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Fuzzy logic algorithm based analytic hierarchy process for delineation of groundwater potential zones in complex topography

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Abstract

Groundwater crisis under the changed climate scenario has now become a global concern. Land use and land cover change and rapid urbanization are some of the prime causes of it. Aquifers are in a vulnerable condition due to the extensive abstraction and over exploitation as the groundwater draft exceeds the groundwater recharge. It is in this context, the present study has been carried out to identify groundwater potential zones of Garbeta block of Paschim Medinapore district of West Bengal, India, which is located in a critical terrain condition and faces extreme water scarcity in terms of both surface and groundwater availability. The region experiences an average annual groundwater level fluctuation between 9 and 11 m. Demarcation of the groundwater potential zones has been made using Fuzzy Analytical Hierarchy Process (Fuzzy AHP) integrated with geospatial techniques. Fuzzy weights have been entrusted to eleven physical parameters namely land use and land cover, soil, geology geomorphology, lineament density, drainage density, relative relief, distance from river, slope, groundwater level fluctuation and normalised difference water index (NDWI), and the final map has been prepared within geospatial environment. The groundwater potential zones have been classified into five classes: very low potential (18.30%), low potential (26.42%), moderate potential (25.99%), high potential (19.55%) and very high potential (9.75%). The calculated results have been validated through field based groundwater level survey. Such studies will provide new vision and incur valuable information to the stakeholders for sustainable water resources management and effective identification of suitable locations for groundwater extraction.

Keywords Fuzzy AHP · Groundwater potential index · Groundwater level fluctuation · Geospatial techniques

Introduction

Water is an important source to sustain life on earth, but with the growing population density, these valuable natural resources have been under stress both in its qualitative and quantitative aspects. Further due to the increase in the variability of surface water resources, the groundwater demand will far exceed the groundwater storage and recharge under changed climate (Kundzewicz and Doll 2009). Drying up of the most river basins, irregularity in the canal water supply system, increase in the precipitation and temperature variability, and decline in groundwater level are giving a treat to global food security. Such uncontrolled consequences of human dependence on groundwater have led the rapid degradation of the world's major aquifer system (Turner et al. 2019). Again with the agrarian development, electrification and modernisation of pumping system, the global groundwater abstraction has been increased from 312 km³/year in the 1960s to about 743 km³/year in 2000 (Wada et al. 2010). Therefore, development of groundwater resource and its management for beneficial use is needed which involves planning in terms of the entire groundwater basin (Todd 2009). Before managing it substantially, delineation of groundwater potential zone acts as a prerequisite work. This underground storage is highly influenced by surface and sub-surface hydrological and hydraulic characteristics like slope of land, geology, topography,

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geomorphology, drainage density and surface water bodies which helps in its replenishment (Biswas et al. 2012). The exploitation of the sub-surface zone increased since groundwater took over the surface water as a primary source of irrigation during the 1980s and at present, it contributes about 34% of the total annual water supply and an important fresh water reserve (Magesh et al. 2012). Exploration of this natural resource can be primed through hydrogeological investigations like soil boring test and geophysical resistivity surveys to determine the water level and delineation of discharge and recharge areas (Moustafa 2017). These methods are costly and time consuming as well (Mukherjee et al. 2012). Complex studies related to groundwater are now being made easier through application of remote sensing and Geographical Information System (GIS). It provides the concise viewing and high resolution coverage for thematic mapping of natural resources (Javed and Wani 2009). Groundwater model using geospatial techniques brings more advantage over traditional practices as numerous parameters can be represented on a single map (Nair et al. 2017). The selection of the most influencing parameters leading to the groundwater recharge is now being widely understood by Multi- Criteria Decision Making (MCDM) techniques. The integrated approach of GIS and MCDM techniques can be validated using different methods such as frequency ratio, certainty factor and watershed modelling (Sener et al. 2018), but the most important of them is the field verification of groundwater level, which is fewer in groundwater studies. Behzad et al. (2019) delineated groundwater potential zones of Leylia watershed, Iran, using remote sensing and GIS techniques incorporating Analytic Hierarchy Process (AHP) with it and selected only five sets of criteria such as drainage density, rainfall, lithology, slope and lineament density. Agarwal et al. (2013) determined groundwater potential zones using two techniques i.e. Analytic Hierarchical process (AHP) and Analytic Network Process (ANP) and verified the index map with the yield data of 37 pumping wells. Remote sensing and GIS techniques can also be used where data availability is poor. Panahi et al. (2017) made an appraisal of groundwater resources in dry areas without using ground based data and made it possible through Remote Sensing and GIS in Tehran Karaj plain in Iran. Siva et al. (2017) used the Geological Survey of India (GOI) maps and IRS- IC LISS III satellite images to prepare different thematic maps and delineated groundwater recharge potential zones based on MCDM techniques in Thanjavar district of Tamil Nadu. Application of MCDM techniques for distinguishing the groundwater potential zones will help the decision makers, water resources investigators and policy makers for sustainable groundwater management in an effective way (Andualem and Demeke 2019). These MCDM techniques are mainly concerned with discrete alternatives which are characterised by a set of criteria that may provide ordinal or cardinal information (Mardani et al. 2015). There are numerous MCDM techniques like the Analytical Hierarchy Process (AHP), Analytic Network Process (ANP) and Base Criteria Method (BCM). Of these methods, AHP requires expert judgement as it uses crisp set which leads to consideration of uncertainty whereas Fuzzy AHP deals with the situation which are vaguely defined and gives accurate values (Mulubrhan et al. 2014). Fuzzy set theory can be used as a modelling tool to deal with complex problems that are under human control but impossible to define them exactly (Aggarwal and Singh 2013). The main objective of FAHP is to prioritise the ranking of alternatives and it is based on the degree of possibilities of each criterion (Tang and Lin 2011). The FAHP technique can be regarded as an advanced tool developed from conventional AHP process (Ozdagoglu and Ozdagoglu 2007). Aouragh et al. (2016) assessed potential zones of groundwater recharge using six thematic layers, classified, weighted and integrated them using GIS with help of Fuzzy logic approach in Middle Atlas plateau, Morocco. Rafati and Nikeghbal (2017) used this Fuzzy logic approach for assessment of groundwater in a region around an anticline in Haji Adabcity in Fars province using only five hydro geologic parameters. Such studies are fewer in number on a global and regional scale under varied terrain and climatic conditions.

In the recent days, dependency on the groundwater for industrial, domestic and agricultural purposes has been increased. About 89% of the groundwater extracted is being used in irrigating the agricultural lands which makes it the higher category user in India (Suhag 2016). According to this report, 50% of the urban water management and 89% of the rural water management are sourced from groundwater. According to Central Ground water Board report (2018), the total annual recharge of groundwater has been decreased from 447 to 432 billion cubic meters. Seventeen percent of the blocks in India has been categorised as 'over exploited' where groundwater abstraction exceeds the annual groundwater recharge. From a field survey conducted by the authors also witnessed the constant and the exploitive use of submersible pumps due to the poor rainfall concentration and drying up of the surface water bodies. Under such backdrop identification of hotspot area or effective aquifer zones for sustainable groundwater recharge should be a prime concern. The state of West Bengal, India has been divided into three categories according to the Central Ground water Board. These are areas of high groundwater yield (> 150 m$^{3/}$h), moderate yield (between 50 and 150 m$^{3/}$h) and lower yield (< 50 m$^{3/}$h) (Ghosh et al. 2016). Rapid urbanisation, deforestation, unscientific exploitation has been leading to the poor groundwater recharge which is being fuelled by delaying monsoon. The study has been carried out in Garbeta block I of Paschim Medinapore district of West Bengal, India. The region is characterised by intensive landform variability consisting of older flood plain, buried pediments and lateritic ravines.

During heavy rainfall period surface runoff are common over the region leading to the removal of surface materials and reduction of the soil capacity to induce recharge (Shit et al. 2014). Therefore, delineation of the groundwater potential zone is necessary for effective management of water resources in one of the complex and critical terrain experiencing drought events. Very few or no studies are there regarding groundwater issues within the selected study area.

The main objective of the present study is (a) to demarcate the groundwater potential zone using Fuzzy AHP approach based on the synthetic extent analysis method integrated with geospatial technique (b) validation of the outcome using groundwater level survey.

Study area setting

Garbeta block 1 is a community development block (Indian country is divided into a number of states and union territories and these states are further subdivided into a number of administrative units or boundaries called districts. The next hierarchical level below it is a block in rural areas which is again subdivided into gram panchayets or village council having a minimum population of 2500) in Paschim Medinapore district of West Bengal, India, experiences hot and humid type of climate with a mean annual temperature of 28 °C and annual rainfall of 1450 mm (Shit et al. 2015). The study area is about 369 km^2 and is located between 22° 47′ 12″ N to 22° 56′ 27″ N latitude and 87° 13′ 17″ E to 87° 23′ 29″ E longitude (Fig. 1). Lateritic uplands along with the flat alluvial terrain can be visible along the banks of river Shilabati, the main channel flowing through the middle of the block from west to east direction for a length of about 26 km approximately. The study area is an extension of Choto Nagpur Plateau characterised by extensive rills and gullies. The main channel of this region is chocked in many areas with high sedimentation from the adjoining land surface, reducing the water carrying capacities which discourages groundwater recharge. The stage of the river is also reducing with growing days (Fig. 2) is another prime cause for poor interaction between surface and sub-surface hydrological system. Garbeta block I consists of quaternary alluvium underlain by tertiary sediments which act as a good infiltrating layer but excessive deforestation and presence of rill and gullies encourage high surface runoff over the region. The region is characterised by the secondary aquifer type having lateritic topsoil above with alternative bands of clay and sand layer. Laterite soil impedes groundwater recharge of the underlying bedrock as the base of laterite soil is characterised by poor permeability (Bonsor et al. 2014). The region falls under Paschim Medinapore district where previous studies showed that groundwater abstraction has been increasing in the recent days due to the inconsistent distribution of rainfall and scarcity of the surface water bodies

resulting in the drying of bore wells and dug wells (Bhunia et al. 2012). Based on the various government reports, the yield of wells within the study area is about 30–50 l per second (lps), whereas transmissivity and specific yield are about 3487 m^2/day and 3.87×10^{-5} respectively. The growing population pressure, agricultural activities, precipitation variability and delayed monsoon influence the groundwater system within the basin which needs effective management.

Materials and methods

The delineation of the groundwater potential zones has been executed using eleven surface and subsurface parameters which influence the groundwater recharge system. These are land use and land cover, drainage density, distance from river network, relative relief, lineament density, slope, soil type, geology, geomorphology, groundwater fluctuation level and normalised difference water index (NDWI). The groundwater potential map has been prepared using MCDM method of Fuzzy AHP and geospatial techniques by incorporating the thematic maps as the input parameters. The step by step methodology of the entire process has been shown in a flow chart (Fig. 3). Survey of India, topographical sheet number 73 N/9, 73 N/6, 73 N/5 and 73 N/11 of scale 1:50,000 have been used to digitise the drainage network. Landsat 8 OLI of path 139 and row 40 has been downloaded from USGS Earth Explorer website (https://earthexplorer.usgs.gov/) to prepare the land use and land cover map. SRTM (Shuttle Rader Topographic Mission) DEM of 30 m resolution has been downloaded from the same USGS Earth Explorer website to prepare the elevation and slope map. Groundwater level data have been obtained from Central ground water Board (CGWB 2018) and soil map from National Bureau of Soil Survey and Land Use Planning (NBSSLUP). The maps obtained in raw file have been scanned and digitised for map preparation. Normalised difference water index (NDWI) has been calculated using the same Landsat 8 OLI Image. Geological data including geological map has been downloaded from Geological Survey of India (GSI) website https://www.gsi.gov.in, and lineaments have been downloaded from Bhuvan website (https://bhuvan.nrsc.gov.in/bhuvan_links.php). To get the specified geology and lineaments of the study area, it has been masked with boundary file and geological map, and lineament density has been prepared and calculated in the ArcGIS software version 10.3. Further discussion of each of the thematic layers has been made under the heading description of parameters.

