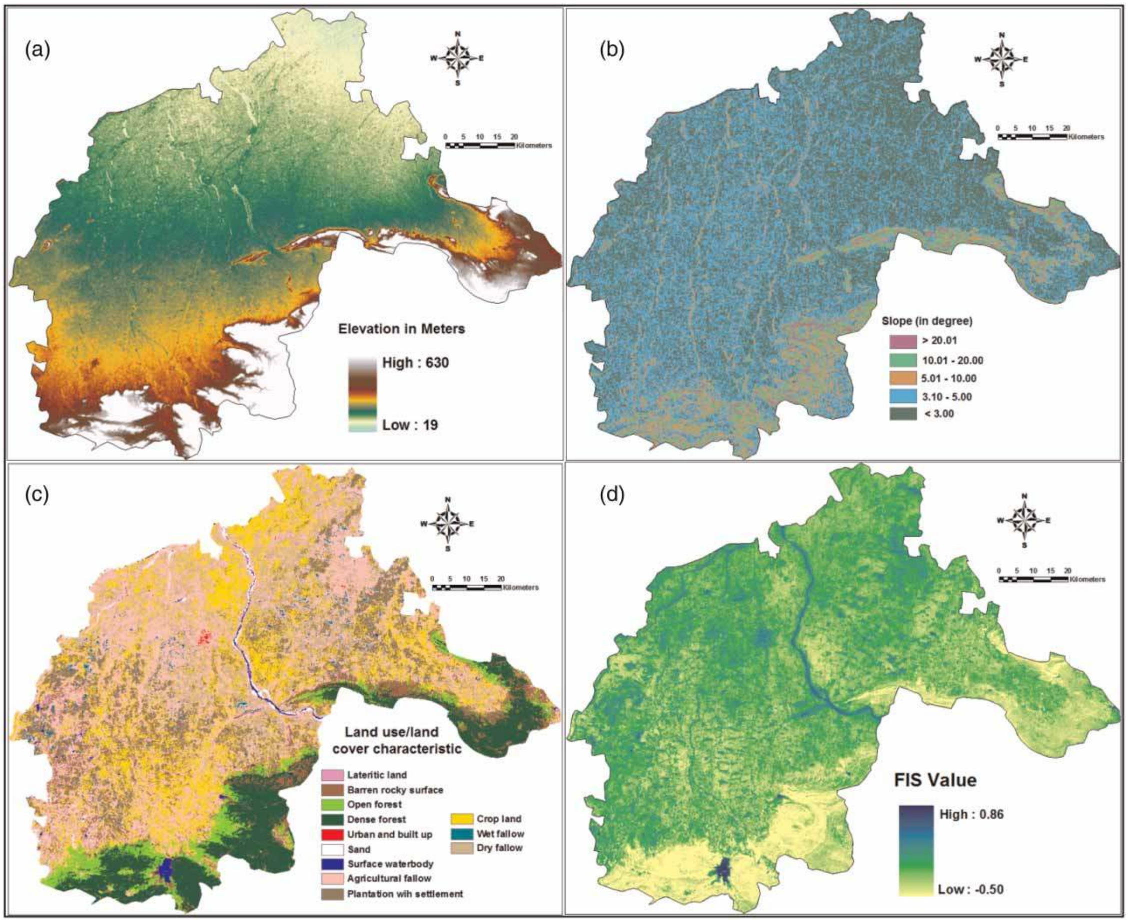

Figure 2 | Thematic maps of Nawada district derived from the satellite data: (a) elevation, (b) slope steepness, (c) land use/land cover characteristics, (d) FIS, (e) drainage density, (f) soil characteristics, (g) pre-monsoon water level, (h) post-monsoon water level, (i) lithological characteristics. (*continued*)

