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Appraisal of groundwater potentiality of multilayer alluvial aquifers of the Varuna river basin, India, using two concurrent methods of MCDM

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Abstract

An approach has been made in this study to delineate the groundwater potential zones of the Varuna river basin, Uttar Pradesh, India, using the analytical hierarchy process (AHP) and multi-influence factor (MIF) techniques. The present groundwater estimation exhibits an increase in the draft (10%) due to expansion in population, agricultural extent, and industrialization, which ultimately causes water table depletion. This backdrop justifies the need for this particular analysis in the multilayer aquifers of the central alluvial zone. The shallow aquifers are silty and unconfined, whereas the deeper aquifers are coarse, sandy-gravelly, and semi-confined. Basement faults and highs often control the thickness of aquifers in the subsurface. The study considered an integrated approach of AHP and MIF methods with remote sensing and GIS approaches. Various themes (land use/land cover (LULC), soil type, geology, elevation, slope, rainfall, normalized difference vegetation index (NDVI), drainage density, recharge rate, groundwater depth) determined by considering different conditioning factors and eventually employed for computation of groundwater potential index (GWPI) and classified for identifying the groundwater potential zones (GWPZ). Two methods applied to capture the results in a more tangible form as the AHP model works on building a pair-wise comparison matrix to relate conditioning factors to each other. Still, the MIF model considered interrelations among the conditioning factors. The GWPZ of the study area generates with overlay weighted sum method by integrating all thematic layers. The resulting groundwater potential index map is categorized into three groundwater potential zones, namely good, moderate, and poor. Ultimately, by constructing the receiver operating characteristic (ROC) curves for both the groundwater potential models, determine the efficiency of performances and the GWPZ map validated using yield data collected from wells scattered over the study area. The findings of the present paper have important implications for ensuring exploration and sustainability groundwater plans in that particular area.

Keywords Groundwater potential zones (GWPZ) · Groundwater management · Analytical hierarchy process (AHP) · Multi-influence factor (MIF) · Satellite imagery

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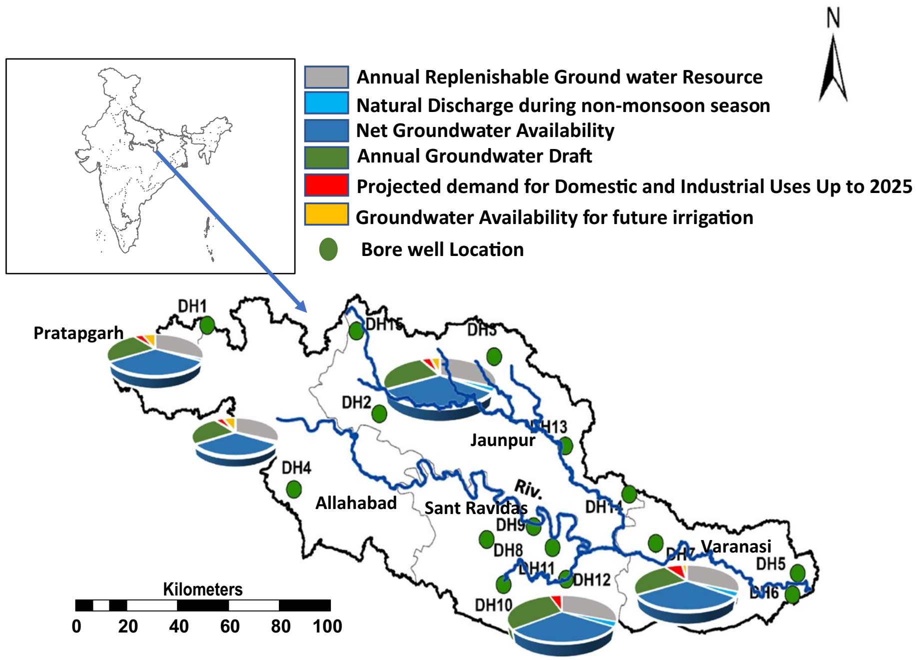


Fig. 1 Location map of Varuna river basin representing the groundwater scenario and location of bore wells used in the cross section (source: CGWB, 2019)

1 Introduction

The incompetent urbanization, along with rapid industrialization, is dragging society into a water-scarce environment owing to an inevitable rise in unplanned groundwater exploitation. Thus, to maintain the adequacy, the identification of groundwater potential zone has gained much attention in water resource management. This paper focused on the potentiality of groundwater of the Varuna river basin, situated in the central part of the Ganga river basin. Apparently, such an area entertains sufficient recharge and forms prolific aquifers. Even though the area suffered from water table depletion, a considerable 16% rise in population from 2001 to 2011 may be responsible for the hike in domestic water need simultaneously along with the intense agricultural need (Chaubey et al., 2020; Census, 2011; CGWB, 2019; Dey et al., 2020; Mall et al., 2006; Mall et al., 2019; Maurya et al., 2021).

Hence, unrestricted use of pumping wells associated with such activities eventually lowered the water table; however, the area has sufficient water reserving capacity. Accounting the area of interest, groundwater estimation was carried out using data available from the "Dynamic Ground Water Resources of India (2017)" report published by the Central Ground Water Board (CGWB) (CGWB, 2019). The approximation exposes the capacity of an annual replenishable groundwater resource of 1.21 bcm in the study area. Among which about 57.5% contribute through monsoon rainfall recharge, and other sources provide 18% of recharge. Net groundwater availability is 1.11 bcm, whereas the annual net groundwater draft is increased by 10% in this region

(Fig. 1). Hence, the allocation of groundwater potentiality is crucial for enhancement of continuous water replenishment in that region to track the recharge sites effortlessly.

Several conditioning factors control groundwater occurrences and movements. The interaction between the climate, geological, hydrological, physiographical, and hydrogeological characteristics influences the aquifer nature (Chaubey et al., 2019; Ebrahimi et al., 2016; Krishnamurthy & Srinivas, 1995; Patra et al., 2018; Pratap et al., 2020; Purnadurga et al., 2019; Srivastava et al., 2020; Taylor et al., 2013). The traditional way to explore the prolific aquifers is by drilling tests after geophysical and hydrogeological surveys, which is a time consuming and quite a costly method (Jha et al., 2010; Pandey et al., 2020; Patra et al., 2018; Paul et al., 2020; Sharma & Biswas, 2013). There are several convenient remote sensing (RS)—geographical information system (GIS)—Multi-criteria decision-making (MCDM) methods to find out the availability of groundwater resources in a particular region (Avtar et al., 2010; Gupta & Srivastava, 2010; Davoodi et al. 2015; Agarwal & Garg, 2016) rapidly and cost-effectively. RS and GIS can efficiently deal with spatiotemporal data. RS provides quick access to the information is about varied influencing factors of groundwater, whereas GIS offers the platform to handle the extensive dataset capably (Aluko & Igwe, 2017; Patra et al., 2018). These processes effectively applied by various researchers from all over the world to evaluate the GWPZ (Adiat et al., 2012; Arulbalaji et al., 2019; Das et al., 2018; Machiwal et al., 2011; Mall & Srivastava, 2012; Mohammadi-Behzad et al., 2017; Shekhar & Pandey, 2014; Thapa et al., 2017) with RS and GIS techniques. These studies involve some thematic layers which differ with each investigation, and the selection of the layers is random (Table 1). These quantitative methods have also been effectively applied in assessment of groundwater potential in different river basins in India (Table 2). Present study involves two efficient, simple, quantitative methods of multi-criteria decision-making methods (MCDM) combining with RS and GIS to delineate the potential recharge zones. The analytical hierarchy process (AHP) method is applied primarily, followed by multi-influencing factors (MIF) method to construct the analysis firmly. AHP is a powerful MCDM application used for countless multi-criteria problems in different scientific fields (Ghorbanzadeh et al., 2018; Pradeep et al., 2015; Razandi et al., 2015). The pair-wise comparison method employs to ranking/weighting the themes in the AHP and is a reliable technique for determining the relationship between different thematic layers (Mohammadi-Behzad et al., 2017). The MIF technique is another operative and straightforward approach because it considers the interrelationship between the conditioning factors and elementary to assign the ranking and weights for the input themes (Biswas et al., 2013; Magesh et al., 2012; Selvam et al., 2014; Shaban et al., 2006). These approaches are useful for reducing complex decisions and then synthesizing the results. The standard limitation and weakness in the methods are that many of the experts involved are not confident to express their opinions in pair-wise comparison matrices for multi-criteria problems due to lack of knowledge related to the nature of the influencing factor.