The MCDM technique of Fuzzy AHP approach based on synthetic extent analysis has been applied here to calculate the weights of each parameter using triangular fuzzy scale (Table 1). The parameters in vector format have been converted into raster using ArcGIS tool box. These raster files are
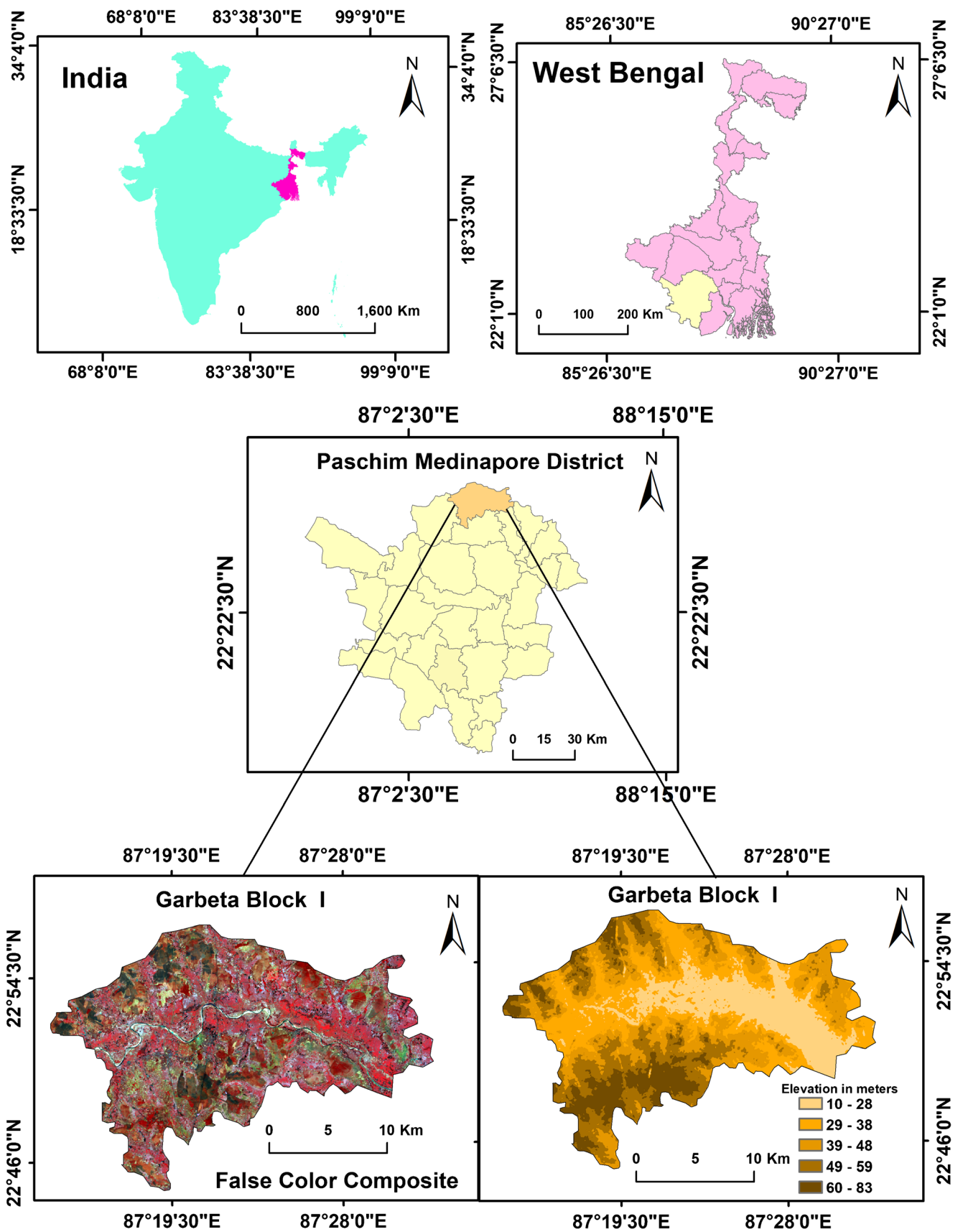
Fig. 1 Location map of the study area

Fig. 2 Condition of the river in Garbeta block I

then reclassified and weights have been assigned to prepare the final potential map using raster calculator in ArcGIS.

Fuzzy AHP based on synthetic extent analysis

A useful tool for MCDM in the fuzzy environment is FAHP (Wang and Chin 2011). It uses the fuzzy set theory to the basic AHP process which has been developed by Saaty (Ayhan 2013). The AHP process takes pairwise comparison matrix of different alternatives with respect to various criteria and solves the MCDM problem. It does not incorporate or reduces the vagueness of personal judgement as it is based on crisp set.

The FAHP is an effective tool to solve this linguistic fuzziness (Peng and Tang 2015). Jayawickrama et al. (2017) used FAHP in evaluating a generic model dealing with manufacturing plant sustainability as a tool for feasibility study. Ayag (2005) made a study on the evaluation process of designing alternatives in a new product development in companies in faster growing markets. FAHP studies related to environmental phenomenon are fewer in number. In this paper, the weight of each input parameter has been calculated based on the synthetic extent analysis method of FAHP as developed by Chang in 1996. The steps of the calculation are shown in the following way.

Say, $X = \{ \times 1, \times 2, \times 3 \dots xn \}$ an object set, and $G = \{ g1, g2, g3 \dots gn \}$ is a goal set. As per the method, each object is considered and extent analysis for each goal has been carried out. Therefore, extent analysis values for each object can be obtained by the following steps (Chang 1996):

$M^1_{gi}, M^2_{gi}, \dots \dots M^m_{gi}, i = 1, 2, 3 \dots \dots n$ where M^j_{gi} ($j = 1, 2, \dots, m$) all are TFNs (Table 1).

The step 1 includes the value of the fuzzy synthetic extent (Si) based on the ith object is defined as Eq. (1)

$$\text{Si} = \sum_{i=1}^{m} M^j_{gi} * \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M^j_{gi} \right]^{-1} \tag{1}$$

Now, in order to obtain the $\sum_{j=1}^{m} M^j_{gi}$, the fuzzy addition operation of the m extent analysis has been done using the following Eq. (2).
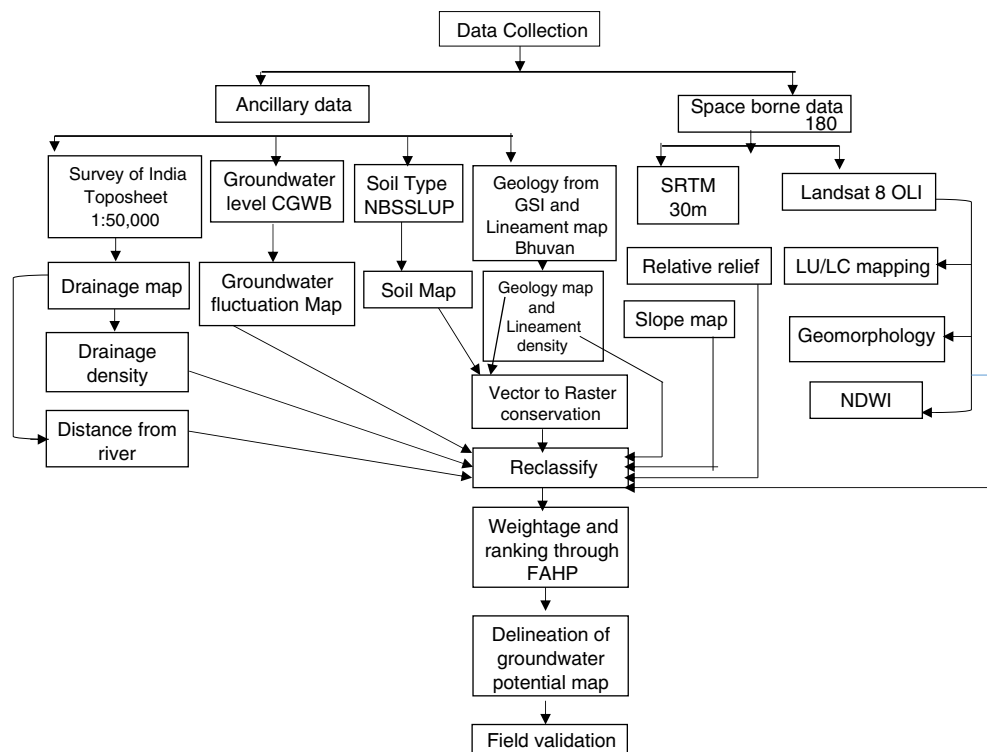
Fig. 3 Flow chart of the methodology

Table 1 Triangular fuzzy scale

Linguistic scale for importance	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Just equal	(1,1,1)	(1,1,1)
Equally important (EI)	(1/2,1,3/2)	(2/3,1,2)
Weakly more important (WMI)	(1,3/2,2)	(1/2,2/3,1)
Strongly more important (SMI)	(3/2,2,5/2)	(2/5,1/2,2/3)
Very strongly more important(VSMI)	(2,5/2,3)	(1/3,2/5,1/2)
Absolutely more important(AMI)	(5/2,3,7/2)	(2/7,1/3,2/5)

$$\sum_{j=1}^{m} M_{gi}^{j} = \sum_{j=1}^{m} lj, \sum_{j=1}^{m} mj, \sum_{j=1}^{m} uj \tag{2}$$

where l = lower limit, m = the middle value and u = the upperlimit of the entire set.

In oder to obtain this equation $[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j}]^{-1}$, the calculation has been performed using Eq. (3)

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j}\right] \sum_{j=1}^{m} li, \sum_{j=1}^{m} mi, \sum_{j=1}^{m} ui \tag{3}$$

Now, the reverse of the formula has been done using Eq. (4)

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j}\right]^{-1}$$
$$= 1/\sum_{i=1}^{n} u_1, 1/\sum_{i=1}^{n} m_1, 1/\sum_{i=1}^{n} l_1, \tag{4}$$

The step 2 includes the calculation of the degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ and is defined as Eq. (5)

$$V(M_2 \geq M_1) = \sup_{y \geq x} [\min(\mu_{M1}(x), \mu_{M2}(y))] \tag{5}$$

The above formula can also be written as Eq. (6).

$$V(M_2 \geq M_1) = \begin{bmatrix} 1, \text{if } m_2 \geq m_1 \\ 0, \text{if } m_2 \geq m_1 \end{bmatrix}$$
$$\frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} \text{ otherwise} \tag{6}$$

where d is the highest interaction point (μ_{M1} and μ_{M2}) (Fig. 4).

The step 3 includes the calculation of possible degree for convex fuzzy number to be greater than k convex fuzzy numbers $Mi = (i = 1, 2, 3\dots k)$ using the following Eq. (7).

$$V = (M \geq M_1, M_2 \dots M_k)$$
$$= \left(V[(M \geq M_1) \text{ and } (M \geq M_2) \text{ and } (M \geq M_k)] \right.$$
$$= \min V(M \geq M_i), i = 1, 2 \text{ and } 3 \dots k \tag{7}$$

It can be assumed that the eq. (8),

$$d_1(A_1) = \min V(S_1 \geq S_k) \tag{8}$$

For $k = 1, 2, \dots\dots, n; k \neq I$, and thus, the weight vector can be obtained by following the Eq. (9).

$$W' = (d'(A_1), d'(A_2), \dots\dots, d'(A_n))^T \tag{9}$$

where $Ai = (1, 2, 3, \dots\dots, n)$ are m elements.

