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ORIGINAL ARTICLE

Assessment of groundwater vulnerability to over-exploitation using MCDA, AHP, fuzzy logic and novel ensemble models: a case study of Goghat-I and II blocks of West Bengal, India

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Abstract

The vulnerability of groundwater to over-exploitation has been assessed in Goghat-I and II blocks of West Bengal using a number of different methods, i.e., MCDA, AHP, fuzzy logic and ensemble method in a GIS environment. Annual groundwater recharge has been measured through the water level fluctuation method, whereas groundwater abstraction data have been obtained from field investigations. The results of the assessment indicate that much of the study area is highly vulnerable to groundwater level decline due to excessive groundwater use. Result of all the methods reveals that very low and low vulnerable zones are present in north-eastern and southern parts in small extent. Extensive areas in the entire western, north-western and south-eastern parts represent high and very high vulnerable zones. Results of all the methods have been validated using the ROC curve, which produce AUC values of more than 0.8 for all the models. It shows that the applied methods produce reliable results. The methodologies developed in this study could be used to assess groundwater vulnerability to over-exploitation in other water-stressed regions.

Keywords Groundwater · Vulnerability · Goghat · ROC

Introduction

Groundwater is the main source of freshwater resources in many regions of the earth. It is a dynamic as well as a common property resource (Shiferaw et al. 2008). It is also a hidden resource, which can be easily extracted and used for various purposes (Das et al. 2018). However, its dependable supply, relatively less polluted nature and low cost of development have led to over-exploitation in many parts of the world (Menon 2007). The demand for groundwater is continuously increasing in India due to population and economic growth, but the availability of groundwater is decreasing at the same time (Black and Talbot 2005; Holden 2014).

In India, rapid growth in groundwater irrigation has been continuing since the green revolution period of 1970 (Shah et al. 2003; Ahmed et al. 2014). The accessibility of groundwater since that time has been greatly increased through the increased availability of low capacity pumps and power subsidies in the agricultural sector (Moench 1995; Kumar 2005; Charalambous and Garratt 2009). Consequently, the area under groundwater irrigation has more than trebled during the time period of 1970–2002 (Reddy 2006). This exponential growth in groundwater irrigation in India has helped to sustain the ever-increasing population through rising food production (Rosegrant et al. 2009). However, the unregulated use of groundwater has created negative impacts on the quality and quantity of groundwater (Dutta 2018) and has led to groundwater depletion in some parts of the region.

The rate of groundwater depletion has been so rapid in the last few decades that the shallow aquifers have been dried up completely in many regions (Brown et al. 2006). It is extremely difficult to restore water levels in depleted aquifers (Menon 2007). Additionally, the accurate estimation

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of groundwater recharge and abstraction rates is difficult in areas where groundwater use is poorly regulated due to lack of reliable information. As a consequence of these issues, stakeholders in many regions with depleted aquifers have been forced to take remedial measures including the use of artificial recharge and restrictions on groundwater use. However, these measures have had limited success in many parts of India (Suhag 2016), mostly due to the lack of real involvement in the management of the resource by local people, and a lack of consideration of the social and political consequences of groundwater mismanagement (Kumar 2005).

These issues have led to increasing interest in identifying the key factors that influence the vulnerability of groundwater resources to anthropogenic factors. The term "vulnerability" refers to a state of change where there is a risk or possibility of any harmful effect on a society (Pal et al. 2019). Historically, groundwater vulnerability was generally used to denote the possibility of groundwater contamination from various pollutants. However, more recently, the vulnerability of groundwater to over-exploitation has also become a significant issue (Ong'or and Long-cang 2007; Witkowski 2016), particularly in water-stressed regions like Goghat.

West Bengal, is a state where groundwater was historically abundant in nature, but is now subject to water scarcity in dry seasons. Uncontrolled agricultural growth has resulted in several groundwater management areas changed from being "safe blocks" to "semi-critical" or "critical blocks" on the basis of groundwater development (Central Ground Water Board 2014). Goghat-I and II blocks in Hugli district in West Bengal have been classified as semi-critical and critical blocks by the central groundwater board (Central Ground Water Board 2017). Severe water scarcity has been observed in this region, which is negatively affecting the society.

The objective of this study is to assess the vulnerability of groundwater resources and to show the vulnerable zones for a water-stressed region like Goghat-I and II blocks.

Characteristics of the study area

Goghat-I and II blocks (22° 46′ 21″ N–23° 01′ 31″ N and 87° 30′ 22″–87° 47′ 27″ E) are situated in the western part of Hugli district of West Bengal, India (Fig. 1). Goghat-I is consists of 7 *gram panchayats* (administrative units comprising a group of villages) with a total area of 186.34 km^2. Goghat-II contains 9 *gram panchayats* that cover an area of 190.05 km^2 (Census of India 2011). The Dwarkeswar river in the eastern part of the area separates these two blocks from the rest of the district.