Moreover, even small changes in layer weightings and the methods employed can have a significant impact on the ranking order of the themes, and accordingly leading to inaccurate outcomes (Feizizadeh & Blaschke, 2014). To overcome this issue, several authors have proposed the use of sensitivity and uncertainty analyses (Feizizadeh & Blaschke, 2014; Ghorbanzadeh et al., 2018 Gogu et al., 2000; Pathak et al., 2008). Additionally, the models are a suitable technique for evaluating the consistency of the result after reducing the bias in the decision-making process. Considering the importance of groundwater evaluation of the area, the main objective of this work is to evaluate the groundwater potential zones in the Varuna river basin, Uttar Pradesh, India. This holistic approach develops the probable

Table 1 Literature review for themes used to delineate groundwater potential zones (GWPZ)

Studies	GL/LT	R1	DD	E	S1	R2	WT	S2	NDVI	LULC	L	GM	SW/DR	AT/WR
Jha et al. (2010)		√	√		√			√				√	√	
Machiwal et al. (2011)	√	√			√		√	√				√	√	
Magesh et al. (2012)	√		√		√	√		√		√	√			
Agarwal et al. (2013)	√		√		√	√	√	√		√	√	√		
Sekhar and Pandey (2014)	√		√		√	√		√			√	√		√
Razandi et al. (2015)*	√		√	√	√	√	√						√	√
Jothibasu and Anbazhagan (2016)*	√		√	√	√	√	√	√		√	√		√	
Mohammadi-Behzad et al. (2017)	√		√			√		√			√			
Nasir et al. (2018)	√			√		√		√		√	√			
Patra et al. (2018)	√	√	√	√	√	√	√	√	√	√		√		
Thapa et al. (2018)	√		√	√	√	√	√	√		√	√	√		
Nithya et al. (2019)	√		√		√	√		√		√	√	√		
Das (2019)	√		√		√	√	√	√		√	√	√		
Kumar et al. (2020)*	√		√		√			√		√	√	√		
Ghose et al. (2020)	√		√		√	√		√		√	√			
Bera et al. (2020)*	√		√		√	√		√		√	√	√		

*Razandi et al. (2015) also considered slope aspects and topographic witness index (Twi) as theme. Jothibasu and Anbazhagan (2016) considered some other indices like stream power index (Spi), topographic witness index (Twi), slope aspect (Sa), and total curvature as themes

Bera et al. (2020) considered curvature and topographic witness index (Twi) as a theme in their study

Where GL/LT is the geology/lithology, R1 is the recharge, DD is the drainage density, E is the elevation, S1 slope, R2 is the rainfall, WT is the water table, S2 is the soil, NDVI is normalized differentiated vegetation index, and LULC is land use/land cover, GM is geomorphology, L is lineament, SW/DR is surface water body/distance from the main river, AT/WR is aquifer thickness/weathered zone thickness

Table 2 Assessment of groundwater yield potential zones in different river basins in India

River basins	Authors	Methods	Year
Muvattupuzha river basin, Kerala	Kumar et al.	GIS techniques	2007
Ken-Betwa River basin, Madhya Pradesh	Avtar et al.	WLC method	2010
Pravara basin, Maharashtra	Das and Pardeshi	IF and FR techniques	2018
Vaigai upper basin, Tamil Nadu	Kaliraj et al.	Analytical hierarchy process (AHP)	2014
Indo-Gangetic Plain	Pathak	WLC method	2016
Loni and Morahi watersheds, Uttar Pradesh	Agarwal and Garg	AHP	2016
Devak and Rui watershed of Jammu and Kashmir	Jasrotia et al.	Weighted index overlay analysis	2016
Ganga Alluvial Plain covering Hooghly district	Patra et al.	RS–GIS and AHP method	2018
Soan Basin of the Outer Himalaya in Una District of Himachal Pradesh	Thakur et al.	RS and GIS method	2018
Dwarka River basin in Birbhum, West Bengal	Thapa et al.	Multi-Influencing Factor technique (MIF)	2018
Chittar basin, Tamil Nadu	Nithya et al.	AHP	2019
Tangon river basin of Barind older alluvial plain of Eastern India and Bangladesh	Pal et al.	Ensemble modeling assembling advance machine learning algorithm like random forest (RF), radial basis function (RBFnn) and artificial neural network (ANN)	2020
Karha river basin, Maharashtra	Bera et al.	AHP	2020
Yamuna subbasin (Panipat region)	Kaur et al.	AHP and catastrophe theory (CT)	2020

guide map for groundwater exploration, which will help to restore and vigilant extraction of groundwater. Eventually, the consequence of the procedure is expected to ensure the sustainability of the aquifer development in a particular area.

1.1 Site descriptions

Varuna river basin is located in the southeastern part of the central Ganga alluvial plain in between 25^{o}39^{o}28.71 N to 25^{o}19^{o}44.61 N latitude and 81^{o}45^{o}57.46E to 82^{o}03^{o}06.59E longitude and is covered 3675km^2 area. A large area of districts of Allahabad, Jaunpur, Sant Ravidas Nagar, Varanasi, and a little part of Pratapgarh encompass the study area. The area experiences semiarid to a sub-humid tropical climate, and generally, the southwest monsoon brings the rainy season here with average rainfall in between 760–1041 mm (study period from 1996 to 2015). There is a considerable variation between summer and winter temperatures. The maximum temperature ranges from approximately 22 °C to 48 °C, and the minimum is approximately 15 °C to 1 °C for the study period. The study area comprises of productive soils and gentle topography, which makes it suitable for agricultural production.

1.2 Regional hydrogeology

The study area is in the peripheral bulge region of the Ganga Plain. The foreland basin setting has a diversified geological architecture that determines the nature of the aquifers. Geomorphologically, the area characterized by the older alluvium (Bhangar) forming the upland terrace surface (T_2 surface), and the younger alluvium (Khadar) represented by the river valley terraces (T_1 surface) (Singh, 1996). Rivers of the area associated with their floodplains and forming the T_0surface are flowing incised in their narrow valleys. Older alluvium is present on the raised areas away from the active river channels, while the younger alluvium is present within the river valleys. Lithologically, the upland terrace surface is made up of silt, silty clay, fine sand, and extensive calcrete horizons. The calcrete units are local to regional in extent showing weak paedogenesis. On the surface, this terrace (older alluvium) has its drainage network having creeks, small channels, lakes, and ponds invoke an excellent terrain for groundwater recharge, whereas the river valley terrace (younger alluvium) comprises of silt, clayey silt, clay, fine to medium-grained sand, and local development of calcrete horizons. River valley terrace is also having a network of yazoo type channels through which the sediment is actively drained to nearby rivers (Singh, 1996). Both these surfaces consist of mainly Himalayan-derived gray-colored graywacke sediments with local beds of Craton-derived pink-colored arkosic sand (Shukla & Raju, 2008; Shukla et al. 2012). Recently, both the older alluvium and the younger alluvium are OSL (optically stimulated luminescence) dated representing Middle Pleistocene to Holocene ages (Shukla et al. 2012; Srivastava & Shukla, 2009). In the area, the Ganga River is the main drainage, and the Varuna River is a tributary meeting to it on the western bank near Rajghat. Both Ganga River and the Varuna River are flowing incised into their narrow valleys exposing 10–20 m high cliffs of the older and the younger alluvium along their banks. Currently, these rivers carry fine-grained sand deposited as sediment bars in the channels and silt and clay deposited on the narrow floodplains developed within the narrow river valleys (Singh et al. 2019).

To understand the subsurface geological architecture of the study area, a set of 15 borewell data of CGWB, spreading randomly over an area of 3675km^2, has been used to prepare the cross section using STRATER 5.0 software (Fig. 2).Such cross sections are capable of revealing the geometry of litho units and their mutual relationship in a given area. Borewell's information shows a very intricate pattern of sandy aquifers bounded by clayey aquiclude at the top and aquitard in the subsurface. The alluvial fill, as revealed by the borewell data in the study area, is 200 m to about 600 m thick (Fig. 2). The whole alluvial package is resting over basement rocks made of Vindhyan Group of rocks and Bundelkhand Granites of Precambrian age (Shukla et al., 2012). In each borewell, the top 20–60 m covered by silt, clay, and silty clay horizons. This horizon also contains a few meters thick silty fine-grained sand units that form shallow and unconfined aquifers and usually full fill the domestic needs. This top cover consists of the Older (Bhangar) and the Younger (Khader) alluviums, which are also seen in the cliff sections along the river banks on the surface (Shukla et al., 2012; Singh et al., 2019). This top horizon is mainly sandy, clayey silt, which permits efficient percolation of rainwater to recharge the sandy aquifers, which are present below 60–80 m level from the surface. These deeper aquifers embrace of alternating several tens of meters to hundreds of meters thick and a few km to hundreds of km wide sandy horizons of Himalayan-derived graywacke and Craton-derived arkosic fine to coarse-grained gravelly sands. Individual sand horizons show lateral thickness variation and are overlapped by clayey horizons, which are tens of meters thick and laterally terminating against sandy horizons for several hundred meters to kilometers (Fig. 2). The sand exhibits sufficient porosity and permeability to make profuse aquifers. Shukla and Raju (2008) interpreted this sand to mud couplets as the product of channel activity and the overlying floodplains in the Pleistocene times. Such an interbedding of sand and clay