In the last step, the normalized weight has been calculated by using Eq. (10).

$$W' = (d(A_1), d(A_2) \dots\dots d(A_n))^T \tag{10}$$

where W is a non-fuzzy number.

The pairwise comparison matrix and the respective calculated weights of all the eleven parameters using the above equations have been shown in Table 2.

Groundwater potential index

Groundwater potential index is a quantification methodology that helps in the identification of potential regions of groundwater recharge by assigning a score to thematic layers. It is a dimensionless index. The weights obtained by various MCDM techniques are applied in a linear combination to get different groundwater potential zones (Agarwal et al. 2013). The overlay tool in ArcGIS can be used to find the index in the most accurate way (Ahmed et al. 2015). Here raster calculator present in spatial analyst function in the ArcGIS toolbox has been used to calculate the index and to prepare the final map (Fig. 17a) which has been shown in a flowchart (Fig. 5). The
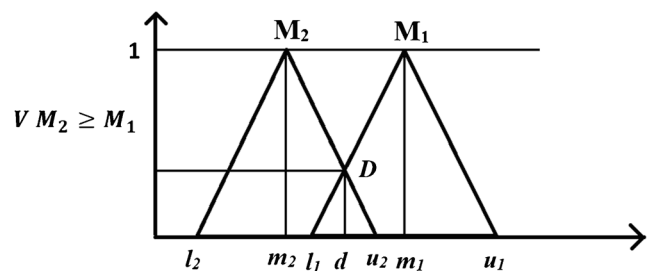

Fig. 4 Intersection between the M_1 and M_2

Table 2 Pairwise comparison matrix and calculated weight

Parameters	LULC	DD	RR	Slope	DFR	NDWI	GWF	LD	Soil	Geomorphology	Geology	Fuzzy AHP Weight
LULC	(1,1,1)	(2/5,1/2,2/3)	(2/5,1/2,2/3)	(3/2,2,5/2)	(1,3/2,2)	(1/2,2/3,1)	(2/5,1/2,2/3)	(2/5,1/2,2/3)	(1/3,2/5,1/2)	(2/5,1/2,2/5)	(1/2,1,3/2)	0.033
DD	(3/2,2,5/2)	(1,1,1)	(1,3/2,2)	(2/5,1/2,2/3)	(3/2,2,5/2)	(3/2,2,5/2)	(2/5,1/2,2/3)	(2/5,1/2,2/3)	(1/3,2/5,1/2)	(1/3,3/2,5/1/2)	(1/2,1,3/2)	0.077
RR	(3/2,2,5/2)	(1/2,2/3,1)	(1,1,1)	(2/5,1/2,2/3)	(3/2,2,5/2)	(3/2,2,5/2)	(2/5,1/2,2/3)	(2/5,1/2,2/3)	(1,3/2,2)	(2/5,1/2,2/3)	(1/2,1,3/2)	0.065
Slope	(2/5,1/2,2/3)	(3/2,2,5/2)	(3/2,2,5/2)	(1,1,1)	(3/2,2,5/2)	(3/2,2,5/2)	(1,3/2,2)	(1,3/2,2)	(2/5,1/2,2/3)	(1,3/2,2)	(1/2,1,3/2)	0.141
DFR	(1/2,2/3,1)	(2/5,1/2,2/3)	(2/5,1/2,2/3)	(2/5,1/2,2/3)	(1,1,1)	(1,3/2,2)	(2/5,1/2,2/3)	(2/5,1/2,2/3)	(2/5,1/2,2/3)	(1,3/2,2)	(2/5,1/2,2/3)	0.014
NDWI	(1,3/2,2)	(2/5,1/2,2/3)	(2/5,1/2,2/3)	(2/5,1/2,2/3)	(1/2,2/3,1)	(1,1,1)	(3/2,2,5/2)	(2/5,1/2,2/3)	(2/5,1/2,2/3)	(1,3/2,2)	(2/5,1/2,2/3)	0.042
GWF	(3/2,2,5/2)	(3/2,2,5/2)	(3/2,2,5/2)	(1/2,2/3,1)	(3/2,2,5/2)	(2/5,1/2,2/3)	(1,1,1)	(2/5,1/2,2/2/3)	(2/5,1/2,2/3)	(1/2,1,3/2)	(2/3,1,2)	0.100
LD	(3/2,2,5/2)	(3/2,2,5/2)	(3/2,2,5/2)	(1/2,2/3,1)	(3/2,2,5/2)	(3/2,2,5/2)	(3/2,2,5/2)	(1,1,1)	(2/5,1/2,2/3)	(3/2,2,5/2)	(2/3,1,2)	0.144
Soil	(2,5/2,3)	(2,5/2,3)	(2/5,1/2,2/3)	(2,5/2,3)	(3/2,2,5/2)	(3/2,2,5/2)	(3/2,2,5/2)	(3/2,2,5/2)	(1,1,1)	(3/2,2,5/2)	(1/2,1,3/2)	0.186
Geomorphology	(3/2,2,5/2)	(3/2,2,5/2)	(3/2,2,5/2)	(2,5/2,3)	(1/2,2/3,1)	(1/2,2/3,1)	(3/2,2,5/2)	(2/3,1,2)	(2/5,1/2,2/3)	(1,1,1)	(2/5,1/2,2/3)	0.075
Geology	(2/3,1,2)	(2/3,1,2)	(2/3,1,2)	(2/3,1,2)	(2/5,1/2,2/3)	(2/5,1/2,2/3)	(1/2,1,3/2)	(1/2,1,3/2)	(2/3,1,2)	(3/2,2,5/2)	(1,1,1)	0.123

groundwater potential index has been calculated using the following Eq. (11).

GWPI (Groundwater Potential Index)

$$= \text{LULC}*w + \text{DD}*w + \text{LD}*w + \text{DFR}*w + \text{RR}*w$$
$$+ \text{Slope}*w + \text{NDWI}*w + \text{Geomorphology}*w$$
$$+ \text{GWF}*w + \text{Soil}*w + \text{Geology}*w \qquad (11)$$

Where LULC is land use and land cover, DD is drainage density, LD is lineament density, DFR is distance from river, RR is relative relief, NDWI is normalised difference water index, GWF is groundwater fluctuation and w is the calculated weight. The weights of each parameter have been calculated through Fuzzy AHP method using the Eq. from (1) to (10).

Description of criteria

Land use and land cover

Land use and land cover pattern play an important role in encouraging runoff and infiltration over a region The land use and land cover classes that are observed in the study area include dense forest, open forest, water bodies, lateritic exposure, dry fallow land, agricultural wet fallow, agricultural land and settlement (Fig. 6). The classification map has been prepared using Landsat 8 OLI of March 2018 in the ERDAS IMAGINE 9.2 software applying supervised classification technique. To measure its accuracy, Kappa index or Kappa Coefficient (Alam et al. 2019) has been calculated which scored around 96%. From the classified map, it can be seen that agricultural land is highly prevalent over the study area which covers about 27.32% of the block. Dry fallow land (16.22%) also predominates over the study area which impedes groundwater recharge, and therefore, low weightage has been assigned (0.053). Here degraded forest and increase in fallow land are quite visible which can be a threat to the groundwater resources present in the study area. The calculated weight of all the land use and land cover classes can be seen in Tables 2 and 3.

Drainage density

Drainage density plays an important role in recharging the sub-surface zone. Drainage density has been calculated using Horton's method introduced in 1945. The algorithm used can be written as Eq. (12) (Horton 1945).

$$D_d = L/A \qquad (12)$$

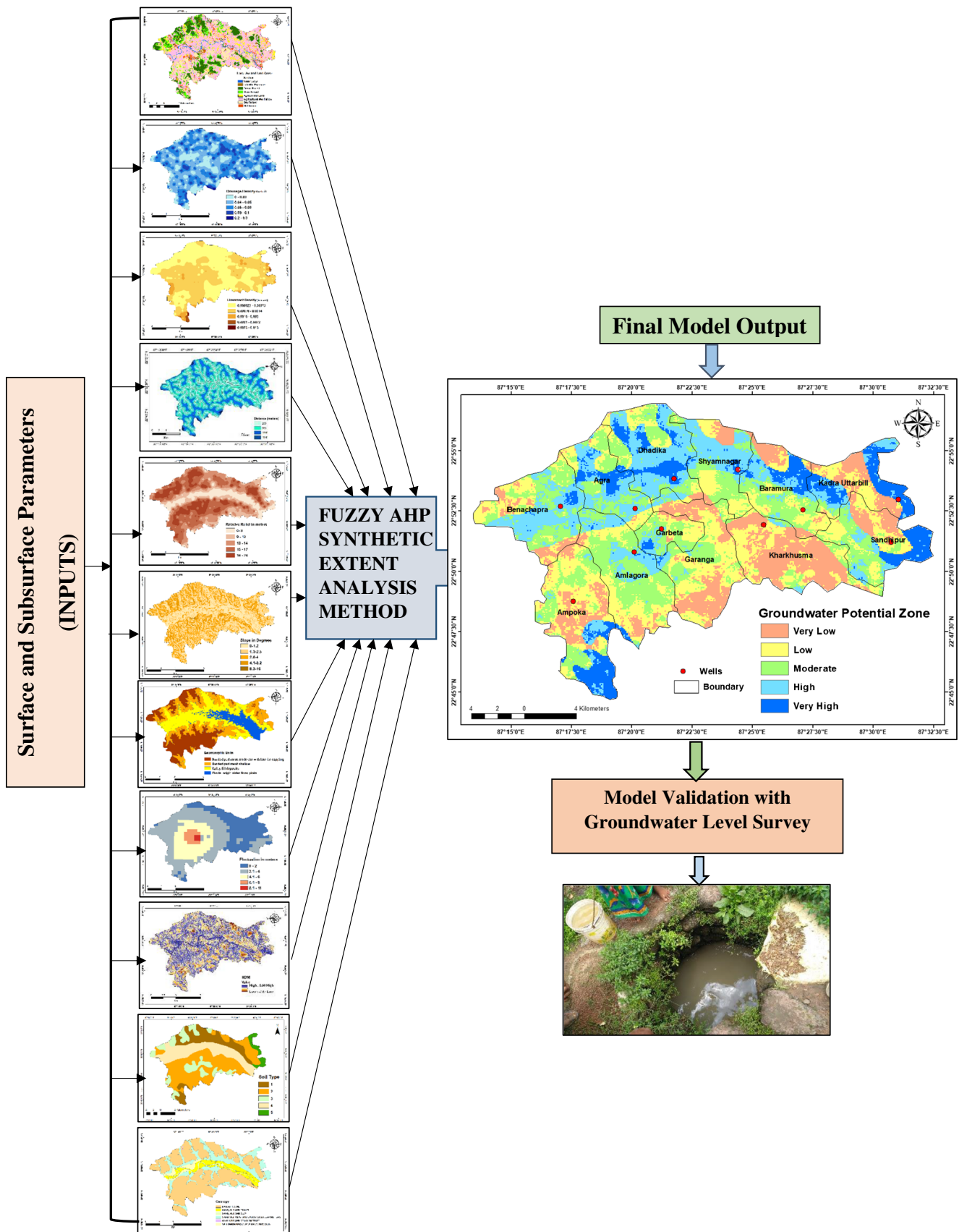where L = total length of the stream (km) and A is the area (km^2).