Goghat-I and II blocks are immediately underlain by a sequence of alluvial sediments known as the older

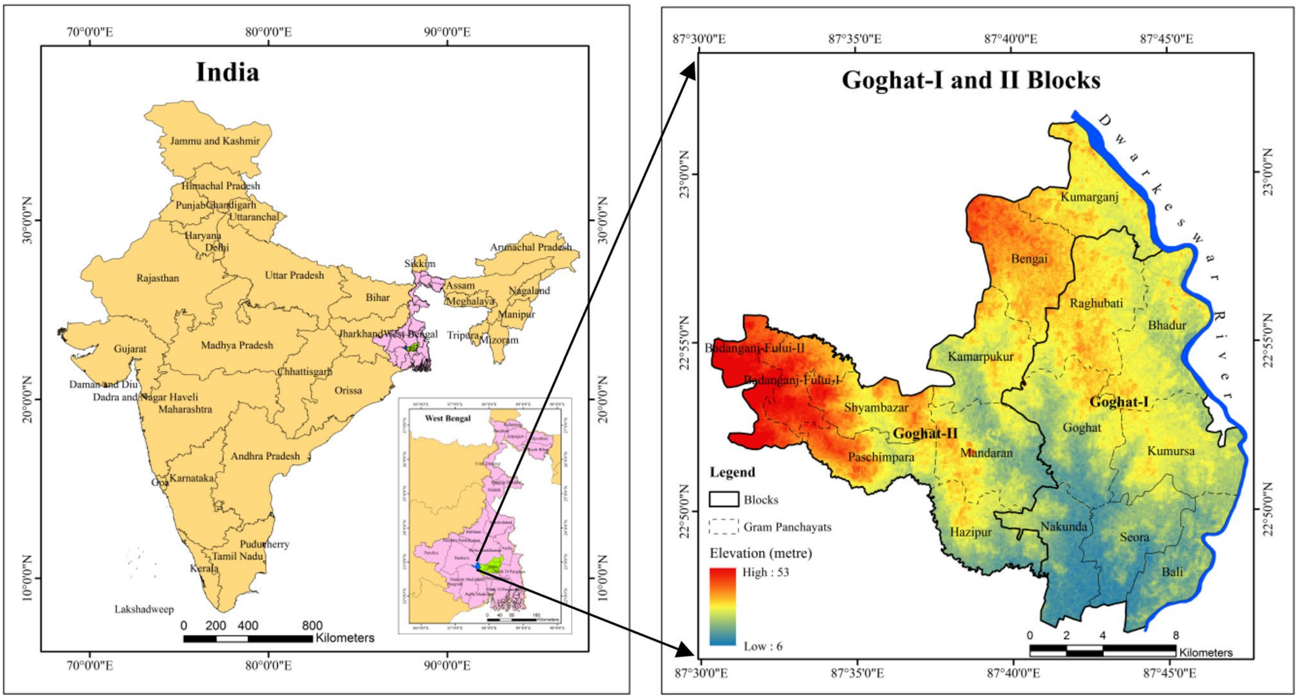

Fig. 1 Location of the study area

alluvium. These consist of sand, silt and silty clay (Geological Survey of India 2006). The region has a tropical monsoon climate (Aw in the Köppen–Geiger classification system), characterised by a cool, dry winter and a warm, humid summer. The mean annual rainfall is about 1500 mm, most of which falls during the period of June–September each year. The economy of this region is primarily dependent upon agriculture. Most of the area is under cultivated land, which has resulted in high cropping intensity.

Materials and methods

The vulnerability of the groundwater resource to over-exploitation has been assessed using a multi-parametric evaluation method that has been performed in a GIS environment (Fig. 2). Thematic layers that have been used in the assessment are groundwater recharge, geology, ground elevation, the groundwater level in the pre-monsoon season, soil texture, and land use land cover (LULC). The geological information has been obtained from a geological map published by the Geological Survey of India. The soil texture map was compiled using information from the National Bureau of Soil Survey and Land Use Planning, Government of India. The LULC map was supplied by the Department of Science & Technology, Government of West Bengal. The ground elevation data for the study area was obtained from a Digital Elevation Model (DEM) that was developed using data from the Shuttle Radar Topography Mission. Groundwater level data for the pre- and post-monsoon seasons were obtained from the Central Ground Water Board, Government of India.

Multi-Criteria Decision Analysis (MCDA), Analytical Hierarchy Process (AHP), Fuzzy-logic and ensemble methods have been applied to find out the groundwater vulnerable zones to over-exploitation. MCDA helps in the decision making process for complex spatial problems with reasonable accuracy (Malczewski and Rinner 2015; Das et al. 2019a), and it is well suited for managing complex decision problems. Weights for each factor in the vulnerability analysis have been assigned through local knowledge and field experience. AHP provides pair-wise comparison matrix, through which the criterions are structured according to their hierarchical order (Chakrabortty et al. 2018). Assigned priorities are given in 1–9 scale in each pair-wise comparison, from which a vector of weights is obtained. The pair-wise comparisons are arranged into a matrix: $C = [C_{kp}]_{n\times n}$. where C_{kp}. is the priority of the pair-wise comparison for the k-th and p-th criteria. A vector of criterion weights, $w = \left[w_1, w_2, \dots, w_n\right]$. is obtained from the pair-wise comparison matrix. The weights are attained from the equation, $C_w = \lambda_{\max} w$., where $\lambda_{\max}$. is the largest eigenvalue of C. (Saaty 1980). The consistency ratio is a significant character of AHP. Consistency ratio of less than 0.10 for a pair-wise comparison matrix signifies that there is