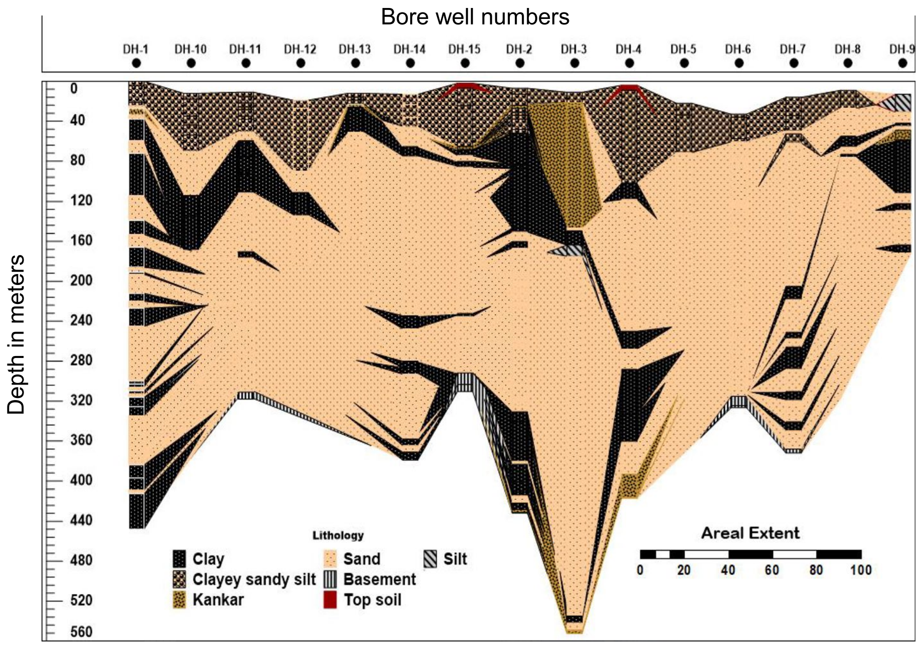


Fig. 2 Cross section showing the subsurface lithological variation in the study area (sand, which is partially confined by the clay horizons, is thickly developed, forming semi-confined aquifers. The top part in each well is fine-grained and silt rich forming a covering on deeper sandy aquifers and also containing a few m thick unconfined sandy-silt aquifers)

favors the development of semi-confined aquifers in the subsurface. These deeper aquifers are capable of serving the domestic as well as irrigational needs for a longer time. Occasionally, a few meters thick silt and calcrete horizons are also encountered in the subsurface profiles.

Moreover, the bore well data reveal another interesting fact regarding the subsurface geology and aquifer development. In borewellDH-3 (Kurni) located at Jaunpur, the alluvial thickness is ranging about 600 m (Fig. 2), which is not encountered in any other bore well penetrating up to the basement. In borewells, clayey horizons are lensoid, frequently terminating laterally and also deflecting up- or- downward. In the upper levels of this borewell, calcrete horizons are also reasonably thick (more than 80 m thick), tabular in geometry, and abruptly terminating against sandy-clayey units (Fig. 2). Increased thickness of alluvium and tabular to lensoidal geometries of litho units imply the location of the depo center and possible presence of a subsurface fault that has controlled the increased alluvial thickness and aquifer development. Because of subsidence along the fault, larger accommodation space is created, which was filled by thick sand deposing multi-storeyed aquifers semi-confined by clay horizons. This aquifer layers may be related to Bundelkhand Massif present in the basement and terminating near the borewell DH-3 (Fig. 2). Such fault-related rapid subsidence has also been recorded by Singh, (2003) in Meerut and Yamuna Puram areas (Bulandshahr) of the Western Ganga plain and related it to Delhi–Haridwar Ridge basement structures of the basin. Throughout the Quaternary, Ganga plain sedimentation, and hence the aquifer development, have been controlled by the tectonic features traversing the basement.

2 Materials and methods

2.1 Data processing

Different thematic maps, viz., geology, soil, elevation (digital elevation model), slope, drainage density, normalized difference vegetation index (NDVI), potential groundwater storage (recharge), rainfall, and annual groundwater table, land use/land cover were generated using satellite imagery and various conventional datasets (Table 3).SRTM(Shuttle Radar Topographic Mission) DEM at 90 m spatial resolution data collected from CGIAR-CSI GeoPortal (srtm.csi.cgiar.org), used to create Elevation (DEM), drainage density, and slope map. The geology and soil maps (hardcopy) were collected from the Geological Survey of India (GSI) and the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) at a scale of 1: 250 000and1:50,000. To prepare thematic layers of geology and soil map first scanned and then rectified the hard copy maps and digitized using ArcGIS 10.5. Rainfall data (grid data)for 20 years are collected from the India Meteorological Department. Land use/land cover data were retrieved from Resourcesat-1, (Bhuban) at a scale of 1:50,000 from 56 m resolution of the year 2011–12. The thematic map of LULC was prepared by digitization using ArcGIS 10.5. NDVI map for the study area was generated from the satellite data collected from Sentinel2A optical.

Groundwater observation well data from 1996 to 2015 were collected from India-Water Resource Information System (WRIS) (www.india-wris.nrsc.gov.in/). The annual average groundwater table maps were generated by the IDW interpolation method to produce groundwater table maps.

Table 3 Data sources of themes considered and assigned and normalized ranks for sub-themes of the individual themes

Themes (sources)	Sub-themes	Area		Suitability for ground-water potential zones	Assigned rank	Normalized ranks (N)through AHP	Ranking through MIF
		Km^2	%				
Geology	Clayey sand	3359.8	91.25	High	7	0.39	11
(District Resource map; GSI, 2017;1:50,000)	Gravel/sand, silt	5.33	0.14	Very high	9	0.50	16
	Sandy clay	310.4	8.43	Low	2	0.11	6
Recharge (m^3/year) (CGWB-WRIS, ISRO; 1996–2017)	35–49	280.6	7.68	Very low	2	0.07	1
	50–57	1405.8	38.46	Low	4	0.15	3
	58–64	1107.7	30.31	Medium	6	0.26	4
	65–72	683.1	18.69	High	7	0.22	6
	73–91	177.7	4.86	Very high	8	0.30	7
Drainage density (km/km^2) (SRTM-DEM; 90 m)	0- 697	1076.5	69.71	Low	2	0.10	3
	698–1041	1510.8	97.83	Medium	4	0.19	5
	1042–1508	922.9	59.76	High	7	0.33	7
	1509–3038	162.4	10.52	Very high	8	0.38	9
Elevation (m) (SRTM-DEM; 90 m)	62–84	694.5	18.90	Very low	7	0.37	11
	85–90	1544.3	42.02	Low	6	0.32	8
	91–96	947.6	25.78	Medium	4	0.21	5
	97–120	489.1	13.31	High	2	0.11	2
Slope (Degree) (SRTM-DEM; 90 m)	0–2	2803.7	76.28	Low	7	0.47	13
	3–5	835.2	22.72	Medium	5	0.33	9
	6–28	36.5	0.99	High	3	0.20	5
Rainfall (mm) (IMD; 1996–2015)	760–811	996.9	27.12	Low	6	0.20	2
	812–870	1661.8	45.21	Medium	7	0.23	5
	870–953	524.4	14.27	High	8	0.27	8
	953–1041	492.7	13.40	Very high	9	0.30	11
Water table (amsl)	65–77	784.8	21.35	Very low	3	0.11	1

Table 3 (continued)

Themes (sources)	Sub-themes	Area		Suitability for groundwater potential zones	Assigned rank	Normalized ranks (N)through AHP	Ranking through MIF
		Km^2	%				
(CGWB-WRIS, ISRO; 1996–2016)	78–83	1291.5	35.14	Low	4	0.14	3
	84–87	793.1	21.58	Medium	6	0.21	4
	88–92	637.4	17.34	High	6	0.21	6
	93–98	168.9	4.60	Very high	9	0.32	7
Soil (NBSS-LUP, ICAR + ISRO; 1: 50,000)	Loam	685.9	18.66	High	8	0.27	7
	Silt loam	85.5	2.33	Low	6	0.20	1
	Clay loam	676.8	18.41	Medium	7	0.23	4
	Sandy loam	2227.3	60.60	Very high	9	0.30	10
NDVI (Sentinel-2A optical; February 2018)	−0.13–0.25	357.1	9.71	Very low	1	0.07	1
	0.26–0.37	609.5	16.58	Low	2	0.12	2
	0.38–0.49	662.2	18.02	Medium	3	0.18	3
	0.50–0.59	860.8	23.42	High	4	0.24	4
	0.60–0.75	1185.9	32.26	Very high	5	0.29	5
LULC (Resourcesat-1, (Bhuban); 1:50,000/56 m/2011–12)	Built-up	70.21	1.76	Low	2	0.08	3
	Salt-Affected	232.98	5.83	Low	2	0.08	5
	Scrubland	69.66	1.74	Low	5	0.20	7
	Agricultural land	3532.74	88.45	Very high	7	0.28	9
	Water Bodies	88.40	2.21	Very high	9	0.36	11

Estimation of annual groundwater storage (Recharge) was based on the water level fluctuation and specific yield approach (Bhattacharjee, 1982; Patra et al., 2018):

$$\Delta S = \Delta h \times A \times sy \tag{1}$$

where = ΔS change in groundwater storage/recharge, Δh = change in the water table (the difference between the highest and the lowest level) during a given period, and s_y = specific yield. The area (A) in Eq. (1) is the area of influence of the respective monitoring wells in the study area. Finally, the annual groundwater recharge map was created in the GIS platform with the help of the individual temporal availability of groundwater storage.