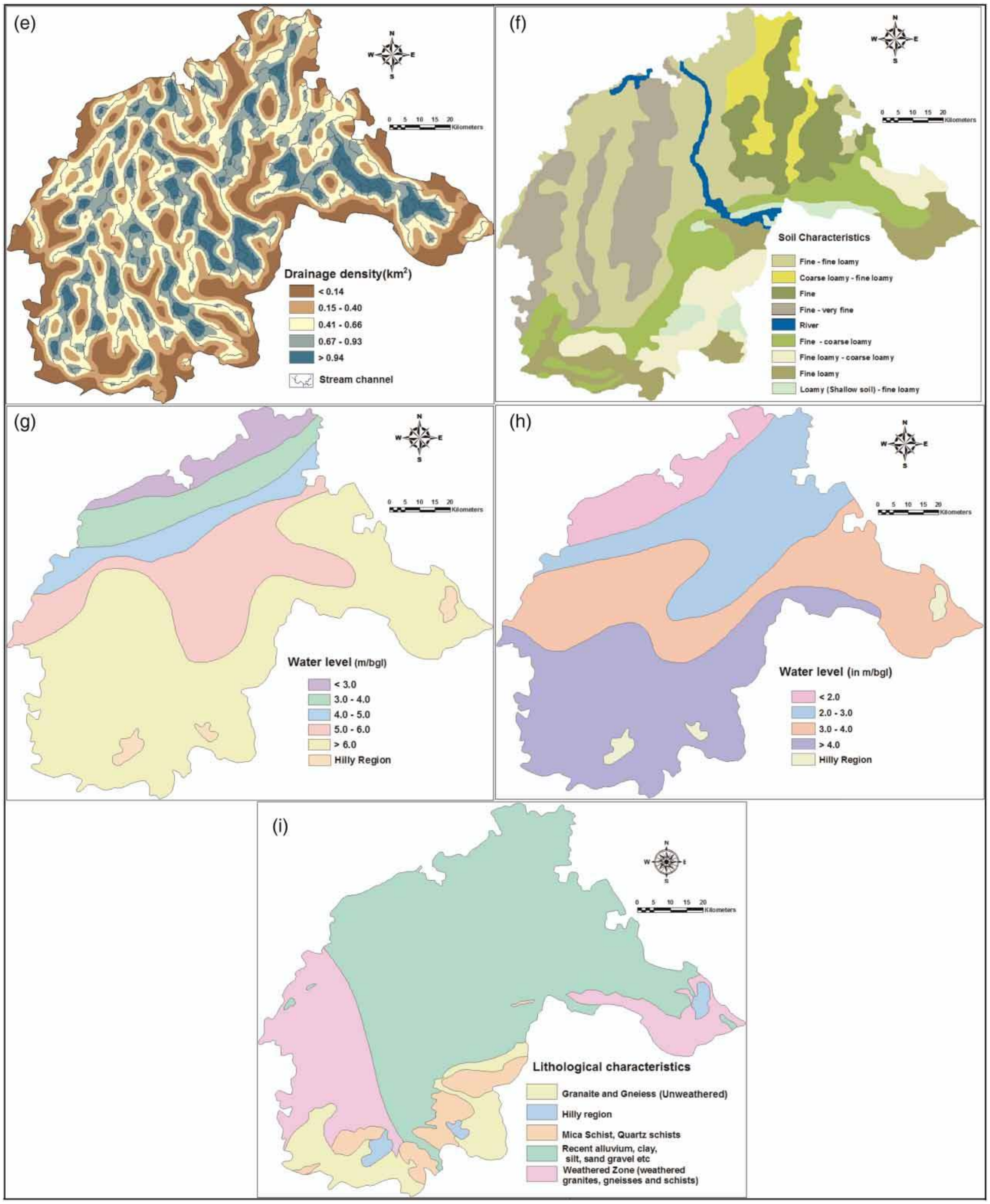

Figure 2 | Continued.

interception and depression storage, and amplify overland flow (runoff). Runoff from impervious surfaces has higher velocities, larger volumes and shorter times of absorption (Brun & Band 2000). The spatial distribution of FIS of the study area is shown in Figure 2(d). The FIS value of the study area varies from 0.50 to 0.85 (mean ± standard deviation 0.17 ± 0.39). Lower FIS values are found in the southern, eastern and southeastern parts of the study area. The medium to high FIS values are delineated in the central and northern part of the study site. Based on the geometric interval, the region

Table 2 | Zonal characteristics of relief of Nawada district

Elevation range (m)	Area (km^2)	Perimeter (km)	Thickness (km)
<50	120.66	635.56	1.70
51–150	209.34	1,254.81	1.70
151–250	838.27	3,518.28	3.92
251–500	1,285.66	3,921.62	4.93
>500	35.56	1,035.95	0.27

Table 3 | Zonal characteristics of slope of Nawada district

Slope range (°)	Area (km^2)	Perimeter (km)	Thickness (km)
<3°	70.14	2,230.09	0.18
3–5°	169.41	10,004.51	0.12
5–10°	559.88	38,854.23	0.07
10–20°	845.59	64,064.37	0.064
>20°	844.44	47,737.44	0.12

was categorized into five FIS regions: (i) <0.07, (ii) 0.08–0.10, (iii) 0.11–0.34, (iv) 0.35–0.59 and (v) >0.59.