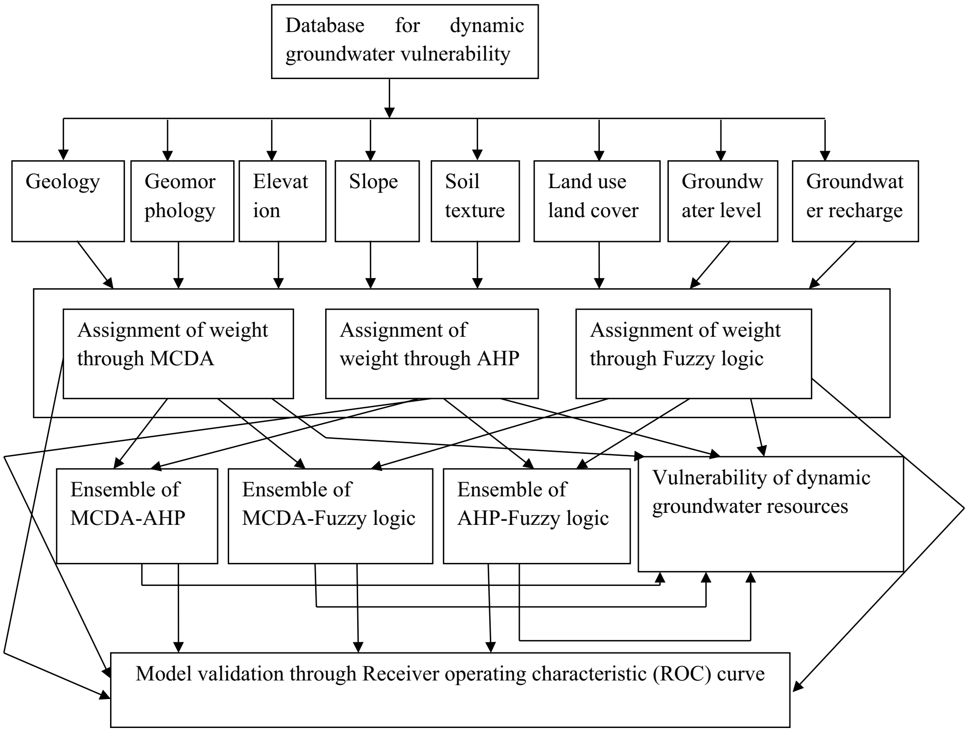

Fig. 2 Methodological framework

reasonable consistency in assigned priorities (Saaty 1980). A random consistency index has been derived from a sample of randomly generated reciprocal matrices (Saaty 1980).

$$\text{Consistency ratio} = \text{Consistency Index}/\text{Random Consistency Index},$$

$$\text{Consistency Index} = (\lambda_{\max} - n)/n - 1.$$

Fuzzy logic is a modification of AHP, where fuzzy ratios are employed in place of exact ratios in a pair-wise comparison for more accurate analysis (Van Laarhoven and Pedrycz 1983). Fuzzy weights are calculated from the fuzzy matrix through the geometric mean method.

$$\tilde{A}^k = \begin{bmatrix} \tilde{d}^k_{11} & \tilde{d}^k_{12} \ldots \tilde{d}^k_{1n} \\ \tilde{d}^k_{21} & \ldots \ldots \tilde{d}^k_{1n} \end{bmatrix}$$

The pair-wise comparison matrix of fuzzy logic is a reciprocal matrix, where $\tilde{d}^k_{ij}$. indicates the kth decision maker's preference of ith criterion over jth criterion, via fuzzy triangular numbers. "Tilde" represents the triangular number demonstration (Ayhan 2013). Fuzzy AHP represents relative importance of each pair of factors in same hierarchy (Das et al. 2019b). Fuzzy numbers can deal with an expert opinion that a ratio d_{ij} is about 1–3 instead of exactly 1/3 (Buckley 1985). When comparing two alternatives, it is sometimes difficult to assign exact ratios (Chang 1996). The calculation of weights using the fuzzy AHP method is also easy and simple. This is done via pair-wise comparison, which allows the fuzzy evaluation matrix to be obtained. The average values are then obtained through the geometric mean method of normalization and then the weights are obtained through the equation $C_w = \lambda_{\max} w$. (Van Laarhoven and Pedrycz 1983).

The ensemble method is applied to eliminate errors associated with the assessment of individual methods. It has several advantages, as it considers the results of other various methods. The ensemble method is derived in the geospatial environment by averaging the respective methods. Dynamic groundwater vulnerability index (DGVI) has been calculated in the GIS platform through the weighted overlay analysis technique (Malczewski 1999; Şener et al. 2018).

$$\begin{aligned} \text{DGVI} = \big[& (\text{Ge}_{\text{w}} \times \text{Ge}_{\text{wi}}) + (\text{Gm}_{\text{w}} \times \text{Gm}_{\text{wi}}) + (\text{El}_{\text{w}} \times \text{El}_{\text{wi}}) \\ & + (\text{Sl}_{\text{w}} \times \text{Sl}_{\text{wi}}) + (\text{St}_{\text{w}} \times \text{St}_{\text{wi}}) + (\text{Lu}_{\text{w}} \times \text{Lu}_{\text{wi}}) \\ & + (\text{Gl}_{\text{w}} \times \text{Gl}_{\text{wi}}) + (\text{Gr}_{\text{w}} \times \text{Gr}_{\text{wi}}) \big], \end{aligned}$$

where, DGVI refers to the dynamic groundwater vulnerability index; Ge stands for geology; Gm for geomorphology; El for elevation; Sl for slope; St for soil texture; Lu for land use land cover; Gl for groundwater level in the pre-monsoon season; and Gr for groundwater recharge. The subscripts w and wi refers to theme weight and class weight of each theme respectively.