Fig. 5 Flow chart of GWPI (Groundwater Potential Index)
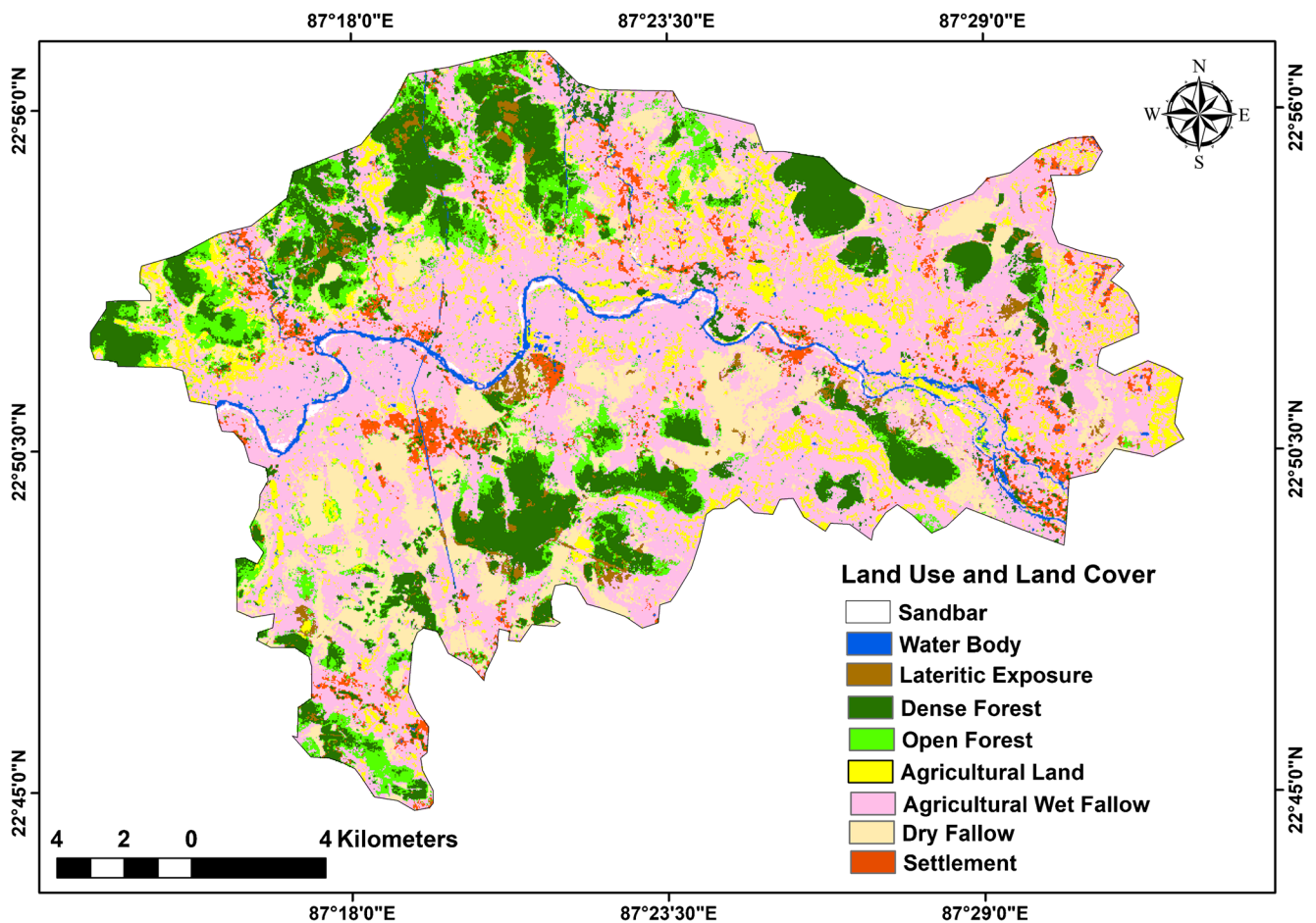
Fig. 6 Land use and land cover map of the study area

Groundwater recharge has a negative relation with the drainage density. The areas where the drainage density is high have low recharge, and the area where drainage density is low is the region of potential groundwater recharge. It has also an inverse relationship with permeability. In Garbeta, the drainage density ranges from 0 to 0.3 km/km^2 (Fig. 7). Small stream originating from the lateritic badlands as gully and rills (Shit et al. 2015) increases the surface runoff over the region and discourage groundwater recharge over the region. Afforestation and sustainable land use and land cover management are at urgent need over the region. The calculated weight of the parameter is shown in Tables 2 and 3.

Relative relief

Relative relief is one of the principal parameters that induce the groundwater recharge over the region. Relative relief has been calculated using the Melton formula introduced in 1957. The algorithm used can be written as Eq. (13) (Melton 1957).

$$R_{\mathrm{r}} = \Delta H / P \tag{13}$$

where H is the difference between the highest and the lowest point within the area, and P is the basin perimeter. The relative relief in this region varies from 0 to 26 m (Fig. 8). The relative relief has an inverse relation with groundwater recharge. In Garbeta, irregular and dissected uplands are common near the bank of river Shilabati where the lateritic ravines can be observed crisscrossed by numerous rills and gullies. The relative relief is lower along the edges of the block boundary in the southern sector. During heavy rainfall events, land subsidence and mudflow are common within the study area (Shit et al. 2014). The areas where the relative relief is very low are the regions with good groundwater potential, and therefore, high weightage has been assigned (0.273). The calculated weight of this parameter has also been shown in Tables 2 and 3.

Slope

Slope is one of the prime controlling factors of surface water infiltration to recharge the sub-surface stratum. The slope map has been prepared using SRTM DEM of 30 m

Table 3   Calculated Fuzzy AHP weights of the sub-parameters

Parameters	Sub-parameters	Area in km^2	Area in %	Fuzzy AHP weight
Land and land cover	Dense forest	33.5	9.04	0.171
	Open forest	34.28	9.25	0.174
	Agricultural land	101.24	27.32	0.085
	Agricultural wet fallow	64.73	17.47	0.100
	Water body	21.62	5.83	0.199
	Dry fallow	61.22	16.52	0.053
	Lateritic exposure	34.24	9.24	0.076
	Settlement	16.43	4.43	0.056
	Sand bar	3.15	0.85	0.086
Drainage density (km/km^2)	0–0.03	77	20.81	0.273
	0.04–0.05	140	37.84	0.257
	0.06–0.08	115	31.08	0.24
	0.09–0.1	36	9.73	0.145
	0.2–0.3	2	0.54	0.086
Relative relief (m)	0–8	54.00	14.63	0.50
	9.0–12.0	62.00	16.80	0.44
	13.0–14.0	84.00	22.76	0.05
	15.0–17.0	107.00	29.00	0.01
	18.0–26.0	62.00	16.80	0.00
Slope in degree	0–1.25	118.89	32.28	0.634
	1.26–2.49	147.99	40.18	0.112
	2.5–3.99	35.87	9.73	0.081
	4–8.23	34.89	9.47	0.173
	8.24–15.9	31.90	8.32	0
Lineament density (km/km^2)	0–0.00075	176.73	47.79	0.061
	0.00076–0.0014	175.38	47.43	0.132
	0.0015–0.003	15.21	4.11	0.192
	0.003–0.0072	2.23	0.60	0.244
	0.0073–0.015	0.24	0.06	0.370
Soil	Poorly drained loamy soil developed on old alluvium	65.01	17.59	0.48
	Very deep well drained fine loamy soil on flood plain with loamy surface	82.56	22.34	0.37
	Poorly Drained fine cracking occurring on level to nearly level low lying alluvial plain	7.62	2.06	0.06
	Very deep imperfectly drained coarse loamy soil	71.68	19.40	0.04
	Fine loamy soil on undulating dissected upland	142.69	39.61	0.04
Geomorphology	Buried pediment with moderate laterite capping	95.44	25.86	0.109
	Valley fill deposits	107.21	29.05	0.236
	Buried pediment shallow	117.2	31.76	0.196
	Fluvial origin older flood plain	41.18	13.33	0.458
Distance for river (m)	200	119.86	32.39	0.571
	500	142.55	38.53	0.183
	1000	100	27.03	0.126
	2000	6.42	1.73	0.120
Groundwater fluctuation (m)	0–2.0	108.00	29.27	0.50
	2.1–4.0	168.00	45.53	0.35
	4.1–6.0	77.00	20.87	0.16
	6.1–8.0	13.00	3.52	0.00

Table 3 (continued)

Parameters	Sub-parameters	Area in km²	Area in %	Fuzzy AHP weight
	8.1–11	3.00	0.81	0.00
NDWI	High	77.21	20.86	1
	Low	291.66	78.82	0
Geology	Lateritic soil	225.13	60.86	0.126
	Sand, silt and gravel	36.98	10	0.252
	Sand, silt and clay	9.42	2.55	0.175
	Sand, silt, clay and calcareous concretions	85.64	23.15	0.127
	Clay, grit and conglomerate	0.33	0.09	0.092
	Yellowish brown fine sand, silt and clay	12.44	3.36	0.152

resolution. The slope map has been prepared using ArcGIS tool box. The areas having a gentle slope are encouraged by high infiltration whereas areas having steep slope discourage the same. The study area has been divided into 5 classes of slope in degrees. Here the slope varies from 0 to 16 degrees (Fig. 9). The slope is higher where the steep gullies are located. Infiltration is assumed to be greater near the areas where the slope ranged between 0 and 1.2 degrees and therefore are the areas having good groundwater potential. The weight assigned to this parameter has been shown in Tables 2 and 3.

Lineament density

Lineaments are the linear configuration of the land features that are quite visible from satellite images that reflects sub-surface geologies of a region. These are mainly the weaker zones which facilitate the flow and movement of groundwater. Lineaments within the study area have been downloaded from Bhuvan website and the lineament density map has been prepared using the ArcGIS software. Lineament density is the length of a linear feature per unit area which depicts regions of potential groundwater recharge (Fashae et al. 2013). The
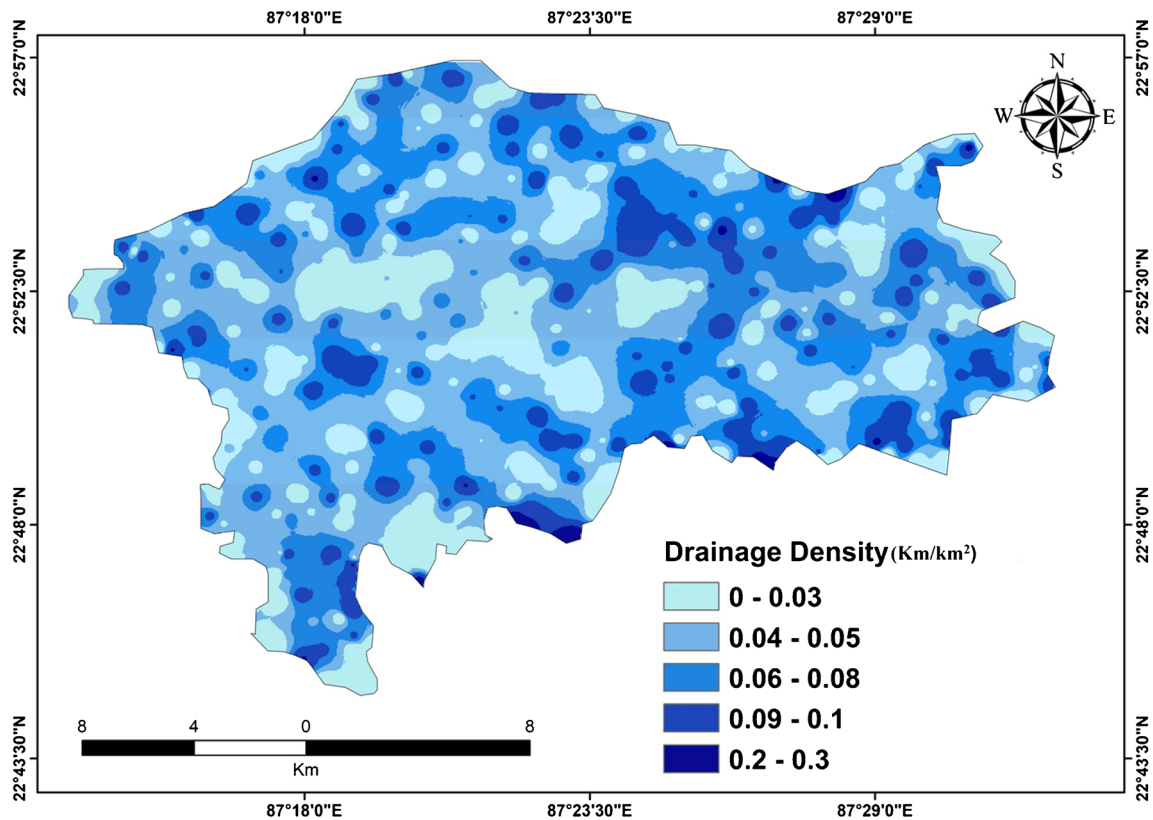