Drainage density and groundwater potentiality

Earlier studies reported that drainage characteristics are tightly related to recharge property from surface water to groundwater (Bhunia *et al.* 2012b). Normally, the denser the drainage network, the lesser becomes the recharge rate and vice versa. In the present study, the extraction of drainage networks was done directly from ASTER images (Figure 2(e)), and the resulting drainage map is categorized into five divisions: (i) low drainage density (<0.14 km^2); (ii) low to medium drainage density (0.15–0.40 km^2); (iii) medium drainage density (0.41–0.66 km^2); (iv) high drainage density (0.67–0.93 km^2); (v) very high drainage density (0.94 km^2).

Soil characteristics and groundwater potentiality

The study of soil is supplementary as an important variable since it controls the infiltration limitation through monsoon precipitation and in granulizing the consequence of surface runoff based on material content. However, plants do not symbolize merely a passive association between the soil and the atmosphere; vegetation, because of the control of evapotranspiration through stomatal regulation, feeds back on the climate and soil moisture regime (Martínez-Fernández & Hernández-Santana 2013). Groundwater potential appears to be useful in characterizing soil properties in relation to water retaining capacity and transferability. In the district, texturally there are eight types of soils. These are: (i) coarse loamy, (ii) fine, (iii) fine-fine loamy, (iv) fine

Table 4 | Land use/land cover characteristics and the classification accuracy of land use classes of the study area

Land use/land cover classes	Area (km^2)	Percent of LULC class	Producer accuracy	User accuracy	Kappa statistics
Lateritic land	11.43	0.46	80.00%	80.00%	0.7889
Barren rocky surface	158.07	6.34	100.00%	100.00%	1.0000
Open forest	128.83	5.16	85.71%	85.71%	0.8458
Dense forest	278.67	11.17	87.50%	77.78%	0.7573
Urban and built up	4.87	0.20	100.00%	100.00%	1.0000
Sand	17.41	0.70	75.00%	60.00%	0.5824
Surface water body	16.46	0.66	66.67%	80.00%	0.7865
Agricultural fallow	718.32	28.79	92.86%	76.47%	0.7240
Wet fallow	23.5	0.94	100.00%	80.00%	0.7912
Dry fallow	295.43	11.84	75.00%	90.00%	0.8855
Plantation with settlement	279.8	11.22	76.92%	100.00%	1.0000
Crop land	561.94	22.53	92.86%	92.86%	0.9162

Overall classification accuracy = 85.26%.
Overall kappa statistics = 0.8350.

loamy, (v) fine loamy fine, (vi) fine to coarse loamy, (vii) loamy and (viii) very fine loamy (Figure 2(f)). The district is dominated by coarse loamy soils that manifest in low groundwater potential. In contrast, very fine and fine loamy soils provide excellent groundwater potentiality. Loam soil is mainly found in Nawada, Sirdala and Akbarpur that evinces moderate to poor groundwater potential. The Pakribarwan and Kauakol blocks are dominated by clay soils which contribute to low groundwater potentiality. Sandy loam soil is predominant in Nawada, Warsalianj, Akbarpur, Narhat and Hisua blocks. The zonal characteristics of each soil division are calculated (Table 5).

Sub-surface water level and groundwater potentiality

To understand the groundwater regime, sub-surface water levels were measured during the pre-monsoon and post-monsoon periods in 2008 to assess the availability of water at the sub-surface zone through hydrograph network stations. Based on this information, sub-surface water level contour maps were generated in ArcGIS v9.3 environment. In the study area, sub-surface water level varies from 2.19 to 8.82 m/below groundwater level (bgl) during the pre-monsoon season (Figure 2(g)), while in the post-monsoon season, the water level ranges between 0.64 and 6.56 m/bgl (Figure 2(h)). Based on the suitability of water level, the study area was categorized into five divisions in the pre-monsoon season and four divisions in the post-monsoon season (Table 6). The depth of the sub-surface water level in the district is not consistent. However, the extent of depth of water level during the year provides a clue of reciprocated relationships between the discharge and the total recharge from varying sources. The changes observed are valuable for recording the long-term vacillation in the water level and support in computing the water balance of the area.