Results and discussion

Geology

The two blocks are underlain by the Lalgarh formation, which consists secondary laterite, lateritised grits and conglomerates of lower Pleistocene age, which cover the western part of this region (Fig. 3a). Much of the study area is underlain by the Sijua formation of middle Pleistocene to Holocene age, which consists of sandy loam, silt and silty clays, whereas Chinsurah and Hugli formations of upper Holocene age are present in small parts of the area. These formations consist of unconsolidated sands, silts and clays of alluvial origin (Geological Survey of India 2006). There is only limited groundwater in the Lalgarh formation due to the low permeability of the laterite. The older sediments in the Sijua formation are more permeable than those of the Lalgarh formation and have a higher potential to contain significant amounts of groundwater. The Chinsurah and Hugli formations are quite favourable for the occurrences of groundwater.

Geomorphology

Upland plains, weathered plains, low lying flat plains and para deltaic flat surfaces are the main geomorphic landforms of this region (Geological Survey of India 2006). Low lying flat plains and para deltaic fan surfaces are composed of fluvially deposited materials including unconsolidated sand, silt, clay, pebbles and gravels. These are found along the stream channels in the north-eastern and south-eastern parts (Fig. 3b). Upland plains and weathered plains are landform units of denudational origin, which are composed of hard consolidated materials. The upland plains in the western parts of the study area consist of lateritised grit and brownish-red residual soil, whereas hard clay is present in the northern and central parts of the area. Weathered plains, comprised of hard clay and silts, are present in the southern part of the study area. There are only limited occurrences of groundwater in upland and weathered plain areas, but there is a greater groundwater availability in low-lying flat plain and para deltaic fan surface areas.

Elevation

The study area is characterized by upland plains coupled with undulating topography. The elevation of the area ranges from 10–50 m above mean sea level (Fig. 3c). Plains in the eastern and southern parts of the study area generally have a lower elevation than in the western part of the area. Elevated upland is underlain by hard laterite, which limits groundwater recharge; whereas lower elevated plain land is typically underlain by newer alluvium sediments that are more favourable for recharge. Groundwater considered to be more vulnerable to over-exploitation in upland areas than areas with a lower elevation. Consequently, different weights were allocated to different elevations.

Slope

The land slope is an important factor that influences the infiltration of water. Due to undulating nature of the terrain, gentle slopes are present throughout the study area. Regionally, land slopes in a southerly to south-easterly direction. On the basis of slope, the region is sub-divided into three classes (Fig. 3d). Areas where the land slope is less than 1°, are considered to be highly favourable for groundwater recharge, and consequently less vulnerable to groundwater over-exploitation. Areas with a 1°–3° slope are comparatively less favourable to recharge and areas where the land slope is greater than 3° are considered to be more vulnerable to groundwater over-exploitation, as the recharge rate is relatively low in these parts.