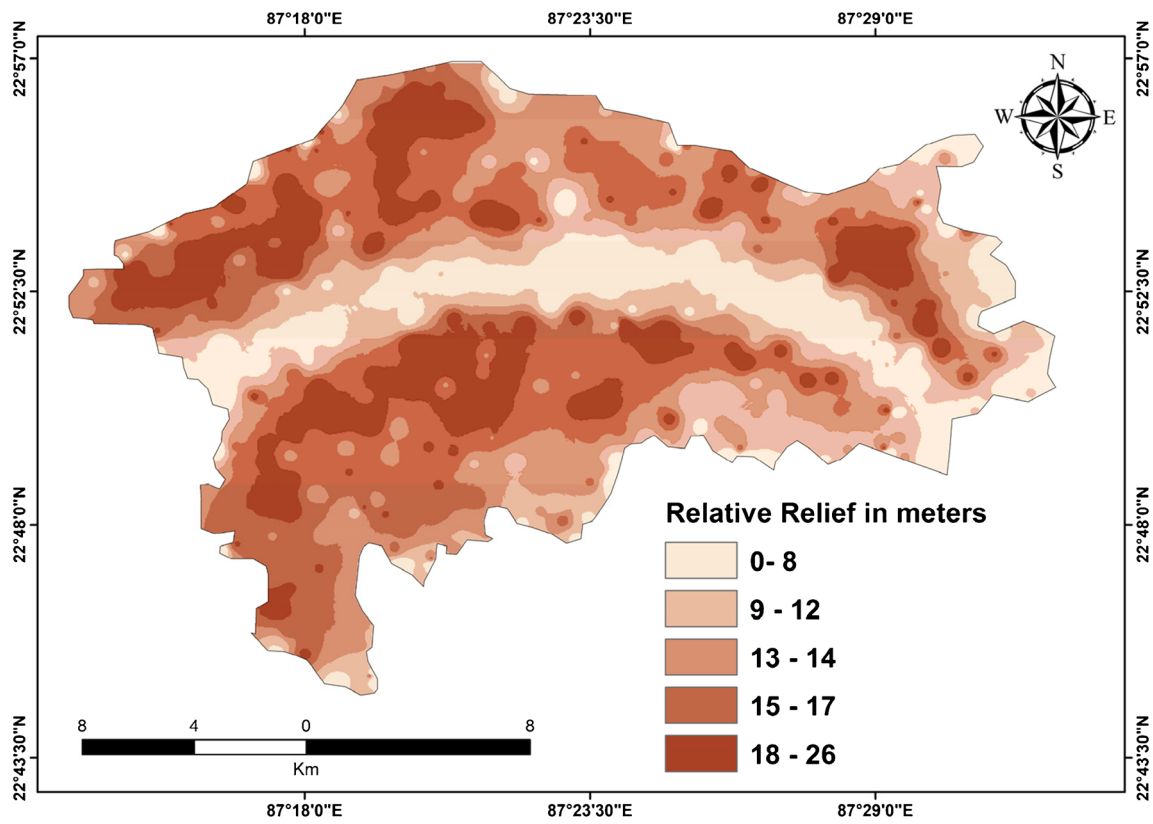**Fig. 7** Drainage density map of the study area

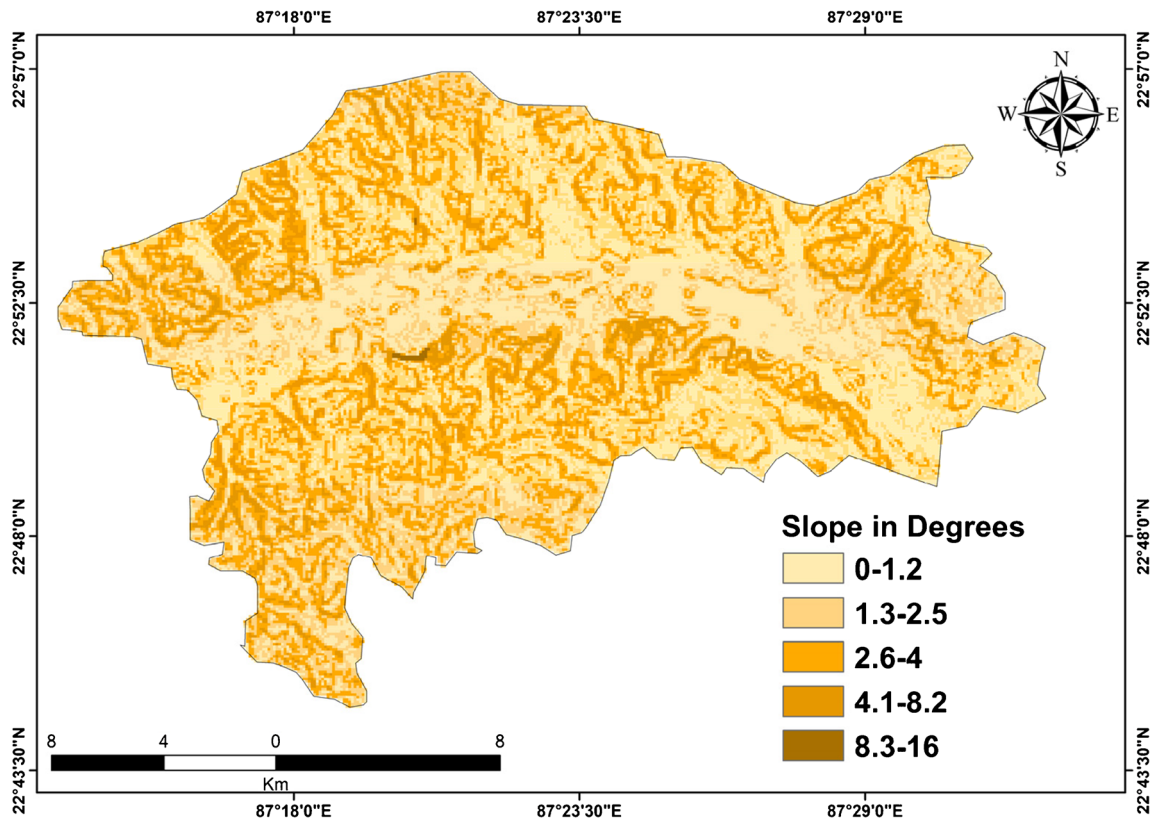**Fig. 8** Relative relief of the study area

Fig. 9 Slope map of the study area

following formula (Eq. 14) has been used to calculate the lineament density (Yeh et al. 2016).

$$\text{Ld} = \frac{\sum_{i=1}^{i=n} L}{A} \quad (14)$$

where L is the total length of lineaments (km) and A is the area (km^2).

The areas where the intersection between lineaments is found can give optimum groundwater recharge. The presence of lineaments is poor over the study area. The lineament density map has been divided into 5 classes. The density varies from 0 to 0.015 km/km^2 (Fig. 10). Lineament density is slightly higher in the south-western sector. The calculated weight of this parameter has been shown in Tables 2 and 3.

Geomorphology

The geomorphic configuration of the study area is embedded with buried pediment moderate with laterite capping (25.86%), buried pediment shallow (31.76%), valley fill deposits (29.05%) and fluvial origin older flood plain (13.33%) (Fig. 11). Buried pediment with laterite capping is found in the northern and southern sections of the study area which is mainly covered with vegetation where the soil is clay loamy type and the topography is undulating in nature. Buried pediment shallow mainly consists of consolidated weathered

material covered with a thin layer of alluvium where open forest can be found. Valley fill deposits are found at the central part of the study area consisting of colluvial material coming from adjoin uplands consisting of fine loamy to clayey soils. The south eastern part is fluvial in origin with older flood plain mostly consisting of clayey soil. The geomorphic configuration of a region is one of the important contributing factors for groundwater recharge. About 29.05% of the study area is covered by valley fills which are the favourable areas of quantifiable groundwater recharge. The areas occupied by buried pediments moderate with laterite capping impede groundwater recharge and encourages high surface runoff and hence low weightage has been assigned (0.109). The weight assigned to this parameter has been shown in Tables 2 and 3.