Table 5 | Soil properties and the soil characteristics of Nawada district

Soil properties	Area (km^2)	Perimeter (km)	Thickness (km)
Coarse loamy	681.19	608.00	3.24
Fine	129.42	173.80	2.65
Fine-fine loamy	253.14	232.00	3.42
Fine loamy	450.27	379.60	4.35
Fine loamy fine	48.57	138.60	0.87
Fine to coarse loamy	342.26	361.00	3.45
Loamy	227.94	211.80	3.33
River	236.59	278.80	2.86
Very fine loamy	74.10	129.60	1.91

Table 6 | Zonal characteristics of sub-surface water level properties in the study area

Water level (m/bgl)	Area (km^2)	Perimeter (km)	Thickness (km)
Pre-monsoon water level			
<3.0	166.98	192.4	6.43
3.1–4.0	213.21	128.8	3.27
4.1–5.0	167.58	151.2	2.36
5.1–6.0	509.94	227.2	7.58
>6.1	1,376.37	469	11.09
Post-monsoon water level			
<2.0	244.83	194	7.44
2.1–3.0	567.64	224.00	8.13
3.1–4.0	765.14	324.20	6.58
>4.1	856.47	316.80	8.73

Although the analysis shows the fluctuation of water level in the northwestern, southern and southwestern regions during the pre-monsoon and post-monsoon seasons, it does however reveal much deeper aquifers during the pre-monsoon season. Thus, it can be inferred that these regions are more prone to drought due to a constant decline in water level during the summer season when water requirement is more, which points to the requirement for water resource planning for its effectual use predominantly during the pre-monsoon period.

Lithological characteristics and groundwater potentiality

The district is covered with crystalline rocks, such as mica schists, granite gneiss, quartzite and quartz schist, hornblendes schist and mica pegmatites, etc. These rock types comprise the hill ranges and envelop southern and eastern parts of Rajauli block, southern parts of Sirdala block, north, central and southern parts of Govindpur blocks and south, south-eastern and northern parts of Kauakol block. Based on the lithological properties, the district was categorized into four divisions: (i) recent alluvium, clay, silt, sand, gravel, etc. which constitutes large yielding prospects for groundwater potentiality; (ii) weathered zone which proposes high to moderate groundwater potentiality; (iii) granite and gneisses (i.e., unweathered zones) record very poor groundwater potentiality; (iv) mica schists and quartz schists constitute poor groundwater repositories (Figure 2(i)). The zonal characteristics of each lithological type are given in Table 7.

Table 7 | Zonal characteristics of lithological properties in the study area

Lithological properties	Area (km^2)	Perimeter (km)	Thickness (km)
Recent alluvium, clay, silt, sand, gravel, etc.	1,546.97	399.80	14.62
Weathered zone	496.94	317.00	6.65
Granite and gneisses	217.49	229.60	3.15
Mica schists and quartz schists	139.04	182.80	2.29
Hilly region	33.64	58.6	1.44

Table 8(a) | Weights of nine themes for groundwater potential zoning

Theme	Weight
Elevation	2.5
Slope	3.5
Soil	3
Drainage density	2.5
FIS	4
Land use/land cover	5
Lithology	4.5
Pre-monsoon water level	2
Post-monsoon water level	1.5

Weight assignment and groundwater potential zoning

Suitable weights were consigned to the nine themes and their individual features after appreciating their hydrological significance in causing groundwater occurrence in the study area. The normalized weights of the individual themes and their different features were obtained through Saaty's AHP. The weights assigned to singular themes are illustrated in Table 8(a). The weights assigned to different features of the individual themes and their normalized weights are presented in Table 8(b). The normalized weights of the subcategories of different features of the nine themes were obtained in a similar manner following Saaty's AHP and are presented in Table 9. The consistency ratio of the entire AHP model was less than 0.10. However, the consistency ratio of elevation, slope, soil, FIS, LULC and depth of post-monsoon water level was less than 0.02; while the pre-monsoon water level and lithology had a consistency ratio of less than 0.017.