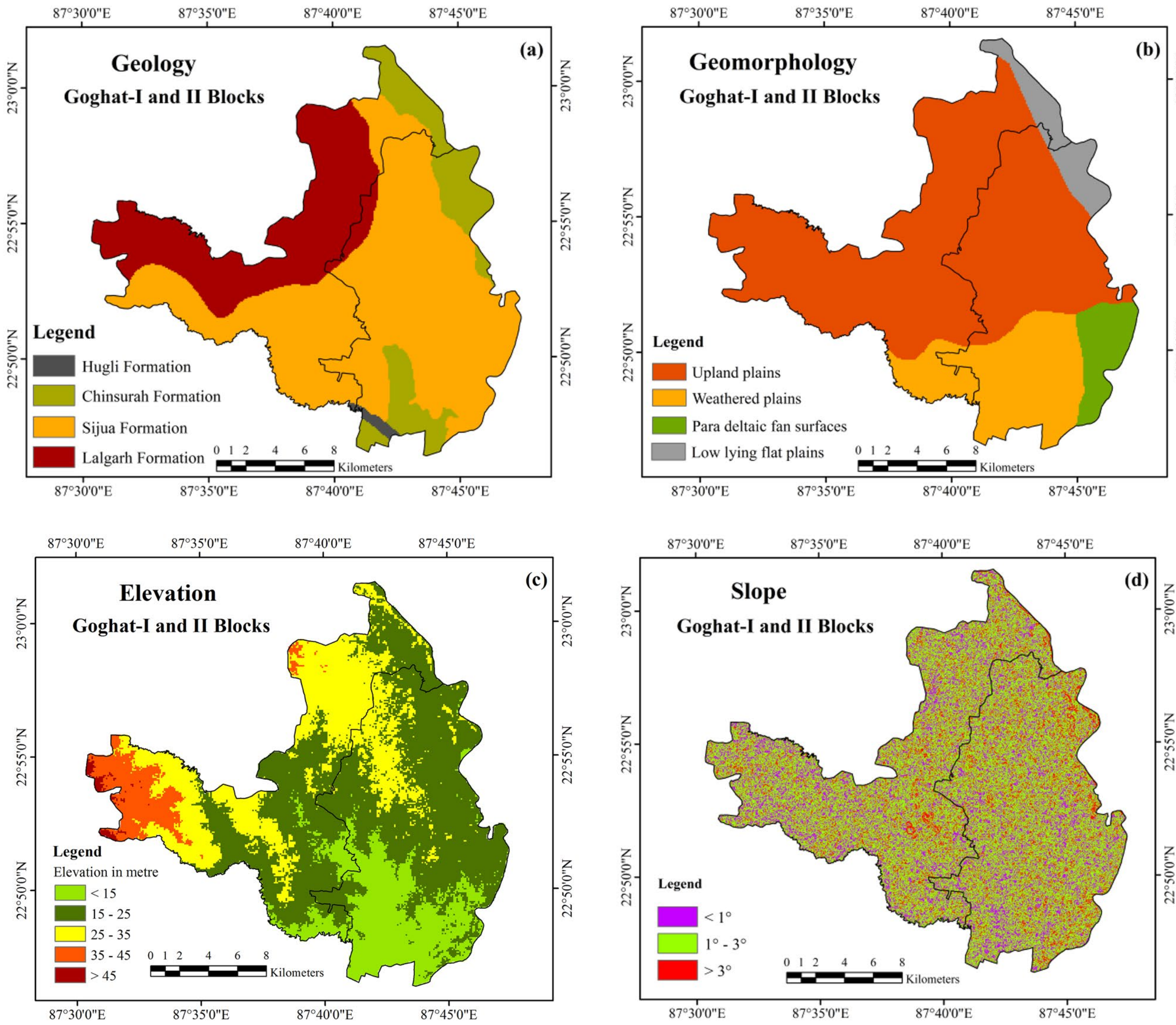

Fig. 3 Factors that influence the vulnerability of groundwater to over-exploitation: **a** geology, **b** geomorphology, **c** elevation, **d** slope, **e** soil texture, **f** land use land cover, **g** pre-monsoon groundwater level, **h** groundwater recharge

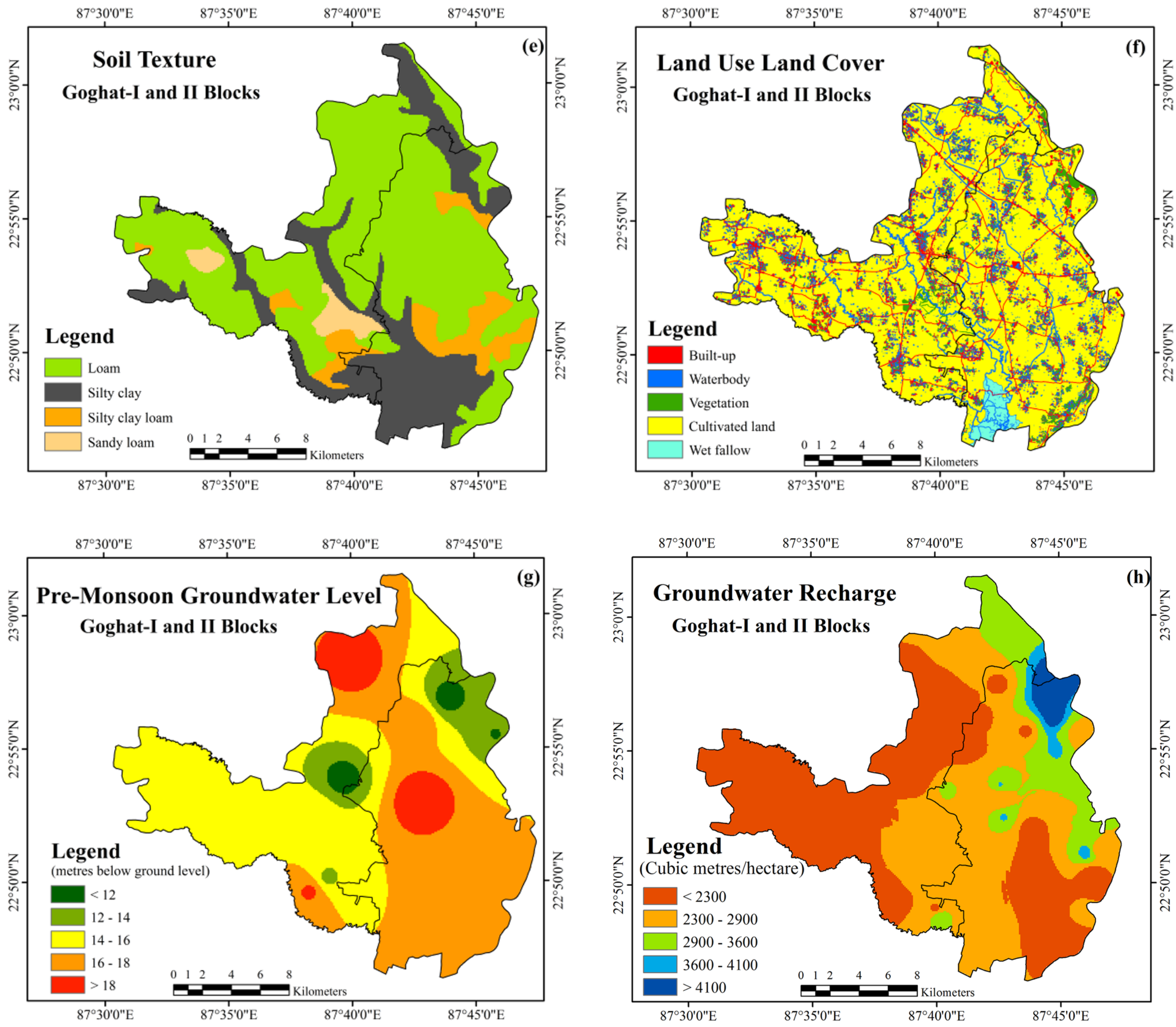

Fig. 3 (continued)