Groundwater fluctuation

The zone of the groundwater fluctuation reveals the recharge potentiality of a region. The areas where the pre-monsoon and post monsoon groundwater level difference is high signifies poor recharge of the aquifer layers from the monsoonal precipitation. Groundwater fluctuation map has been prepared using groundwater level data as obtained from Central Ground water Board (CGWB 2018). The data obtained in dbf format with latitude, longitude and depth of wells are imported in ArcGIS and converted into points. Inverse
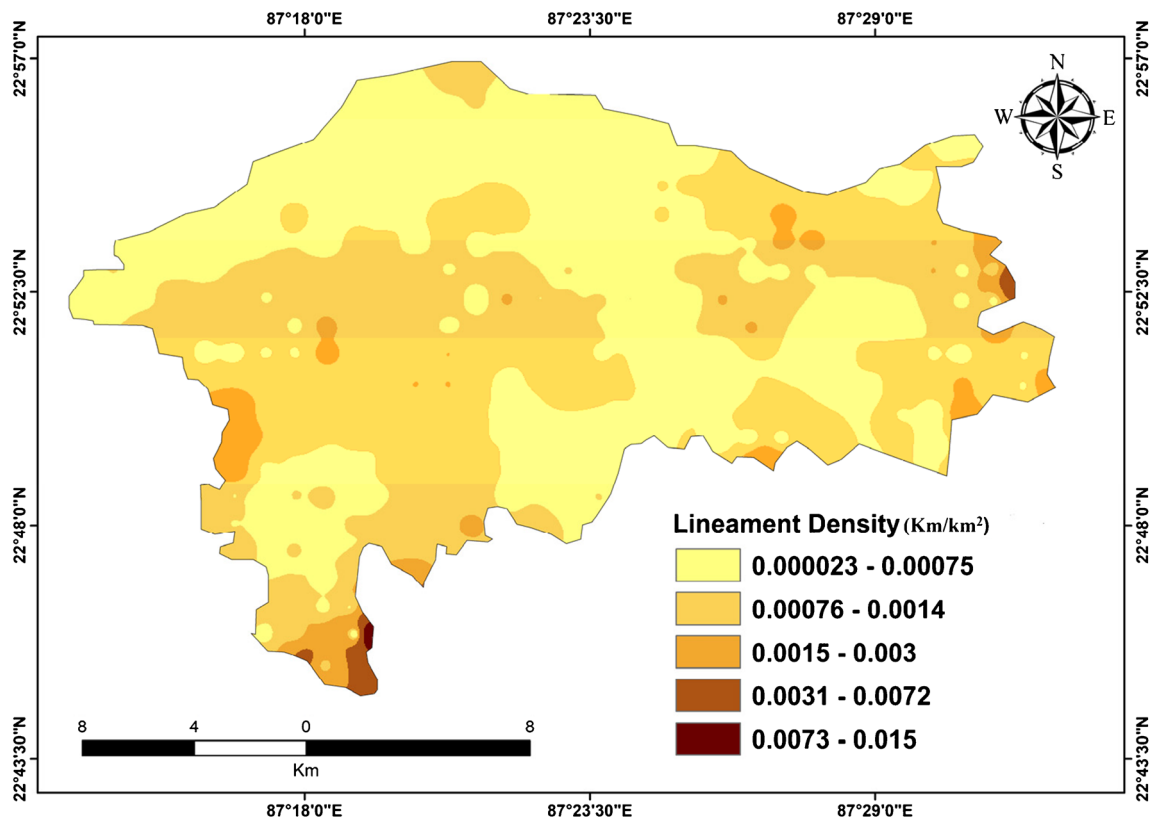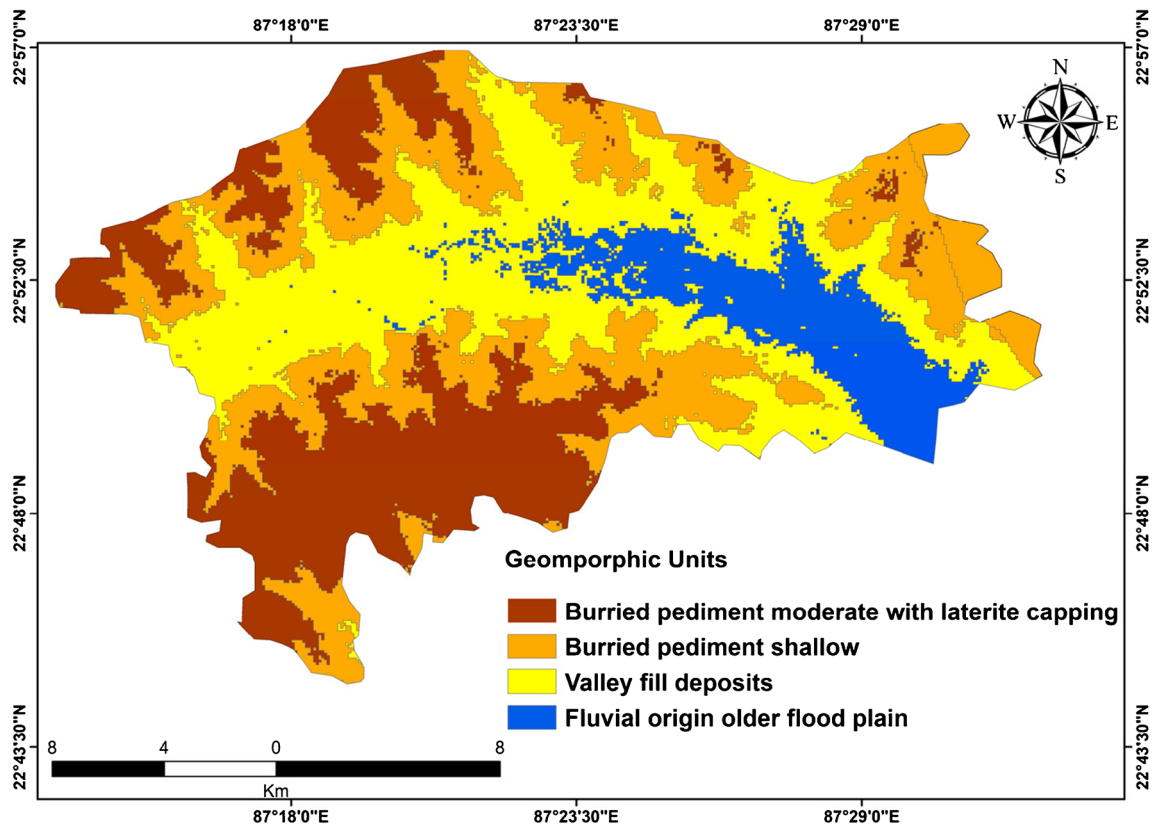

Fig. 10 Lineament density of the study area

Fig. 11 Geomorphic map of the study area

distance weighted (IDW) technique has been applied for the interpolation of the groundwater level data and to prepare the final fluctuation map. Groundwater fluctuation is the highest in the regions where the pre-monsoon and post monsoon depth varies remarkably. Fluctuation depends on how quickly the aquifer responds to a rainfall event and on the physical parameters of the aquifer (i.e. transmissivity and specific yield). The disparity between the level of the winter and summer water table is known as the 'zone of intermittent saturation'. In the study area, the groundwater fluctuation ranges between 0 and 11 m (Fig. 12). The fluctuation is higher near the central part of the block where lateritic ravines are located. The weight assigned to this parameter has been shown in Tables 2 and 3.

Distance from river network

Streams and groundwater have a close relation reflecting the effluent and influent character. Areas close to a surface water source are the areas of good groundwater prospects. Groundwater recharge or deep drainage or deep percolation is a hydrologic process where water moves downward from surface to the underground. Extensive groundwater abstraction hampers the inner connectivity between the two systems. The main channel flowing through the study area is Shilabati river system having numerous small tributaries, but in the

recent days, drying of the river beds is common during the summer months (Fig. 2). Under such condition, extensive extraction of groundwater can be seen over the region using submersible shallow pumping system for agricultural irrigation, and hence, depletion of groundwater level takes place (Halder et al. 2020). Rejuvenation of the surface water is therefore remains the prime concern in this region. Here buffer analysis of each streamline has been made at a distance of 200 m, 500 m, 1000 m and 2000 m respectively (Fig. 13) to study the impact of groundwater recharge through river water percolation. The calculated weight assigned to this parameter has been shown in Tables 2 and 3.

Normalized difference water index

NDWI is an index mapping of the liquid water content of a region prepared using Green and Near Infra-Red bands (NIR) of Landsat 8 OLI. In this paper, the NDWI has been prepared using the formula (Eq. 15) given by McFeeters (1996).

$$NDWI = \frac{Green + NIR}{Green - NIR} \qquad (15)$$

The areas where the liquid water content is higher can be assumed as the area potential to recharge the sub-surface aquifer. The index value for this region ranges from − 7 to 0.60
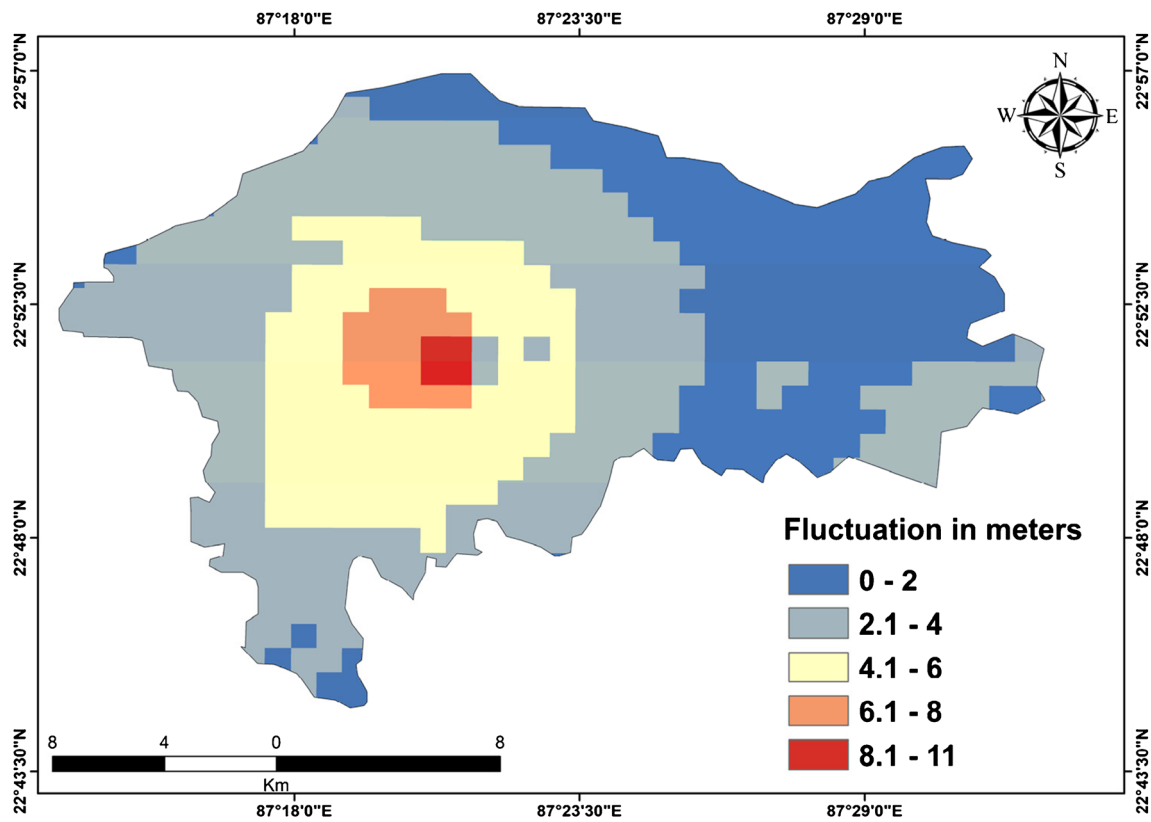
Fig. 12 Groundwater fluctuation map of the study area

(Fig. 14). The areas having negative values are mostly the bare lands where the soil moisture is poor and fails to saturate the deeper layers. The calculated weights assigned to this parameter have been shown in Tables 2 and 3.

Soil character

Soil is the most important of all the factors that controls the infiltration of surface water to saturate the underground layers