2.2 MCDM methods to assign the groundwater potentiality

Traditional MCDM techniques mainly follow three stages. First, the identification and construction of spatial database followed by the preparation and processing of thematic maps by using these datasets and finally evaluation of output map and its categorization, interpretation, and validation after analysis of the relationship between groundwater conditioning factor (Fig. 3).

2.2.1 Analytical hierarchy process (AHP) method

Analytical hierarchy process model combines the analysis of multi-class maps (Gumma & Pavelic, 2013), which firstly had introduced by Saaty (1980).The process involves the quantification of relative priorities for a set of significant themes based on the intuitive

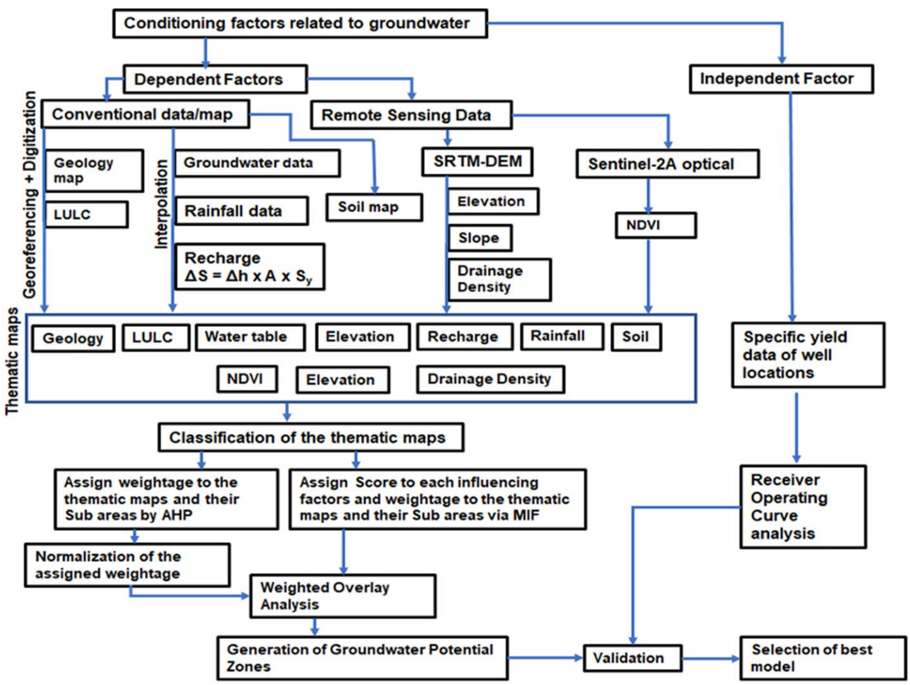


Fig. 3 Schematic flowchart showing the methodology for delineation of groundwater potential zones

judgment of the decision-makers and stresses on the consistency of the comparison of themes in the decision-making process (Saaty, 1980).The specialty of this approach is that it organizes discernible and indiscernible themes in an organized way and provides a well-structured, simple solution to the decision-making problems (Skibniewski et al., 1992). Moreover, it is an exciting approach that logically diagnoses a problem, starts with the large to descending in gradual steps, and eventually, one can connect, through paired comparison judgments, the small to the large (Al-Harbi, 2001).

2.2.1.1 Assignment of normalized weight and consistency judgment Different themes and sub-themes were structured hierarchically, and the relative weightings were generated indirectly through comparison judgments by using the relative scale measurement of Saaty's 1–9 scale (Table 4). Sub-themes are classified under individual themes to consider the best possible variations of the study area and ranks assigned through relative weighting accordingly. Weight assignment to different themes and sub-themes were decided based on field experiences and review of existing literature. The judgment matrix (A)was constructed by comparing the thematic maps with each other in a pair-wise comparison matrix and finally assigned the normalized weight (W) for the considered themes. The pair-wise comparisons are made in terms of which element dominates the other. Normalized ranks (N) are considered for sub-themes. The calculation for normalization is as follows (Patra et al. 2018).

$$\mathrm{P} = \frac{a_n}{\sum (a_1 + a_2 + a_3 \ldots \ldots . + a_n)} \tag{2}$$

where P is normalized weight (W)/normalized ranks (N); a_1, a_2, a_3…… a_n is assigned weight/rank of 1st to nth individual themes and sub-themes consistency ratio (CR) is the measuring key to check the consistency of original preference ratings after assigning the relative weights. Consistency ratio is represented by (Ghorbanzadeh et al. 2018)

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI} \tag{3}$$

where RI is the random consistency index, which has a meaningful relationship with the number of comparing themes as shown in Table 4 (Alonso & Lamata, 2006; Saaty, 1980)., and CI is the consistency index, which is denoted by

$$\mathrm{CI} = \frac{\lambda \mathrm{max} - n}{n - 1} \tag{4}$$

where $\lambda_{\mathrm{max}}$is the largest eigenvalue of the judgment matrix and represented by

$$\lambda \mathrm{max} = \sum\nolimits_{m=1}^{n} \frac{(\mathrm{AV})_m}{n\mathrm{V}_m} \tag{5}$$

where A is the judgment matrix; V is the weight vector (column-wise); and m is the number of groundwater conditioning factors, in practice, the judgment matrix is acceptable only when CR ≤ 0.1 (Saaty, 1980).

2.2.1.2 Delineation of the groundwater potential zones (GWPZ) by defining groundwater potential index (GWPI) Normalized weights and normalized ranks were used to evaluate the groundwater potential index (GWPI) (Eq. 6), which is a dimensionless quantity (Patra et al. 2018; Razandi et al. 2015). The groundwater potential zones (GWPZ) were finally prepared by using the GWPI. The thematic maps were reclassified and rasterized. All the

Table 4 Saaty's 1–9 scale of relative importance (Saaty, 1980) and random consistency index (RI) for different values of *n*

Scale/n	1	2	3	4	5	6	7	8	9	10
Saaty's scale of importance	Equal	Equal–moderate	Moderate	Moderate–strong	Strong	Strong–very Strong	Very strong	Very strong–extreme	Extreme	–
RI	0	0	0.58	0.89	1.12	1.24	1.32	1.41	1.45	1.49

processed maps were integrated using the raster calculator tool in ArcGIS to generate the GWPI. The GWPI was calculated through weighted linear combination (WLC) technique (Razandi et al. 2015; Shekhar & Pandey, 2014)

$$GWPI = GL_W GL_N + R1_W R1_N + DD_W DD_N + E_W E_N + S1_W S1_N + R2_W R2_N + WT_W WT_N + S2_W S2_N + N_W N_N + L_W L_N \quad (6)$$

where GL is the geology, R1 is the recharge, and DD is the drainage density, E is the elevation, S1 slope, R2 is the rainfall, WT is the water table, S2 is the soil, N is the NDVI (normalized differentiated vegetation index). L is the land use/land cover, while W and N are the normalized weight of the theme and normalized rank of the individual themes. Based on the natural break classification method, GWPI was categorized into three classes—"Low," "Moderate," and "High," in which each class contained the same number of features (Nampak et al., 2014; Thilagavathi et al., 2015).

2.2.2 Multi-influencing factor method

The method considers the interrelationship among different conditioning factors (themes) and assigns weights accordingly (Magesh et al., 2012; Thapa et al., 2018).