Soil texture

Occurrence of groundwater in a region is influenced by the texture of underlying soils. This is because the magnitude of groundwater recharge is dependent upon the porosity and permeability of the soil, which in turn is controlled by the texture of the soil. The soil texture represents four major categories namely loam, sandy loam, silty clay and silty clay loam (National Bureau of Soil Survey and Land Use Planning 2001). Sandy loam is present in a small extent in the middle and western parts (Fig. 3e). Loamy soil is present in maximum portions. Sandy loamy and loamy soils are favourable for percolation. Silty clay and silty clay loam are also present in this region. These soils are relatively less favourable for groundwater recharge.

Land use land cover

The vulnerability of groundwater to excessive abstraction is influenced by the land use land cover of a region. This is because land use land cover directly controls the recharge capacity of an area. Cultivated land is the most dominant land use type within the study area (Fig. 3f). Groundwater is heavily used in agricultural purpose. Overuse of groundwater for irrigational purposes is increasing the vulnerability of replenishable groundwater resources. Although the region is rural in nature and the degree to which the land surface is covered with paved surfaces is comparatively low, the recharge is generally low in the urbanized areas. Vegetation, waterbodies and wet fallow areas are quite favourable for groundwater occurrence and development. In this study, the maximum weightage has been given to cultivated land due to excessive water use in the agricultural land.

Pre-monsoon groundwater levels

Groundwater level of a region indicates the hydrological condition of an aquifer and the degree to which it has been affected by abstraction. Measured groundwater levels have their lowest values in the pre-monsoon season and are an indicator of the vulnerability of the system to excessive groundwater use. Although groundwater levels in the pre-monsoon season decline due to natural reasons, the rate of declination has increased in last few decades due to overuse of groundwater for *Boro* rice cultivation, which is creating extra stress on the aquifer. Water levels in most of the study area remain 14 m below ground level during the pre-monsoon season (Fig. 3g) (Table 1). Pre-monsoon groundwater level of more than 18 m below ground level has been given maximum weight as this region is already is in a vulnerable condition.

Groundwater recharge

Groundwater recharge estimation is an essential task for using the resource in a sustainable manner. In the study area, rainfall infiltration is the principal source of groundwater recharge. This has been estimated in the study area using the water level fluctuation (WLF) method, which takes into account the specific yield of the aquifer and the magnitude of groundwater level fluctuations (Central Ground Water Board 2014). Using this approach, groundwater recharge has been computed using data from 2014. Actual volumetric amount of groundwater recharge from WLF method is expressed as

$$R = h \times \mathrm{Sy} \times A,$$

where, R refers to the actual recharge, h corresponds to the increase in water level, Sy is the specific yield of the water bearing formation and A represents the area of the assessment unit.

Specific yield values were derived from the results of pumping tests carried out in the study area. The porosity and permeability of the aquifer matrix control the specific yield values. Ground Water Estimation Committee in 1997 considered field studies, long-duration pumping tests and various water balance studies to recommend specific yield values for the alluvial regions. As per the recommendation of the committee, specific yield values of sandy, silty

Table 1 Pre-monsoon and post-monsoon groundwater levels

CGWB well no.	Groundwater level in 2014 (metres below ground level)		Increase of groundwater level in 2014 (m)
	Pre-monsoon	Post-monsoon	
WBHG12	11.93	10.24	1.69
WBHG32	10.53	7.60	2.93
WBHG34	21.27	17.35	3.92
WBHG61	15.42	12.00	3.42
WBHG62	17.05	15.16	1.89
WBHG63	16.69	14.14	2.55
WBHG70	13.43	9.00	4.43
WBHG75	10.73	6.85	3.88
WBHG76	19.73	16.54	3.19
WBHG85	18.46	15.77	2.69
WBHG91	17.95	14.36	3.59

Table 2 Variation of recharge in Goghat-I and II blocks

Block	Gram Panchayat	Recharge in 2014 ('000 cubic metres)
Goghat-I	Bhadur	10,158.6
	Raghubati	8322.1
	Goghat	8530.6
	Nakunda	5313.6
	Saora	5051.1
	Bali	3887.9
	Kumursa	8034.1
Total		49,298.0
Goghat-II	Kumarganj	7679.8
	Bengai	6101.7
	Kamarpukur	4719.1
	Mandaran	7163.7
	Hazipur	4696.6
	Paschimpara	3587.8
	Shyambazar	3702.3
	Badanganj-Fului-I	2897.1
	Badanganj-Fului-II	3042.6
Total		43,590.7

and clayey alluvium are 0.16, 0.10 and 0.06, respectively (Ground Water Estimation Committee 1997). CGWB has been using these values for groundwater recharge estimation over this alluvial region.