The assimilation analysis of different thematic maps and image data proved valuable for the demarcation of zones of groundwater potential. The groundwater potential map of the Nawada district evaluated by the weighted linear combination (Figure 3) reveals five distinct classes representing

Table 8(b) | Comparison matrix of groundwater potential variables of Nawada district derived through Saaty's analytical hierarchy process

Variables	Elevation	Slope	Soil	DD	FIS	LULC	Lithology	Water level[a]	Water level[b]	PV	Mean	Normalized weight	CI
Elevation	1.00	0.71	0.83	1.00	0.63	0.50	0.56	1.25	1.67	0.79	0.84	0.09	±0.010
Slope	1.40	1.00	1.17	1.40	0.88	0.70	0.78	1.75	2.33	1.11	1.18	0.12	±0.010
Soil	1.20	0.86	1.00	1.20	0.75	0.60	0.67	1.50	2.00	0.95	1.01	0.10	±0.010
DD	1.00	0.71	0.83	1.00	1.60	0.50	0.56	1.25	1.67	0.92	0.94	0.10	±0.069
FIS	1.60	1.14	1.33	1.60	1.00	0.63	0.89	2.00	2.67	1.24	1.31	0.14	±0.014
LULC	2.00	1.43	1.67	2.00	1.25	1.00	1.11	2.50	3.33	1.58	1.69	0.17	±0.010
Lithology	1.80	1.29	1.50	1.80	1.13	0.90	1.00	2.25	3.00	1.43	1.52	0.16	±0.010
Water level[a]	0.80	0.57	0.67	0.80	0.50	0.40	0.44	1.00	1.33	0.63	0.67	0.07	±0.010
Water level[b]	0.60	0.43	0.50	0.60	0.38	0.30	0.33	0.75	1.00	0.48	0.51	0.05	±0.010

CI = consistency index; DD = drainage density; FIS = fractional impervious surface; LULC = land use/land cover.

[a] Pre-monsoon water level.

[b] Post-monsoon water level.

Table 9 | Estimation of normalized weights for the individual features of nine themes for groundwater potential zoning

Theme	**Sub-categories**	**Groundwater prospect**	**Mean**	**Normalized weight**
Relief (in meters)	<50	Very good	2.47	0.40
	51–150	Good	1.65	0.26
	151–250	Moderate	1.44	0.23
	251–500	Poor	0.47	0.08
	>500	Very poor	0.21	0.03
Slope (°)	Very gentle slope (<3°)	Very good	1.99	0.35
	Gentle slope (3–5°)	Good	1.65	0.29
	Moderate slope (5–10°)	Moderate	1.16	0.20
	Steep slope (10–20°)	Poor	0.54	0.09
	Extreme slope (>20°)	Very poor	0.40	0.07
Land use/land cover	Lateritic land	Poor	0.68	0.05
	Barren rocky surface	Very poor	0.56	0.04
	Open forest	Moderate	1.14	0.08
	Dense forest	Good	1.29	0.09
	Urban and built up	Very poor	0.30	0.02
	Sand	Poor	0.91	0.07
	Surface water body	Very good	2.73	0.20
	Agricultural fallow	Moderate	1.48	0.11
	Wet fallow	Moderate to good	0.68	0.05
	Dry fallow	Poor	0.91	0.07
	Plantation with settlement	Very poor	1.14	0.08
	Crop land	Very good	2.05	0.15
FIS	<0.07	Very good	0.33	0.05
	0.08–0.10	Good	2.67	0.43
	0.11–0.34	Moderate	1.67	0.27
	0.35–0.59	Poor	1.00	0.16
	>0.59	Very poor	0.51	0.08
Drainage density (km^2)	Low drainage density (<0.14)	Very good	1.96	0.35
	Low to medium drainage density (0.15–0.40)	Good	1.47	0.26
	Medium drainage density (0.41–0.66)	Moderate	1.31	0.23
	High drainage density (0.67–0.93)	Poor	0.57	0.10
	Very high drainage density (0.94)	Very poor	0.33	0.06
Soil	Coarse loamy	Poor	0.46	0.08
	Fine	Moderate	0.93	0.15
	Fine-fine loamy	Very good	2.08	0.34
	Fine loamy	Poor	0.97	0.16
	Fine loamy fine	Good	1.62	0.27
Lithological properties	Recent alluvium, clay, silt, sand, gravel, etc.	Good	1.23	0.22
	Weathered zone	Very good	2.15	0.39
	Granite and gneisses	Moderate	1.07	0.19
	Mica schists and quartz schists	Moderate to poor	0.63	0.11
	Hilly region	Poor	0.46	0.08
Pre-monsoon water level	<3.0	Very good	1.64	0.31
	3.1–4.0	Good	1.31	0.25
	4.1–5.0	Moderate	1.15	0.22
	5.1–6.0	Poor	0.67	0.13
	>6.1	Very poor	0.49	0.09
Post-monsoon water level	<2.0	Good	1.54	0.36
	2.1–3.0	Moderate	1.16	0.27
	3.1–4.0	Poor	0.97	0.23
	>4.1	Poor	0.58	0.14