2.2.2.1 Determination relative weighs and ranks of themes through MIF The themes which have a significant influence on groundwater potentiality were considered under major effect (P), and those with minor impact were grouped under minor effect (Q). P and Q had assigned a score of 1.0 and 0.5, respectively (Nasir et al., 2018), and the themes with no effect had allocated 0 (Fig. 4). Interrelationship among themes is required so that one theme should be related to at least one minor/major effect to be assigned a score and be processed in weighted

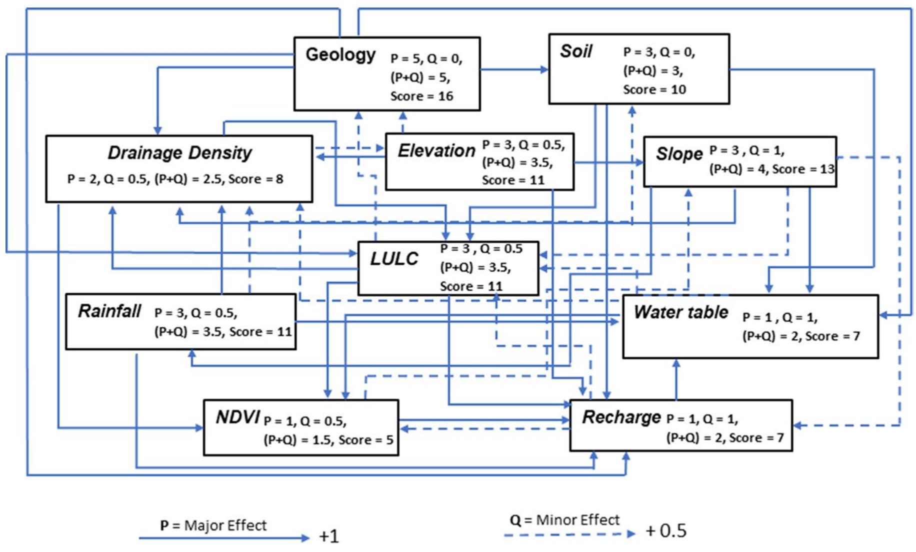


Fig. 4 The interrelationship between influencing themes with their major-minor effects (P and Q) and proposed ranks (P + Q) and scores of each factor

overlay analysis (Thapa et al., 2018). The proposed relative weights were then calculated by adding both major and minor effects (P + Q) to define the cumulative effect.

The proposed score, which is the final weight for each influencing theme, was calculated by the following formula (Eq. 6) (Magesh et al., 2012; Nasir et al., 2018):

$$\text{Proposed Score(Pi)} = \frac{P + Q}{\sum P + Q} 100 \tag{7}$$

The weightage (W_i) of sub-themes of each theme was assigned, and the rank classification was done by dividing the final weight (P_i) by the number of sub-themes (n) under each influencing theme. The sub-theme having more significant influence got the same score as $P_{i,}$ and the first next sub-theme was assigned the rank using Eq. 8 (Das et al. 2018).

$$\text{Wi} = \text{Pi} - (\text{Pi}/n) \tag{8}$$

The rank for the second next sub-theme was calculated by subtracting the (P_i/n) from the first next sub-theme, and the same procedure was followed to rank the rest of the sub-themes.

Lastly, the GWPZ was generated by calculating GWPI (Eq. 9) using the weightage for each P_i and W_i of themes and sub-themes.

$$GWPI = \sum_{i=1}^{n} \text{Pi}XWi \tag{9}$$

where i = 1, 2, 3, 4……n, were the number of thematic layers and subclasses.

2.3 Validation

Sensitivity analysis attends to uncertainties associated with the model inputs as well as output (Crosetto et al., 2000). It quantifies the weights and ranking values assigned to the individual themes accurately to achieve an acceptable precision in the model output. It can be carried out by removing one or more thematic maps through map removal sensitivity and estimating the impact of particular themes through single parameter sensitivity. The test that identifies the sensitivity of the groundwater potentiality zone map by removing one or more-thematic maps was employing Eq. (10) (Pathak et al., 2009)

$$S_i = \left| \frac{V_i}{N} - \frac{V_{x_i}}{n} \right| \tag{10}$$

where S_i is the sensitivity (for ith unique location) associated with the removal of one thematic map (of theme X), V_i is GWPI computed using Eq. (6) on the ith location, V_{Xi}, GWPI of the ith location excluding one thematic map layer (X), N is the total number of thematic map layers used to compute GWPI, and n is the number of thematic map layers excluding one map. Variation index (Var_i) represents the magnitude of the variation and estimates using Eq. (11)(Napolitano & Fabbri, 1996)

$$Var_i = \frac{\text{V}_\text{i} - \text{V}_{\text{x}_\text{i}}}{\text{V}_\text{i}} * 100 \tag{11}$$

where V_i is GWPI computed using Eq. (6) on the ith location, and V_{xi} represents the potential index of the ith location, excluding one parameter.

Effective weight (W_{xi}) reflects the actual or real weight of each theme and is calculated using Eq. 12 (Gogu et al., 2000).

$$W_{x_i} = \frac{X_{w_i} X_{r_i}}{V_i} * 100 \tag{12}$$

where X_{wi} and X_{ri}in Eq. (12) are the theoretical weights and assigned rankings of the X theme over the ith location.

3 Result and discussion

GWPZ developed considering various groundwater conditioning factors, which affect the productivity of the aquifers. Different thematic maps (Fig. 5) were categorized under the following factors (Table. 3).

3.1 Categorization of topographic factors

3.1.1 Elevation

The variation in elevation regulates the surface runoff and infiltration of a particular area. The higher elevation facilitates higher runoff and lower infiltration, whereas lower elevation is associated with lower runoff and higher infiltration (Rajaveni et al., 2017). The maximum area comes under the low elevation category, which may be due to the lesser resistance of alluvial materials that enables good reservoir recharge (Patra et al., 2018). The Eastern parts show relatively lower elevation and gradually increase toward the west. The western part of the Varuna river basin lies on the Interfluve (Doab) surface, which is the upland terrace surface (T_2 surface) having higher elevation (Prakash et al., 2016; Shukla et al., 2013).

3.1.2 Slope

The gradient of the slope is directly proportional to the surface runoff and inversely proportional to infiltration (Naghibiet al., 2016; Thapa et al., 2018). The lower slope retains precipitated water, and it allows sufficient time for infiltration to the saturated zone. A higher slope aids more surface runoff but restricts the intensity of infiltration. The maximum area came under the lower slope category with coverage of 2803.7 km^2 (76.3%), 835.2 km^2 (22.7%) area was under the medium category, and only 0.99% area shows the high slope.

3.1.3 Land use/land cover

The changes in land due to various anthropogenic activities are an important parameter that controls the infiltration of the soil from precipitation. Agricultural land, vegetation, and wetland restrict the surface runoff and enhance the percolation. Scrublands, built-up and salt-affected areas, etc., have the insufficient water-holding capacity as the paved and impervious surfaces permit an insignificant amount to groundwater. In the

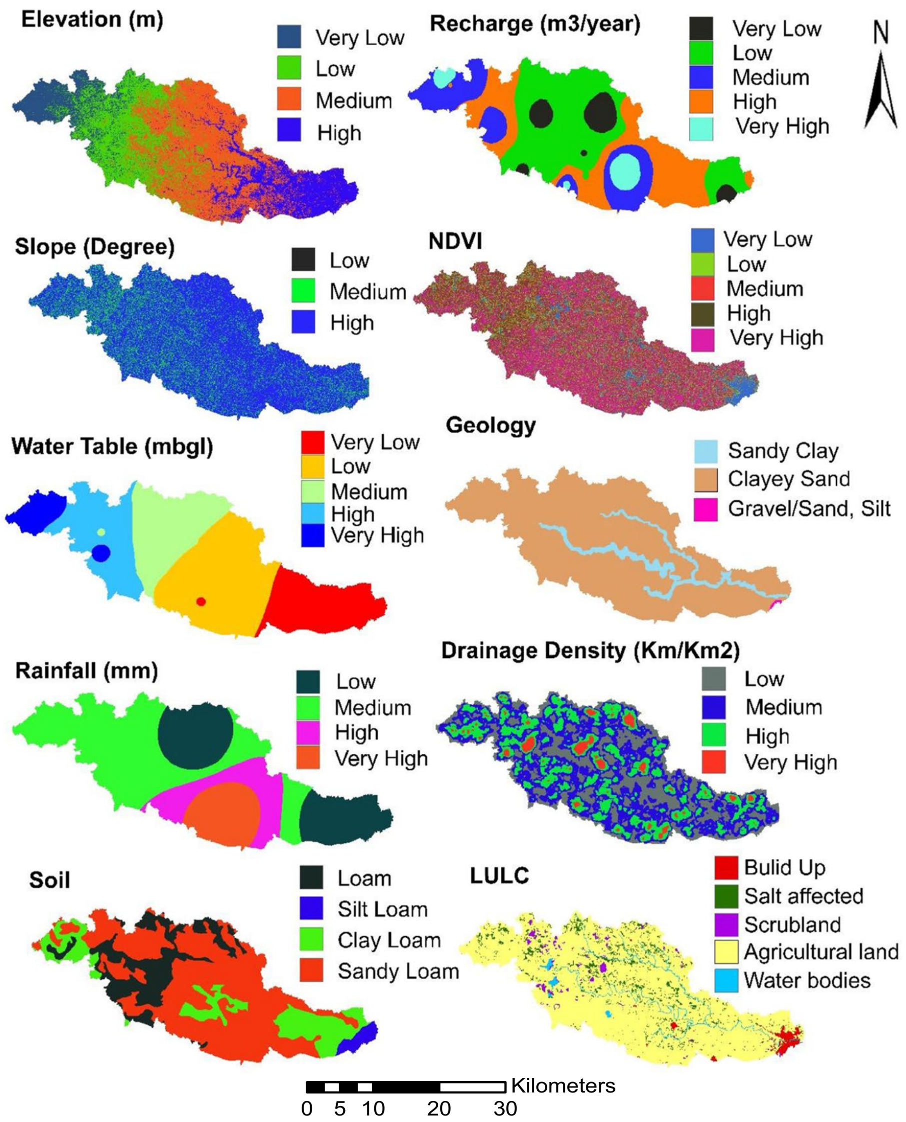


Fig. 5 Different thematic maps of the study area considered for the analysis

Varuna river basin, 88.45% area is covered by the agriculture land and 2.21% area by water bodies, which have excellent groundwater prospects. Approximately 232.98 km^2 (5.83%) area comes under salt-affected, 69.66 km^2(1.74%) under scrubland, and 70.21 km^2(1.76%) under built-up which has low groundwater potentiality.