Specific yield values in this study have been estimated from borehole lithological records, which has been taken from the Agri-Irrigation Department and Public Health Engineering Department of West Bengal. Lithological logs were analyzed to compute the specific yield values. The abundance of sandy alluvium in the north-eastern part of the study area resulted into the high values of specific yield in this area, whereas lower values were determined in the western part due to presence of thick hard clayey alluvium.

This assessment has indicated that groundwater recharge is limited throughout much of the study area, although it is comparatively high in a small section of the north-eastern part of the area. Groundwater recharge is very low in south-eastern and western parts of the study area (Fig. 3h). Groundwater recharge has been calculated for different gram panchayats, which is presented in Table 2.

Table 3 Weight of different themes and their classes according to MCDA

Theme	Theme weight	Class	Class weight
Groundwater Recharge	0.24	< 2300 m^3/ha	0.33
		2300–2900 m^3/ha	0.25
		2900–3600 m^3/ha	0.20
		3600–4100 m^3/ha	0.14
		> 4100 m^3/ha	0.08
Geology	0.18	Hugli formation	0.11
		Chinsurah formation	0.17
		Sijua formation	0.29
		Lalgarh formation	0.43
Geomorphology	0.15	Upland plains	0.38
		Weathered plains	0.31
		Para-deltaic fan surfaces	0.19
		Low lying flat plains	0.12
Pre-Monsoon Groundwater depth	0.13	< 12 m	0.09
		12–14 m	0.12
		14–16 m	0.20
		16–18 m	0.27
		> 18 m	0.32
Elevation	0.10	< 15 m	0.05
		15–25 m	0.12
		25–35 m	0.21
		35–45 m	0.27
		> 45 m	0.35
Land use land cover	0.08	Waterbody	0.05
		Vegetation	0.08
		Wet fallow	0.12
		Built-up	0.36
		Cultivated land	0.39
Soil texture	0.07	Sandy loam	0.14
		Loam	0.17
		Silty clay loam	0.32
		Silty clay	0.37
Slope	0.05	< 1°	0.21
		1°–3°	0.33
		> 3°	0.46

Table 4 Theme weight through pair-wise comparison matrix of AHP

Theme	Ground-water recharge	Geology	Geomorphology	Pre-monsoon groundwater depth	Elevation	Land use land cover	Soil texture	Slope	Weight
Groundwater recharge	1	2	2	2	3	3	3	3	0.24
Geology	0.5	1	2	2	3	4	4	4	0.21
Geomorphology	0.5	0.5	1	2	3	3	3	3	0.16
Pre-monsoon groundwater depth	0.50	0.50	0.50	1	3	3	4	4	0.15
Elevation	0.33	0.33	0.33	0.33	1	2	2	2	0.08
Land use land cover	0.33	0.25	0.33	0.33	0.5	1	2	2	0.06
Soil texture	0.33	0.25	0.33	0.25	0.5	0.5	1	1	0.05
Slope	0.33	0.25	0.33	0.25	0.5	0.5	1	1	0.05
Consistency ratio: 0.039									

Table 5 Class weight of different themes through AHP

Theme	Class	Decision matrix in AHP scale					Weight
Groundwater recharge (consistency ratio: 0.039)	< 2300 m^3/ha	1	2	3	3	4	0.39
	2300–2900 m^3/ha	0.5	1	2	3	4	0.27
	2900–3600 m^3/ha	0.33	0.5	1	3	3	0.18
	3600–4100 m^3/ha	0.33	0.33	0.33	1	2	0.10
	> 4100 m^3/ha	0.25	0.25	0.33	0.5	1	0.06
Geology (consistency ratio: 0.022)	Hugli formation	1	1	0.5	0.33		0.14
	Chinsurah formation	1	1	0.5	0.33		0.14
	Sijua formation	2	2	1	0.33		0.23
	Lalgarh formation	3	3	3	1		0.49
Geomorphology (consistency ratio: 0.030)	Upland plain	1	2	3	4		0.45
	Weathered plain	0.5	1	3	4		0.32
	Para-deltaic fan surfaces	0.33	0.33	1	2		0.14
	Low lying flat plain	0.25	0.25	0.5	1		0.09
Pre-monsoon groundwater depth (consistency ratio: 0.015)	< 12 m	1	0.5	0.33	0.33	0.25	0.07
	12–14 m	2	1	0.5	0.33	0.25	0.10
	14–16 m	3	2	1	1	0.5	0.21
	16–18 m	3	3	1	1	0.5	0.23
	> 18 m	4	4	2	2	1	0.39
Elevation (consistency ratio: 0.028)	< 15 m	1	0.5	0.33	0.33	0.25	0.07
	15–25 m	2	1	0.5	0.33	0.33	0.11
	25–35 m	3	2	1	0.5	0.33	0.17
	35–45 m	3	3	2	1	0.5	0.26
	> 45 m	4	3	3	2	1	0.39
Land use land cover (consistency ratio: 0.020)	Waterbody	1	1	0.5	0.25	0.25	0.08
	Vegetation	1	1	0.5	0.33	0.25	0.09
	Wet fallow	2	2	1	0.33	0.33	0.14
	Built-up	4	3	3	1	0.5	0.29
	Cultivated land	4	4	3	2	1	0.40
Soil texture (consistency ratio: 0.017)	Sandy loam	1	0.5	0.33	0.33		0.11
	Loam	2	1	0.5	0.33		0.17
	Silty clay loam	3	2	1	1		0.34
	Silty clay	3	3	1	1		0.38
Slope (consistency ratio: 0.010)	< 1°	1	0.5	0.33			0.16
	1°–3°	2	1	0.5			0.30
	> 3°	3	2	1			0.54