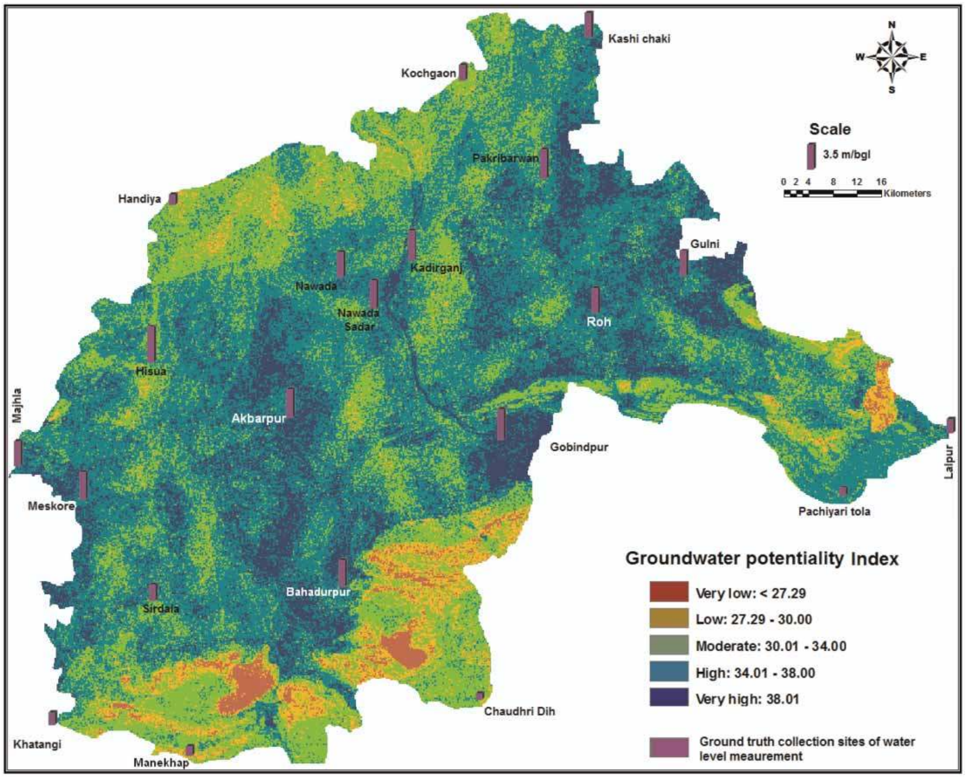

Figure 3 | Groundwater potential zone of Nawada district. Bar diagram plotted along the map, representing the depth of water level derived from the data of exploratory well drilled by Central Groundwater Board (CGWB), Nawada district, Bihar (India).

'very good', 'good', 'moderate', 'poor' and 'very poor'. The zones of 'very high' and 'high' groundwater potential are present in the central and northeastern part of the study area. Measures to be taken could include water-harvesting for amplification of groundwater resources and also through the completion of appropriate best management practices for watersheds throughout the region. The zone of moderate groundwater region was observed in the extreme northwestern and southeastern part of the study area. Some small pockets were also observed in the central and eastern part of the study site. 'Very low' and 'low' groundwater potential zones were found in the southeast and very small pockets in the eastern corner of the district. However, poor groundwater potentials are restricted mostly to the hilly terrain and in settlement areas. Finally, groundwater level information was extracted from the exploratory wells drilled by the Central Groundwater Board (CGWB), Nawada district, and the data have been verified with the potential zone of groundwater derived through weighted linear combination method in the study area (Figure 3). However, our results were encouraging. High groundwater potentiality was found in Nawada Sadar, Gobindpur, Kashi Chaki, Akbarpur and Bahadurpur, which also matched that of the exploratory wells drilled by the CGWB. However, the groundwater potential in the northwestern and southeastern parts of the study area is poor, and this information also coincides with the water levels of Manekhap, Chaudhri Dih, Handiya and Kochgaon.

CONCLUSION

The results of the present study illustrate that geospatial technology is a dominant tool for evaluating groundwater potential zones, based on which appropriate locations for groundwater withdrawal can be delineated. The methodology has been effectively used and established for evaluation of groundwater potentiality of Nawada district. Contemplation of a sufficient number of thematic layers and appropriate assignment of weights are keys to the accomplishment of geospatial techniques in recognizing groundwater forecasts. Detailed research is essential in the study area for the proficient and sustainable management of this limited natural resource. The major portion of the study area exhibits poor to moderate groundwater potential; it can be inferred that groundwater resources are somewhat limited. The method generally exercises surface features and hydrologic parameters, and hence it would be generally efficient in demarcating fairly shallow aquifer systems. Future studies should concentrate on the improvement of competent methodology for weight assignment so as to lessen or evade the bias. The effectiveness of the geospatial method for groundwater estimation could be further enhanced by considering sufficient amounts of information and data having direct or indirect control over groundwater storage.