3.2 Categorization of geological factors

3.2.1 Soil

Soil characteristics have an enormous impact on the infiltration and permeability of groundwater. The properties like porosity, texture, adhesion, and consistency control the recharge potentiality of the area (Thapa et al., 2018). Soils are the weathered and eroded parts of the underlying geology. The study area comprises of loam soil, which is the mixture of sand, silt, and clay (Shukla et al., 2012; Singh et al., 2019). The soils, e.g., sandy loam, silt loam, and clay loam, categorize depending on the degree of the proportion of sand, clay, and silt. The soils of the basin include sandy loam (60.6%), loam (18.66%), clay loam (18.417%), and silt loam (2.33%). Sandy loam occupied the maximum area of 2227.2 km^2 with enough drainage capacity, but cannot hold significant water and is considered as "very good" category. Loam spreads over 685.9 km^2 in the western part. Generally, loam soil contains more moisture and nutrients, has better infiltration capability, and brings it into the "good" category. Clay loam accounting 676.8km^2 is situated maximum over the eastern part, whereas a little bit portions encompass the central and western part. Clay resists permeability and allows low storage, which increases the surface runoff. Hence, it is categorized under "moderate" class. Only 85.4km^2 area in the easternmost part consists of silt loam soil. The presence of silt makes the soil less permeable and comes under the "poor" category.

3.2.2 Geology

Newer and older alluvium covers most of the entire basin (Shukla, 2013; Shukla et al., 2012). In the study area, three types of geological accumulations have been observed, namely (a) clayey sand (91.3%) (older alluvium), (b) sandy clay (8.43%) (newer alluvium), and (c) gravel/sand, silt (0.14%). The maximum area is covered by clayey sand, which has good conductivity brings into high potentiality. This sandy area also known as the upland terrace surface (T^2) is present on the overbank regions of the rivers (Shukla et al. 2012).

3.3 Categorization of climate-related factor

3.3.1 Rainfall

Rainfall dominantly influences the recharge of groundwater. The spatial and temporal variations of rainfall primarily navigate to the groundwater storage system and are one of the essential members of input in the water budget. Low rainfall causes less recharge and vice versa. The spatial distribution of the average annual rainfall map was generated by inverse distance weighting (IDW) interpolation method from 1996 to 2015 time period. The study area is divided into three categories: (a) low (760–811 mm) is received by 996.9 km^2 (27.1%) area, which is mainly located within Jaunpur and Varanasi district, (b) medium (812–870 mm) rainfall received by a top part of the study area and covers an area of 1661.8 km^2 (45.2%) and (c) high (870–953 mm) rainfall category covers an area of 524.3 km^2 (14.2%).

3.4 Categorization of water-related factors

3.4.1 Drainage density

An area with high drainage density enhances the surface runoff more than infiltration. It is the permeability preview of any region. Low drainage density attributes to good infiltration/permeability and favors better groundwater potential zones. The maximum study area came under the medium category.

3.4.2 Normalized difference vegetation index (*NDVI)*

NDVI assists in the identification of healthy vegetation and can utilize to assess water availability indirectly (Patra et al., 2018). The higher values depict high vegetation cover where the NDVI value ranges between 0.6 and +1 (Pradhan, 2013) due to the sufficient water availability. The lower values (0 to –1) represent the low to sparse vegetation and lack of water resources (Pradhan, 2013). The study area was categorized under a highly vegetated area (32.3%). The easternmost part of the basin near Varanasi district shows a lack of vegetation, followed by Sant Ravidas Nagar, Jaunpur, and Allahabad.

3.5 Categorization of hydrogeology factors

3.5.1 Water table

The groundwater level is essential for the demarcation of potential zones because of its dynamic nature, which helps in the increment of the groundwater storage (Patra et al., 2018). Decadal variation of the water table from 2007 to 2017 varied from 65 to 98 m from the mean sea level. The western part of the basin comprises of high to the very-high water table as compared to the eastern region. It is since the east part of the basin area occupied by the river channels is relatively low-lying as compared to the western part (Singh et al., 2019).

3.5.2 Recharge

Groundwater recharge is crucial to maintain the sustainability of groundwater as the extracted volume from an aquifer needs to be recovered by the recharged volume for the long term. The area with ample recharge reflects good potentiality with a high infiltration rate and vice versa (Patra et al., 2018). The maximum part of the study area (western part and central part) came under low (38.46%) and medium (30.3%) recharge zones. The Eastern part of the site is characterized under medium to very low category though it is nearer to the confluence zone of the Varuna and Ganga River. The area is underlain by silt, clay with subordinate sand, which restricts the infiltration, whereas, in the western part, the presence of sand with meager clay supports the infiltration (Shukla et al., 2012; Singh et al., 2019). The overpopulated Varanasi and Sant Ravidas Nagar suffer from recharge deficiency, mainly endured by overexploitation.

3.6 Application of AHP and MIF models

The pair-wise comparison matrix (Table 5) specified that soil, geology, recharge, and rainfall had taken the highest weights. The consistency ratio reflects a satisfactory level of consistency in the pair-wise matrix. The normalized rank of each theme of the conditioning factors is tabulated in Table 3. The final resultant map (Fig. 6) obtained by the AHP model showed 45% area comes under the moderate category, 37% under the high category, and 18% under the low category.

In the MIF model, ten different influencing themes are unified by considering the influence of each theme (Selvam et al. 2014; Thapa et al. 2018). Accordingly, the proposed ranks and scores of each influencing theme revealed that geology, slope, elevation, rainfall, and LULC obtained the highest weight (Fig. 4). The final output of the groundwater potential map (Fig. 6) showed a moderate potentiality region for 1544.2 km^2(43%), approximately 1465.5 km^2 (40%) area under high potential, and 595.9 km^2(17%) of the study area comes under the low potential category.

In the western part of the study area, Yamuna river basin forms a part of Indo-Gangetic plains covered by older and younger alluvial deposits of Quaternary to Recent age, consisting of clay and sand. Maximum part encompasses moderate potential zone (Kaur et al., 2020). Basically, poor prospect of groundwater in that region is attributed to geological as well as anthropogenic issues. MIF technique which was applied to delineate the potential of the Dwarka River basin, situated in the eastern part of the study area, showed the efficiency of the applied technique and maximum part fall under moderate groundwater prospect zone. Both the models representing the maximum area of Varuna river basin also comprise under moderate groundwater potentiality followed by high and low potentiality. West to the south-western part of the region represents high to moderate potentiality, and north to the eastern part of the region characterizes with moderate to low and low potentiality zones. The high potential zone of the study area mainly comprises alluvium deposition, which is under loam, clay loam, and sandy loam soil (Shukla et al., 2012). However, the area attains relatively high elevation and slope at the west. Southern parts favor the groundwater storage supported by the combinations of very high, high to moderate rainfall, recharge. In addition, a limited drainage system provides more space for infiltration facilitates high groundwater potentiality. Moderate

Table 5 Pair-wise comparison matrix for the AHP process

Themes	Themes										Normalized weight (W)
	GL	R1	DD	E	S1	R2	WT	S2	N	L	
Geology (GL)	8/8	8/7	8/5	8/4	8/5	8/7	8/6	8/9	8/4	8/5	0.13
Recharge (R1)	7/8	7/7	7/5	7/4	7/5	7/7	7/6	7/9	7/4	7/5	0.12
Drainage Density (DD)	5/8	5/7	5/5	5/4	5/5	5/7	5/6	5/9	5/4	5/5	0.08
Elevation(E)	4/8	4/7	4/5	4/4	4/5	4/7	4/6	4/9	4/4	4/5	0.07
Slope (S1)	5/8	5/7	5/5	5/4	5/5	5/7	5/6	5/9	5/4	5/5	0.08
Rainfall (R2)	7/8	7/7	7/5	7/4	7/5	7/7	7/6	7/9	7/4	7/5	0.12
Water table (WT)	6/8	6/7	6/5	6/4	6/5	6/7	6/6	6/9	6/4	6/5	0.10
Soil(S2)	9/8	9/7	9/5	9/4	9/5	9/7	9/6	9/9	9/4	9/5	0.15
NDVI(N)	4/8	4/7	4/5	4/4	4/5	4/7	4/6	4/9	4/4	4/5	0.07
LULC (L)	5/8	5/7	5/5	5/4	5/5	5/7	5/6	5/9	5/4	5/5	0.08