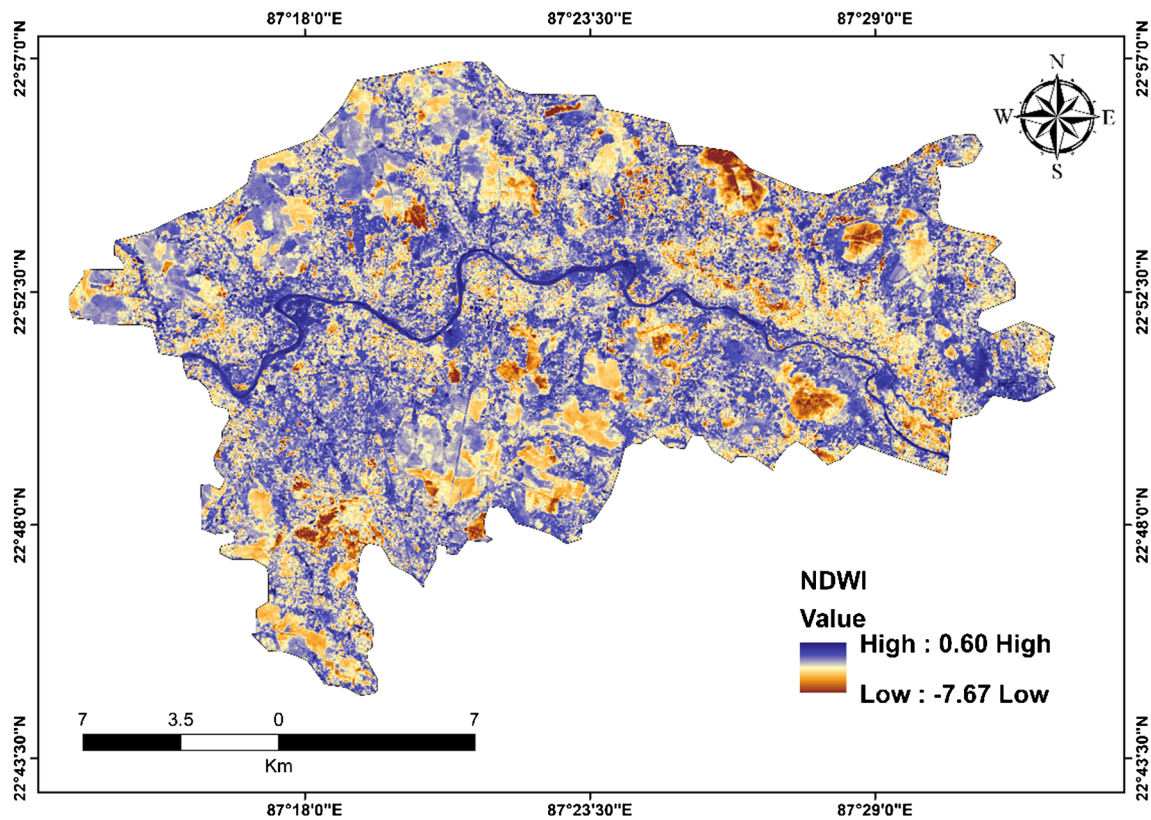**Fig. 13** Water body proximity map of the study area
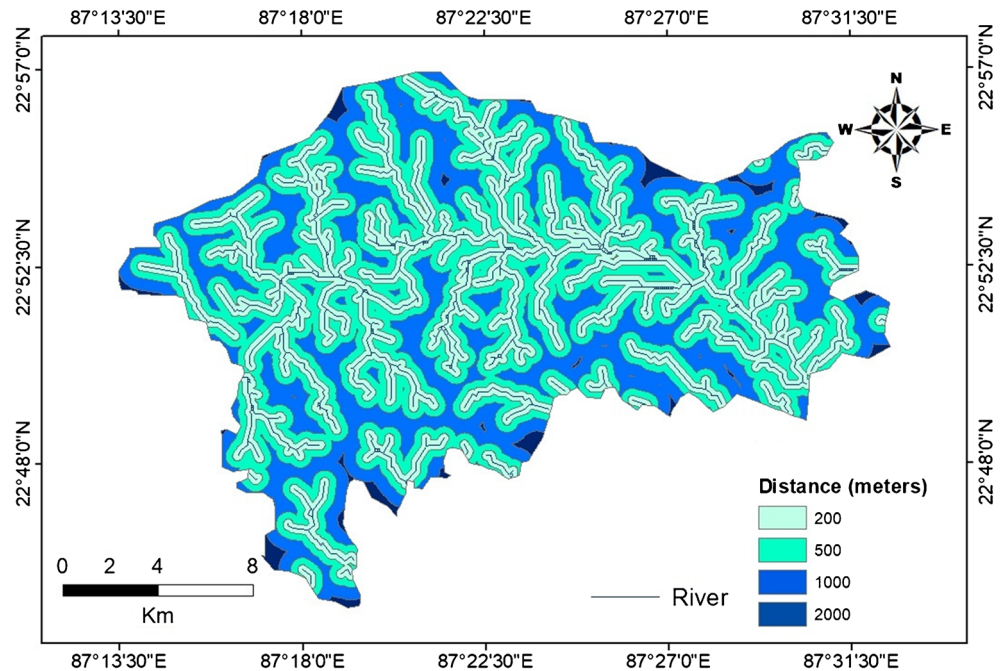
Fig. 14 NDWI map of the study area

below. The porosity and permeability are the two important characteristics that alter the recharge process. Sandy soil has high infiltration capacity while clayey soil shows poor values. The study area is covered by lateritic ravines and older flood plain consisting of loamy, bits of clayey and sandy soil (Fig. 15). Areas covered with loamy soil can be good for infiltration and groundwater recharge. The soil type of this region mainly includes poorly drained loamy soil developed on old alluvium (17.59%) found at the northern section, fine loamy soil on undulating dissected upland (39.61%) mainly found at the southern section where the elevation is quite high. Very deep imperfectly drained coarse loamy soil (19.40%) is found at the edges of the block whereas very deep well drained fine loamy soil on flood plain with loamy surface (22.34%) can be seen found at the middle section. Parts of north eastern section are covered with poorly drained fine cracking surface soil (2.06%) occurring on level to nearly level low lying alluvial plain. The calculated weights assigned to this parameter have been given in Tables 2 and 3.

Geology

Geological formation is one of the most important parameters that control the surface water percolation and movement into the deepest layers. The geological formation of the region includes lateritic soil (60.86%), sand silt gravel (10%), sand silt clay (2.55%), sand silt clay and calcareous concretions (23.15%), clay grit and conglomerate (0.09%) and lastly yellowish brown fine sand silt and clay (3.36%) (Fig. 16). Laterite is one of the predominant geological units found over the region which is mainly concentrated at the upland areas and is covered by dry deciduous forest dissected by east flowing Shilabati river basin and at the central part lateritic badlands locally called Gongoni can be found having alternative bands of sandstone and siltstone overlaid by ferruginised sediments (Ghosh and Guchhait 2020). Alternative bands of sand, silt, clay, gravel and calcareous concentrations are found near the river bed which shows good infiltration and groundwater recharge. Within the study area, small coverage of clay, grit and conglomerate and yellowish brown fine sand, silt and clay can be found which indicates poor to moderate groundwater potential. The calculated weights assigned to this parameter have been given in Tables 2 and 3.

Results and discussion

Delineation of the groundwater potential zone

The groundwater potential zone has been demarcated using eleven different parameters including surface and subsurface parameters and is classified into 5 zones (Fig. 17a). During
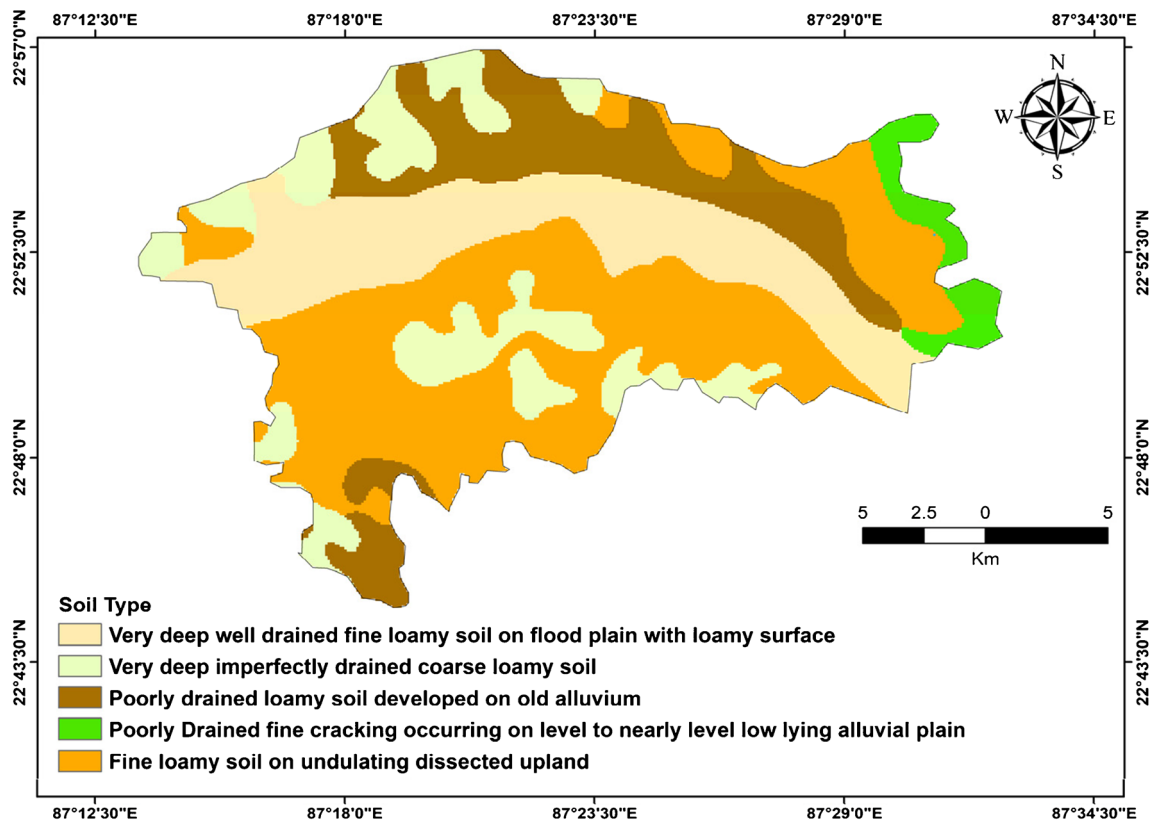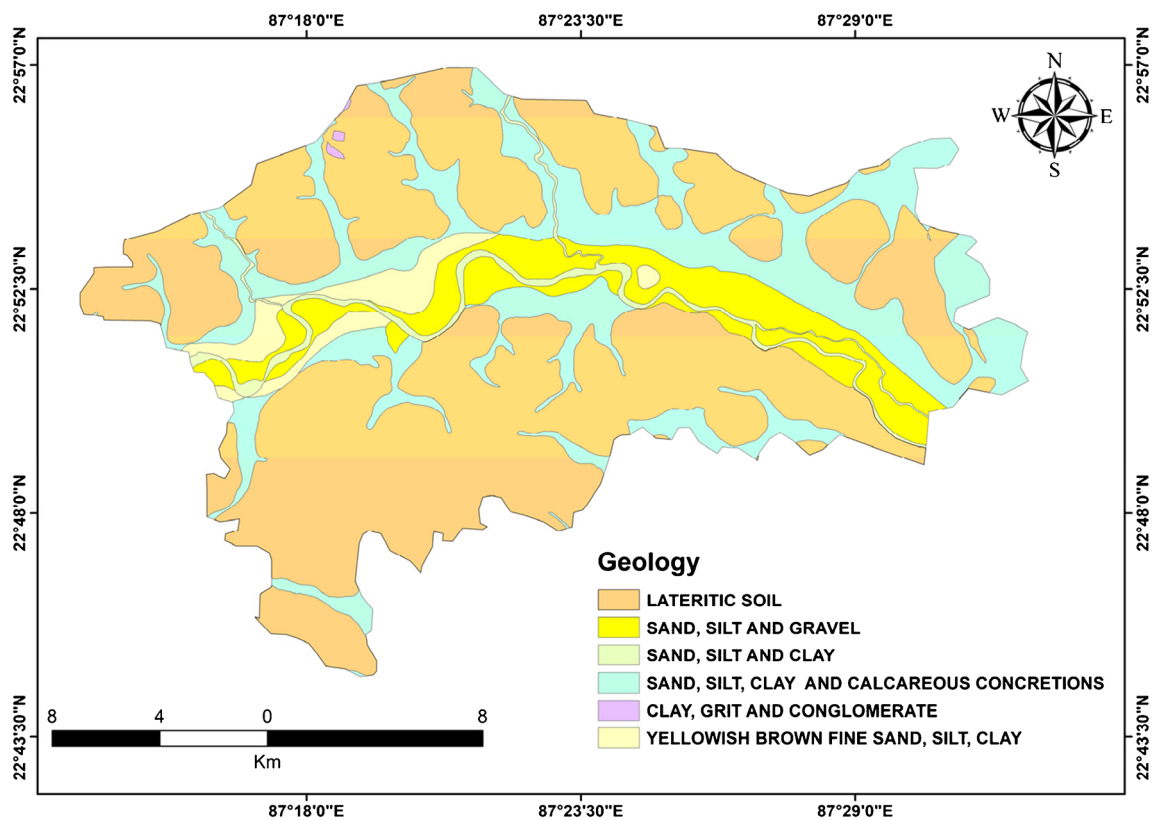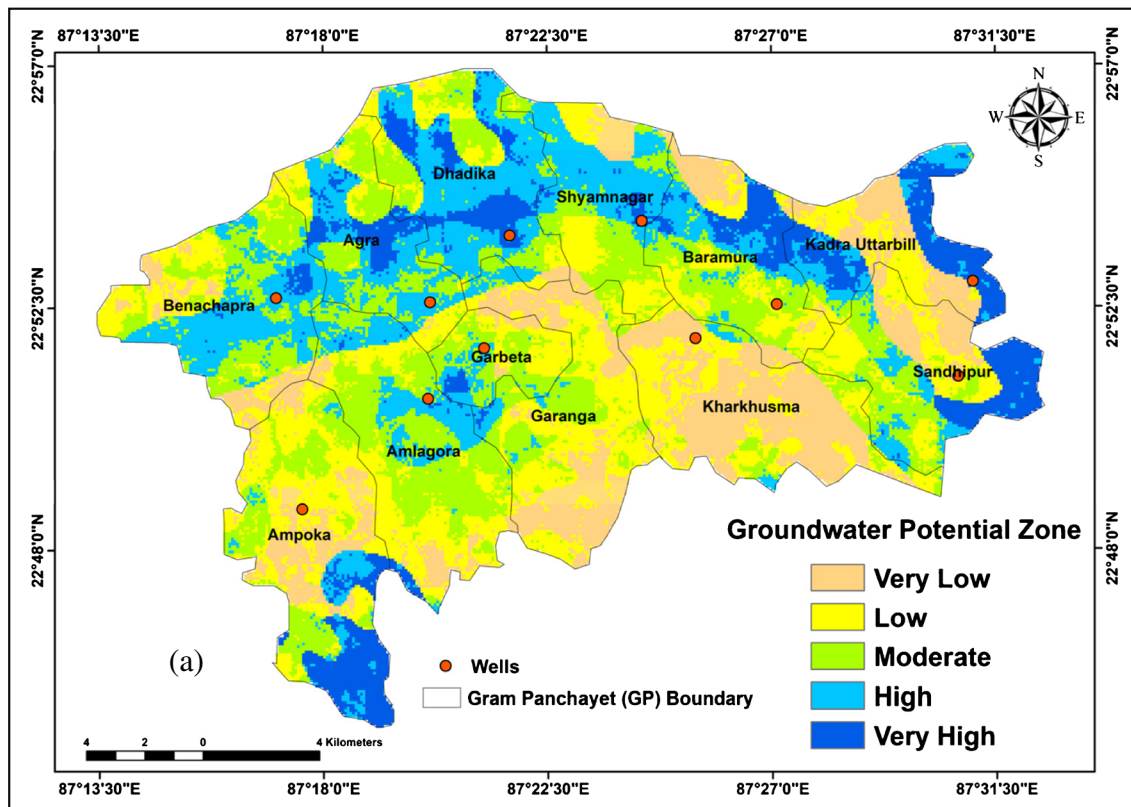
Fig. 15 Soil map of the study area