ACKNOWLEDGEMENTS

We thank the USGS Earth Explorer community for freely providing the satellite data to carry out this research work. We are also grateful to Central Ground Water Board, Mid-Eastern region, Patna Bihar (India) Ground Water Board, Bihar for providing us with data and information.

REFERENCES

Antony Ravindran, A. 2012 Azimuthal square array resistivity method and groundwater exploration in Sanganoor, Coimbatore District, Tamilnadu, India. *Res. J. Rec. Sci.* **1** (4), 41–45.

Bhattacharya, A. K. 2010 Artificial ground water recharge with a special reference to India. *Int. J. Res. Rev. Appl. Sci*. **4** (2), 214–221.

Bhunia, G. S., Samanta, S. & Pal, B. 2012a Deciphering prospective ground water zones of Morobe province, Papua New Guinea. *Int. J. Eng. Res. Appl. (IJERA)* **2** (3), 752–766.

Bhunia, G. S., Samanta, S., Pal, D. K. & Pal, B. 2012b Assessment of groundwater potential zone in Paschim Medinipur District, West Bengal – A meso-scale study using GIS and remote sensing approach. *J. Environ. Earth Sci*. **2** (5), 41–59.

Bihar's Agriculture Development 2008 Opportunities & Challenges – A Report of the Special Task Force on Bihar, April 2008. Available at: http://planningcommission.nic.in/aboutus/-taskforce/tsk_adoc.pdf.

Brun, S. E. & Band, L. E. 2000 Simulating runoff behavior in an urbanizing watershed. *Comput. Environ. Urban Syst*. **24** (1), 5–22.

Carlson, T. N. & Ripley, A. J. 1997 On the relationship between fractional vegetation cover, leaf area index and NDVI. *Remote Sens. Environ*. **62**, 241–252.

Central Ground Water Board 2008 Ground Water Information Booklet, Nawada District, Bihar State, Ministry of Water Resources (Govt. of India), Mid-Eastern Region, Patna. Available at: http://cgwb.gov.in/District_Profile/Bihar/Nawada.pdf.

Congalton, R. G. 1991 A review of assessing the accuracy of classifications of remote sensed data. *Remote Sens. Environ*. **37**, 35–46.

Congalton, R. G. & Green, K. 1999 *Assessing the Accuracy of Remotely Sensed Data: Principles and Practices*. Lewis Publishers, New York, pp. 17–49.

ESRI 2001 ArcGIS Spatial Analyst: Advanced GIS Spatial Analysis Using Raster and Vector Data. Available at: http://www.esri.com/library/whitepapers/pdfs/arcgis_spatial_analyst.pdf.

Goodchild, M. F. 1993 The state of GIS for environmental problem-solving. In: *Environmental Modeling with GIS* (M. F. Goodchild, B. O. Parks & L. T. Steyaert, eds). Oxford University Press, New York, pp. 8–15.

Hadithi, M. A., Shukla, D. C. & Israil, M. 2003 Evaluation of groundwater resources potential in Ratmau-Pathri Rao watershed Haridwar district, Uttaranchal, India using geo-electrical, remote sensing and GIS techniques. In: *Proceedings of the International Conference on Water and Environment (WE-2003)*, Bhopal, India, Ground Water Pollution, pp. 123–125.

Israil, M., Al-Hadithi, M. & Singhal, D. C. 2006 Application of resistivity survey and geographical information system (GIS) analysis for hydrogeological zoning of a piedmont area, Himalayan foothill region, India. *Hydrogeol. J*. **14**, 753–759.

International Water Management Institute (IWMI) 2001 *The Strategic Plan for IWMI 2000–2005*. Colombo, Sri Lanka. Available at: http://www.iwmi.cgiar.org/.

Jaiswal, R. K., Mukherjee, S., Krishnamurthy, J. & Saxena, R. 2003 Role of remote sensing and GIS techniques for generation of groundwater prospect zones towards rural development: An approach. *Int. J. Remote Sens*. **24**, 993–1008.