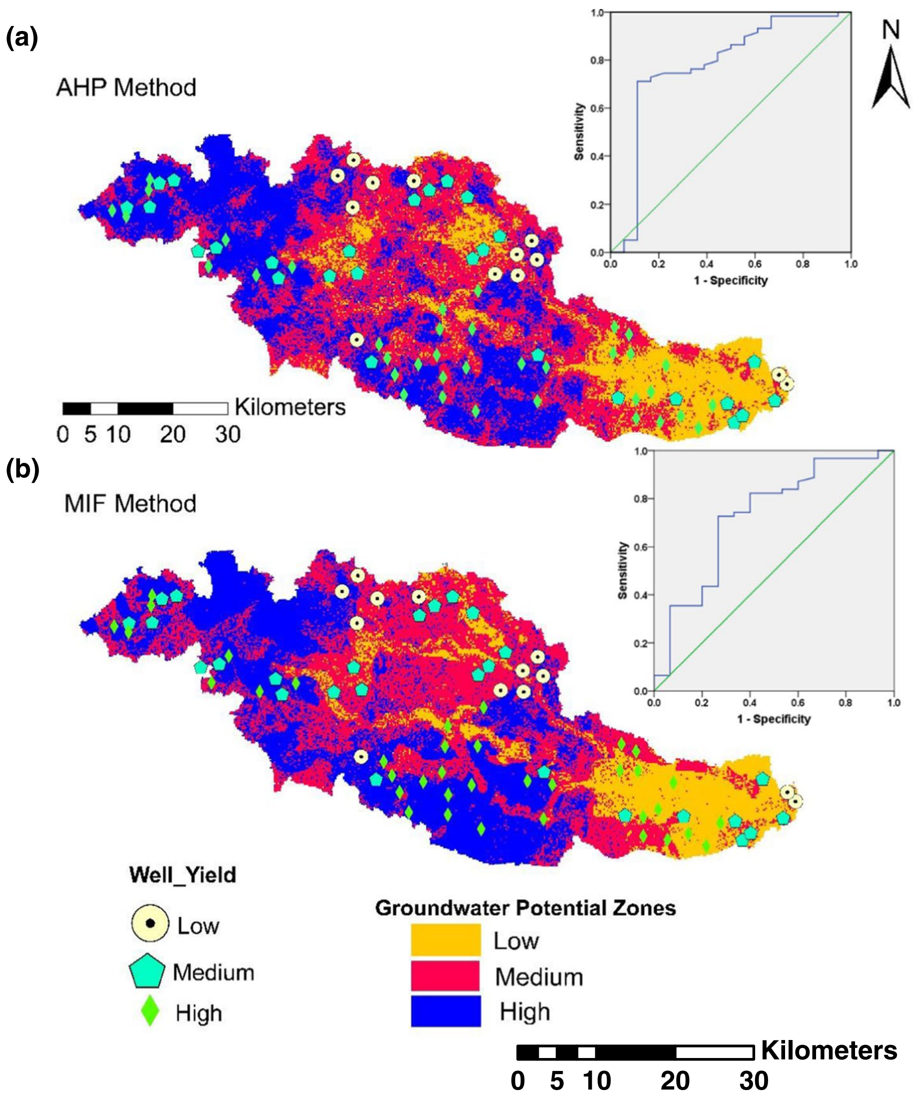


Fig. 6 Groundwater potential zones through **a** AHP method **b** MIF method with well discharge points and ROC curve for the groundwater potential maps

groundwater potentiality mainly concentrated at the central part of the region and dispersed randomly throughout the area. The region belongs to sandy loam soil having the characteristics of holding very high potentiality and recharging capacity. Still the presence of high to very high drainage density as well as the salt-affected area restricts the infiltration (Singh et al., 2019). The extreme eastern part of the region, situated nearly at the confluence zone of the Varuna and Ganga, accomplishes minimum elevation and slope, which should enhance the infiltration by increasing the residing time but represents low groundwater potentiality mainly because of high clay content in soil (Prakash et al., 2016). The area facilitates low rainfall, low to very low vegetation index, moderate to very low recharge along with the maximum build-up region and soil types, mainly restricted to the clay loam to silt loam, and has medium to low suitability in terms of groundwater potential zones.

3.7 Validation through sensitivity analysis

The consistency of analytical results and model performances may achieve by sensitivity analysis. The statistics of the sensitivity analysis (Table 6) confirms the significant variation in the groundwater potential zones by removing the single parameter at a time in map removal sensitivity analysis. According to the variation index, the maximum deviation recorded after the removal of geology in both the models, attributed by the presence of unconsolidated sediments in older alluvium deposits of Middle-Upper Pleistocene to Holocene age (Srivastava & Shukla, 2009). These are the primary regulators for infiltration of groundwater, but finally, areal geology controls the aquifer nature. Hence, high theoretical weight was observed in the soil in both the models,' but maximum variation occurs in the removal of geology. All the parameters considered here have shown a remarkable variation after removal. Therefore, the result showed that all ten parameters are significant for this study, and no parameter could be removed. As the variation index directly depends upon the weighting system, effective weights have been calculated (Table 6). The effective weight is a function of the value of the single parameter concerning the other nine parameters, along with the weight assigned to it by the prediction model (Keita & Zhonghua, 2017; Rahman, 2008). The effective weight of the geology (14.26% in AHP and25.79% in MIF) and slope (12.22% in AHP and 17.14% in MIF) shows a significant increase in the theoretical weight assigned in the original model (13.33% and 16% for geology and 8.33% and 13% for slope in AHP and MIF model, respectively). This pattern was may be due to the availability of groundwater at shallow depth and the low slope. These two parameters have a significant role in groundwater potentiality measures. Light increase in the effective weight of drainage density, slope, recharge, and soil has been noticed against the theoretical value in the AHP model. Still, except geology and slope, all the parameters have lower effective weight in the MIF model.

Validation of the predicted groundwater map was carried out through considering the yield of the existing observation wells collected from the regional Central Ground Water Board. Yield is one the most critical indicators of the potentiality of an aquifer. Total 77 yield data were clustered by grouping analysis in the ArcGIS environment into low (32.76 m^3/h–103.32 m^3/h), moderate (106.2 m^3/h–149.82 m^3/h), and high (156 m^3/h–198.6 m^3/h). The descriptive statistics of yield data are shown in Table 7. Hence, yield data were superimposed on predicted groundwater potential map to observe the coherence beBetween actual and predicted potentiality.

The model performance and quantitative validation of the groundwater potential map were evaluated by calculating the AUC through ROC analysis (Pradhan, 2013; Pourtaghi & Pourghasemi, 2014; Razandi, 2015). Both the models showed better performance according to AUC, which represented 78% in the AHP model and 73% in the MIF model (Fig. 6).

3.8 The sustainable development plan for groundwater management over the Varuna river basin

Ambiguous use of groundwater in the study area dragged into unsustainable depletion of groundwater, which became an extensive societal problem. A comprehensive challenge

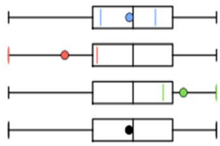
Table 6 Statistics of sensitivity analysis by removing one theme

Themes	Theoretical weight (%)		Effective weight (%)								Variation index (%)							
			Min		Max		Mean		SD		Min		Max		Mean		SD	
	AHP	MIF	AHP	MIF	AHP	MIF	AHP	MIF	AHP	MIF	AHP	MIF	AHP	MIF	AHP	MIF	AHP	MIF
Geology	13.33	16	11.64	20.42	17.39	37.53	14.26	25.79	1.23	3.60	14.48	25.07	39.57	49.61	25.63	36.80	4.49	5.21
Recharge	11.67	7	7.65	3.41	11.43	6.27	9.37	4.31	0.81	0.60	0.27	0.97	18.34	8.96	8.73	4.39	4.15	2.08
Drainage Density	8.33	8	6.99	5.22	10.43	9.59	8.55	6.59	0.74	0.92	-7.34	-9.80	14.49	15.45	5.43	5.72	4.74	5.60
Elevation	6.67	11	5.66	8.29	8.45	15.25	6.92	10.48	0.60	1.46	-2.48	3.26	14.49	17.19	5.84	8.69	3.28	3.96
Slope	8.33	13	9.98	13.57	14.90	24.95	12.22	17.14	1.06	2.40	-4.03	7.74	18.25	20.07	6.77	10.80	3.87	2.96
Rainfall	11.67	11	9.98	8.65	14.90	15.91	12.22	10.93	1.06	1.53	0.77	3.13	21.73	18.88	10.95	8.02	4.00	4.23
Water table	10.00	7	6.65	3.41	9.94	6.27	8.15	4.31	0.71	0.60	4.09	-9.19	9.76	17.15	7.22	4.89	1.68	4.72
Soil	15.00	10	13.31	6.28	19.87	11.54	16.29	7.93	1.41	1.11	3.49	1.29	25.34	16.89	15.70	9.83	4.55	5.15
NDVI	6.67	5	4.32	1.74	6.46	3.20	5.30	2.20	0.46	0.31	-7.25	0.64	13.31	5.33	5.34	2.54	3.88	1.05
LULC	8.33	11	5.66	8.93	8.45	16.42	6.92	11.28	0.60	1.58	-7.78	-3.89	14.31	14.40	2.90	8.25	4.23	2.38