Fig. 16 Geological map of the study area

Fig. 17 **a** Groundwater potential index map of the study area. **b** Well survey in a village with TLC meter. **c** Condition of a well in Shyamnagar GP

and after rainfall events, the initiation of the recharge depends upon the land use and land cover type as well as on the surface morphometric and physical features. The MCDM technique of FAHP synthetic extent analysis method has been applied here to prepare the pairwise comparison matrix using triangular fuzzy scale, and the weight of each parameter has been calculated. The weightage of each of the parameter's sub-

categories has also been calculated following the similar technique (Table 3). Soil type ranked the first among all the calculated weights of the parameters (Table 2). Soil (0.186) is definitely the foremost parameter influencing groundwater recharge as it allows the flow and movement of water in layers both horizontally and vertically. Soil type is followed by the parameter lineament density with 0.144 weightage value,

slope (0.141) and geology (0.123); these four important parameters mostly determine the recharge pattern of a region effectively. Other parameters like groundwater fluctuation, drainage density and geomorphology ranked consecutively. All the thematic layers are reclassified in the ArcGIS software and through raster calculator the final map has been prepared. The groundwater index ranged between 0.86–.3.0 (Table 4). The map reveals that 25.99% of the area has moderate groundwater recharge found scattered over the region. Very high groundwater potential zone consists of 9.75% of the study area mainly found at the northern part where the vegetation is thick and is covered by loamy soil over old alluvium and valley fill deposits leading to good recharge of subsurface layers. The slope, relative relief and groundwater fluctuation are also low in this zone particularly in the north eastern part and can be a suitable site for groundwater harvesting. Very low potential zone covers 18.30% of the area mainly found at the south eastern part which is covered with dissected uplands with lateritic exposures (Shit et al. 2015). Low potential and high potential zone cover 26.42% and 19.55% of the area found scattered all over the study area. The socio-economic survey conducted by the authors also witnessed extensive degradation of the forest cover for the extension of agricultural activities over the region. As a result of which areas significant for groundwater recharge are reducing. Due to the climate change, the nature of precipitation has become erratic over the recent years (Ghosh 2019) leading to the drying up of most of the surface water bodies encouraging extensive abstraction of groundwater for domestic, irrigation and industrial purpose. This unscientific and uncontrolled abstraction is causing groundwater level decline. Global groundwater extraction is more than 650 km^3/year in India, the USA, China, Pakistan, Iran, Mexico and Saudi Arabia accounting 75% of the total groundwater abstraction at a global scale (Giordano 2009). Bhunia et al. (2012) demarcated groundwater potential zone of Paschim Medinapore district, West Bengal, India, and found no uniform spatial distribution in groundwater resources and water level ranges from 1.5 to 9.2 mbgl (meters below ground level). In this area, block wise studies have not been done earlier applying fuzzy logic that will help in strategic groundwater management in a sustainable way. Garbeta block I consisting of 12 g panchayets or village council (the

smallest administrative unit). The gram panchayet (GP) boundary has been overlaid on the zonation map (Fig. 17a). Groundwater potential zone wise area (km^2) of each gram panchayet has been analysed and given in a tabular format (Table 5). Gram panchayets namely Kadra Uttarbill, Amkopa and Dhadhika have the highest area under very high potential zone that is 9.707 km^2, 8.13 km^2 and 7.517 km^2 respectively. These areas have good prospect for groundwater recharge are mainly covered with forested land, low slopes, less built-up areas, low relative relief and where geomorphology mainly includes valley fill deposits and buried pediment shallow. Considerable area (22.55 km^2) under very low potential zone is found in Kharkushma GP where the normalized difference water index is showing low or negative values and having moderate slope and relative relief denoting poor or low groundwater recharge. Such studies will furnish valuable data related to the availability of groundwater resources over the region for sustainable management.

Validation of groundwater potential zone

Validation is one of the important methodologies in any scientific study. The efficiency of Fuzzy AHP technique has been validated using a groundwater level survey. Groundwater level of wells located within the block has been measured using Temperature Level Conductivity Meter (TLC) (Fig. 17b). The depth of the wells in this region ranges from 30 to 100 m. Water level and general water quality parameters like pH, TDS and temperature of the water have been checked. The pH of the water collected from the wells range

Table 4   Areal coverage of each groundwater potential zone

Potential index	Index value	Area in %
Very low potential	0.86–1.4	18.30
Low potential	1.5–1.8	26.42
Moderate potential	1.9–2.0	25.99
High potential	2.1–2.2	19.55
Very high potential	2.2–3.0	9.75

Table 5   Gram panchayet wise areal coverage of groundwater potential zone

Gram panchayet	Total area of the gram panchayet (GP) in km^2	Very low (area in km^2)	Low (area in km^2)	Moderate (area in km^2)	High (area in km^2)	Very high (area in km^2)
Shyamnagar	27.32	2.202	6.34	8.293	9.56	0.921
Kadra Uttarbill	27.063	7.236	4.998	0.756	4.366	9.707
Sandhipur	24.42	5.96	7.996	0.203	3.405	6.856
Kharkushma	39.89	22.55	11.26	5.3	0.256	0.522
Baramura	30.70	4.991	8.5	9.56	2.391	5.257
Garanga	41.64	13.277	16.402	9.201	2.556	0.207
Dhadhika	37.683	0.606	5.31	8.26	15.99	7.517
Agra	26.49	0.35	4.556	8.56	8.565	4.456
Garbeta	12.57	0.96	3.689	4.96	2.31	0.654
Benachapra	29.101	4.36	8.12	12.63	3.025	0.966
Amkopa	46.41	9.65	16.02	9.36	3.25	8.13
Amlagora	26.38	2.63	12.56	2.463	8.029	0.694

Table 6 Locational analysis of well based on groundwater potential zone and water level

Well location at gram panchayet	Groundwater level in mbgl	Groundwater potential zone
Well at Shyamnagar	2.0	Very high potential zone
Well at Kadra Uttarbill	6.5	Low potential zone
Well at Sandhipur	10.9	Low potential zone
Well at Kharkushma	11.17	Very low potential zone
Well at Baramura	3.9	Moderate potential zone
Well at Dhadhika	3.16	Very high potential zone
Well at Agra	3.5	High potential zone
Well at Garbeta	11.12	Moderate potential zone
Well at Benachapra	3.18	High potential zone
Well at Amkopa	11.78	Low potential zone
Well at Amlagora	4.1	Moderate potential zone

from 6.03–7.69 signifying the water quality is in its limit. The groundwater level of the well located at Amkopa GP is about 11.78 mbgl (meters below ground level). The well falls under the low potential zone as shown in Table 6. The well located at gram panchayets namely Dhadhika and Shyamnagar (Fig. 17c) showed a higher water level i.e. 3.16 mbgl and 2 mbgl respectively, and the wells are also located under the very high potential zone signifying greater recharge from surface water source. The depth of all the wells measured has been given in tabular format (Table 6).

Conclusion

Application of geospatial technology integrated with MCDM technique for the demarcation of groundwater potential zone is less time consuming. It is cost-effective and covers inaccessible areas within a short period of time. In the present study, Fuzzy AHP based on synthetic extent analysis method was coupled with the remote sensing and GIS has been used to calculate the groundwater potential zone index. The zonation mapping has revealed the degrading nature of the groundwater potential in some regions due to the increase in dry fallow land as observed from the land use and land cover map and extensive extraction of groundwater resources because of the drying nature of the surface water resources existed within the region. For the identification of recharge potential zone, eleven surface and subsurface parameters like land use and land cover, soil, geology, geomorphology, lineament density, drainage density, relative relief, distance from river, slope, groundwater level fluctuation and normalised difference water index (NDWI) have been used. These parameters play an important role in the initiation of recharge after every rainfall events. The weight of each of the parameters has been calculated applying MCDM technique and their thematic mapping has been done. The thematic maps are then reclassified and the final map has been prepared

using the ArcGIS software. The highest weight has been assigned to the soil type (0.186) which is regarded as one of the most influential factors inducing sub-surface recharge. The groundwater potential index ranged from 0.86–3.0 and is divided into five classes namely very low potential (18.30%), low potential (26.42%), moderate potential (25.99%), high potential (19.55%) and very high potential (9.75%). The northern section of the block is the most suitable area enriched with good groundwater resources and is mostly under the very high to high potential zone. The region is mainly covered by forest comprising valley fill deposits and buried pediment shallow, whereas the moderate, low and very low potential zone are concentrated at the southern section where lateritic exposure with dissected uplands, bare soil and degraded forest are common. Gram panchayets namely Kadra Uttarbill (9.707 km^2), Amkopa (8.13 km^2), and Dhadhika (7.517 km^2) is considered to have the highest area under very high potential zone. The obtained result has been validated using the groundwater level survey conducted in the month of monsoon. Well locations at gram panchayets like Garbeta (11.12 mbgl), Amkopa (11.78 mbgl) and Kharkushma (11.17 mbgl) fall under the moderate to very low potential zone showing groundwater level at greater depth. Wells situated at Dhadhika (3.16 mbgl) and Shyamnagar (2 mbgl) fall under very high potential zone showing shallow groundwater depth, but the water level of these wells further declines during the dry periods as observed from the socio-economic and field survey thus requires continuous monitoring. The results of the present study can be beneficial for the watershed planners and decision makers to undertake programmes related to groundwater resource assessment and sustainable management of the comprehensive water resources present within the study area. The applied approach is significant and provided compliant outcome which can be utilized in other regions effectively having similar hydrologic scenario with appropriate modifications.

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