Jha, M. K. & Peiffer, S. 2006 Applications of remote sensing and GIS technologies in groundwater hydrology: Past, present and future (J. Hoffman, G. Wimmer & A. Burchart, eds). Available at: http://www.bayceer.uni-bayreuth.de/bayceer/html/bfoe/bfoe112_order.pdf.

Khan, M. A. & Maharana, P. C. 2002 Use of remote sensing and GIS in the delineation and characterization of groundwater prospect zones. *Photonirvachak. J. Indian Soc. Remote Sens.* **30**, 131–141.

Krishnamurthy, J., Mani, A. N., Jayaram, V. & Manivel, M. 2000 Groundwater resources development in hard rock terrain: An approach using remote sensing and GIS techniques. *Int. J. Appl. Earth Observ. Geoinfo*. **2**, 204–215.

Machiwal, D., Jha, M. K. & Mal, B. C. 2011 Assessment of groundwater potential in a semiarid region of India using remote sensing, GIS and MCDM techniques. *J. Water Resour. Manage*. **25** (5), 1359–1386.

Martínez-Fernández, J. & Hernández-Santana, V. 2013 Soil water reserve estimation and vegetation relationships in a Mediterranean sub-humid forested catchment. *Hydrol. Res*. **43** (3), 167–178.

Owen, T. W., Carlson, T. N. & Gillies, R. R. 1998 Remotely-sensed surface parameters governing urban climate change. *Int. J. Remote Sens*. **19**, 1663–1681.

Perumal, K. & Bhaskaran, R. 2010 Supervised classification performance of multispectral images. *J. Comput*. **2** (2), 124–129.

Rao, Y. S. & Jugran, D. K. 2003 Delineation of groundwater potential zones and zones of groundwater quality suitable for domestic purposes using remote sensing and GIS. *Hydrolog. Sci. J*. **48**, 821–833.

Ravi Shankar, M. N. & Mohan, G. 2006 Assessment of the groundwater potential and quality in Bhatsa and Kalu river basins of Thane district, Western Deccan Volcanic Province of India. *Environ. Geol*. **49**, 990–998.

Ridd, M. K. 1995 Exploring a V-I-S (Vegetation-Impervious Surface-Soil) model for urban ecosystem analysis through remote sensing: comparative anatomy for cities. *Int. J. Remote Sens*. **16**, 2165–2185.

Saaty, T. L. 1980 *The Analytical Hierarchy Process*. McGraw-Hill, New York.

Saaty, T. L. 2004 Fundamentals of the analytic network process – multiple networks with benefits, costs, opportunities and risks. *J. Syst. Sci. Syst. Eng*. **13** (3), 348–379.

Sener, E., Davraz, A. & Ozcelik, M. 2005 An integration of GIS and remote sensing in groundwater investigations: a case study in Burdur, Turkey. *Hydrogeol. J*. **13**, 826–834.

Shaver, E. J. & Maxted, J. R. 1995 *The Use of Impervious Cover to Predict the Ecological Condition of Wadable Nontidal Streams in Delaware*. Delaware County Planning Department, Ellicott City, Maryland, USA, p. 7.

Sikdar, P. K., Chakraborty, S., Adhya, E. & Paul, P. K. 2004 Land use/land cover changes and groundwater potential zoning in and around Raniganj coal mining area, Bardhaman District, West Bengal: A GIS and remote sensing approach. *J. Spatial Hydrol*. **4**, 1–24.

Sreedevi, P. D., Srinivasulu, S. & Raju, K. K. 2001 Hydrogeomorphological and groundwater prospects of the Pageru river basin by using remote sensing data. *Environ. Geol*. **40**, 1919–1924.

Srivastava, P. & Bhattacharya, A. 2006 Groundwater assessment through an integrated approach using remote sensing, GIS and resistivity techniques: A case study from a hard rock terrain. *Int. J. Remote Sens*. **27**, 4599–4620.

Stafford, D. B. 1991 *Civil Engineering Applications of Remote Sensing and Geographic Information Systems*. ASCE, New York, 360 pp.

Todd, D. K. 1980 *Groundwater Hydrology*, 2nd edn. John Wiley & Sons, New York, pp. 111–163.

Yasuda, H., Berndtsson, R., Hinokidani, O., Huang, J., Saito, T., Zheng, J. & Kimura, R. 2013 The impact of plant water uptake and recharge on groundwater level at a site in the Loess Plateau of China. *Hydrol. Res*. **44** (1), 106–116.

First received 26 March 2013; accepted in revised form 13 August 2013. Available online 21 September 2013