Table 7 Descriptive statistics for three clusters of the yield of the wells

YIELD_M3_: R2 = 0.85

Group	Mean	Std. Dev.	Min	Max	Share
1	129.1622	13.2644	106.2000	149.8200	0.2630
2	77.5774	21.5674	32.7600	103.3200	0.4255
3	172.1733	11.6703	156.0000	198.6000	0.2569
Total	128.8356	41.1317	32.7600	198.6000	1.0000



emerges in this respect to generate positive groundwater management to assure the availability of freshwater resources regularly. An attempt has been targeted to suggest some sustainable planning by comparing groundwater potentiality with the stage of development recorded as per CGWB (CGWB 2019) across the blocks within the river basin (Table 8). Depending on the physical and socioeconomic characteristics of each block, mitigation plans were made. Careful implementation of water tariff, surface water conservations, and awareness programs related to water preservation can prevent the accelerating rate of depletion. Primary agriculture depends on rice cultivation in the area, which is a water-intensive crop. Therefore, executing alternative cropping patterns of low water consuming crops and proper scientific planning for irrigation may be sufficient for long-term sustainability. Immediate attention is required to diminish the volume of extraction for household usage to reduce the load over the aquifer. Awareness of domestic water-saving practices is also necessary.

4 Conclusion

The subsurface aquifer development is related to fluvial style, dimension, sand to mud ratio, and channel migration pattern throughout the Quaternary period in the Ganga plain. Hence, the thickness of alluvium and the basement architecture comprising faults and ridges dissecting the basin into blocks having differential subsidence, control the aquifer development.

The study applied widely accepted models, AHP and MIF, within RS–GIS environment for the delineation of groundwater potential zones over the Varuna river basin. The final output derived from the models was categorized into three classes—"Low," "Moderate," and "High" groundwater potential area. Both the models represent the maximum extent of the study area comprises under moderate (45% and 43% in AHP and MIF, respectively) groundwater potentiality. That followed by high (37% and 40% in AHP and MIF, respectively) and then low (18% and 17% in AHP and MIF, respectively) potentiality. The favorable geology and soil texture promote high potentiality. Still, the anthropogenic interventions restrict the maximum potentiality under moderate potential zones justified by the stage of development recorded in the CGWB report. The ROC plots showed that the accuracy of the possible maps produced by the AHP and MIF models was 78% and 73%, respectively. The performance study reveals that AHP and MIF showed better efficiency in predicting the potentiality.

The integration of potential mapping and the reported situation of the present stage of development generate the basis of groundwater sustainability planning. According to the stage of development, 31% block comes under overexploited, and 15% comes under the critical zone. This present exhaustive situation can be manageable through the participatory

Table 8 Blockwise sustainable groundwater management plan to maintain groundwater favorable condition

	Groundwater development stage and category as per CGWB		Groundwater favorability condition as per predicted potentiality (%)			Sustainable groundwater planning
	Stage of ground water development (in %)	Category (safe/semi-critical/critical/over exploited)	Low	Moderate	High	
GAURA	101.5	Overexploited	0.05	17.96	82.00	Highly favorable condition prevails in the parts of blocks present within the basin, but the overall draft of the block reaches to over-exploitation. Surface irrigation through canal, rivers, and ponds needs to reserve the groundwater resources to protect overexploitation. Surface water conservation techniques significantly need to apply to minimize the stress on the aquifer. Awareness in domestic water-saving practices is necessary
BAHRIA	123.44	Overexploited	0.09	22.31	77.60	
MAUAIMA	127.9	Overexploited	NA	17.59	82.41	
DHANUPUR	125.99	Overexploited	1.75	51.09	47.16	Moderately favorable condition prevails here so to combat the over-draft situation improvement of irrigation practices and changes in traditional cropping pattern is necessary
ARAJILINE	120.89	Overexploited	74.69	24.99	0.32	The block categorized under the overexploited zone and unfavorable groundwater conditions, which imitates the present level of groundwater extraction, are at an alarming stage. Immediate attention is required to reduce the volume of groundwater extraction through water conservation practices and alternative cropping patterns
HARHUA	113.05	Overexploited	85.34	14.44	0.22	
RAMNAGAR	93.66	Semi-critical	5.61	49.93	44.46	Favorable potential condition prevails for groundwater development. To minimize the stress of aquifers, surface water conservation, and improved irrigation practices should be required
RAMPUR	87.35	Semi-critical	11.48	61.99	26.53	
SURIYAWAN	87.74	Semi-critical	16.33	55.56	28.11	
AURAI	89.52	Semi-critical	0.17	31.44	68.39	
BARSATHI	88.87	Semi-critical	30.84	61.86	7.30	Low to moderate groundwater condition zone prevails over the part of the blocks. An additional increase in groundwater extraction should be restricted. Initiation of the awareness programs should be promoted within the people to protect groundwater conditions
MARIAHU	85.87	Semi-critical	23.10	61.01	15.88	
BARAGAON	86.1	Semi-critical	58.23	40.43	1.33	

Table 8 (continued)

	Groundwater development stage and category as per CGWB		Groundwater favorability condition as per predicted potentiality (%)			Sustainable groundwater planning
	Stage of ground water development (in %)	Category (safe/semi-critical/critical/over exploited)	Low	Moderate	High	
CHIRAI GAON	87.15	Semi-critical	83.61	16.39		The present groundwater condition reflects an alarming stage. Proper scientific planning to reduce the volume of groundwater extraction through water conversation practices and alternative cropping pattern may sustain the future groundwater reservoirs
PRATAPPUR	91.07	Critical	14.76	57.93	27.31	Moderately favorable condition prevails here so to combat the over-draft situation improvement of irrigation practices and changes in traditional cropping pattern is necessary
BHADOHI	90.15	Critical	6.80	40.60	52.60	Present status of this urbanized block covered by high and moderate groundwater favorable conditions. However, the groundwater draft reaches critical condition. Therefore, implementation of water recycling facilities, water tariffs, domestic and industrial water-saving practices is mandatory
GYANPUR	93.13	Critical	1.11	38.83	60.06	
PINDRA	95.05	Critical	66.34	33.38	0.28	Considering the present situation, immediate action should be taken to reduce groundwater extraction. Implementation of water conservation practices, alternative cropping pattern is required
PHULPUR	60.84	Safe	0.05	23.24	76.71	The part of the block falls under the high potential zone category. Conscious and judicious water use practice needs to implement to maintain the necessity of future needs
SORAON	64.94	Safe		28.11	71.89	
SAIDABAD	72.86	Safe	1.51	47.92	50.57	Moderate to high favorable conditions need to sustain for its agricultural support, a proper groundwater management practice should implement to maintain the present state
MOGRA BADSHAHPUR	45.31	Safe	10.84	53.93	35.24	
SUJANGANJ	69.44	Safe	7.28	62.20	30.52	
MACHHALISHAHR	59.15	Safe	10.12	68.02	21.86	

Table 8 (continued)

	Groundwater development stage and category as per CGWB		Groundwater favorability condition as per predicted potentiality (%)			Sustainable groundwater planning
	Stage of ground water development (in %)	Category (safe/semi-critical/critical/over exploited)	Low	Moderate	High	
SEVAPURI	82.5	Safe	56.93	40.96	2.11	Mostly urbanized block, covered by the low and moderately favorable groundwater condition. Domestic and industrial water-saving practices, Progressive water tariffs, Water recycling facilities, etc., need to be implemented to sustain water management
KASHI VIDYA PEETH	76.45	Safe	84.59	15.12	0.29	

planning process and a comprehensive assessment of the study area for the judicious use and extraction of the resources. Policymakers can then take their decisions accordingly for maintaining the quality and quantity and subsequently reducing the risk factors and adverse impacts.

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Data availability Data are available on request.

Code availability ArcGIS 10.5, STRATER 5.0, and SPSS 22.0 software application.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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