Table 6 Comparison matrix and weight values of themes according to Fuzzy logic

Theme	Groundwater recharge	Geology	Geomorphology	Pre-monsoon groundwater depth	Elevation	Land use land cover	Soil texture	Slope	Weight
Groundwater recharge	(1, 1, 1)	(1, 2, 3)	(1, 2, 3)	(1, 2, 3)	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)	0.23
Geology	(0.33, 0.50, 1)	(1, 1, 1)	(1, 2, 3)	(1, 2, 3)	(2, 3, 4)	(3, 4, 5)	(3, 4, 5)	(3, 4, 5)	0.21
Geomorphology	(0.33, 0.50, 1)	(0.33, 0.50, 1)	(1, 1, 1)	(1, 2, 3)	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)	0.17
Pre-monsoon groundwater depth	(0.33, 0.50, 1)	(0.33, 0.50, 1)	(0.33, 0.50, 1)	(1, 1, 1)	(2, 3, 4)	(2, 3, 4)	(3, 4, 5)	(3, 4, 5)	0.15
Elevation	(0.25, 0.33, 0.50)	(0.25, 0.33, 0.50)	(0.25, 0.33, 0.50)	(0.25, 0.33, 0.50)	(1, 1, 1)	(1, 2, 3)	(1, 2, 3)	(1, 2, 3)	0.08
Land use land cover	(0.25, 0.33, 0.50)	(0.20, 0.25, 0.33)	(0.25, 0.33, 0.50)	(0.25, 0.33, 0.50)	(0.33, 0.50, 1)	(1, 1, 1)	(1, 2, 3)	(1, 2, 3)	0.06
Soil texture	(0.25, 0.33, 0.50)	(0.20, 0.25, 0.33)	(0.25, 0.33, 0.50)	(0.20, 0.25, 0.33)	(0.33, 0.50, 1)	(0.33, 0.50, 1)	(1, 1, 1)	(1, 1, 1)	0.05
Slope	(0.25, 0.33, 0.50)	(0.20, 0.25, 0.33)	(0.25, 0.33, 0.50)	(0.20, 0.25, 0.33)	(0.33, 0.50, 1)	(0.33, 0.50, 1)	(1, 1, 1)	(1, 1, 1)	0.05

Vulnerability of groundwater to exploitation

In this study, vulnerability has been assessed in terms of the response of groundwater levels to external stresses such as increases in groundwater use. Different methods such as MCDA, AHP and Fuzzy logic have been applied to find out the vulnerable parts of this region. Weightage has been assigned as per the local experience and field survey. Direct weightage has been given in case of MCDA (Table 3), whereas priorities have been allocated on a scale of 1–9 for AHP, and final weight has been taken after assessment using a pair-wise comparison matrix (Tables 4, 5). Weightage has been given in a set for fuzzy logic, and the final weight was taken after the analysis of fuzzy ratios (Tables 6, 7).

All of the vulnerability assessment methods produced similar results. “Very low” and “low” vulnerability classes are scattered in north-eastern, central and southern parts of the study area (Fig. 4a–f). “High” and “very high” vulnerability zones are found in the western, north-western and south-eastern parts of the study area. Almost half of the study area is classified as having “high” and “very high” vulnerability classes (Table 8).

Groundwater abstraction

Groundwater abstraction is one of the main causes of groundwater depletion in the study area. Primary field survey has been done to estimate the magnitude of agricultural and domestic groundwater use in the study area. The dominant groundwater use in the area is for irrigated crops (Table 9), and to a lesser extent, for domestic use (Table 10).

In 2014, 84% and 91% of the renewable groundwater resource had been used in Goghat-I and Goghat-II blocks respectively (Table 11). This has resulted in the depletion of groundwater levels in these areas. The trend of declining water levels was observed for both the pre and post-monsoon seasons, the rate of decline is much greater in the post-monsoon season (Fig. 5a, b). The decline of groundwater levels in the post-monsoon season suggests that the amount of groundwater recharge has decreased in recent years. Though the stage of groundwater development is lower in case of Goghat-II, but the groundwater level decline trend is worse in this block. This is mainly due to the natural groundwater flow, which is towards the south-east (Fig. 6a, b). Severe water scarcity is visible in the western part of Goghat-II and south-eastern part of Goghat-I. Cultivators in the Badanganj-I and II, Paschimpara, Bali *gram panchayats* have been forced to change their cropping pattern due to unavailability of groundwater. *Boro* cultivation has been replaced by sesame in these parts, but this change is only found in water scarce areas only.

Validation of the groundwater vulnerability assessment

Validation is one of the important aspects of any scientific study. The results of the groundwater vulnerability assessment obtained in this study were reviewed using the

Table 7 Comparison matrix and weight values of sub-classes through fuzzy logic

Theme	Class	Decision matrix of fuzzy logic					Weight
Groundwater recharge	< 2300 m^3/ha	(1, 1, 1)	(1, 2, 3)	(2, 3, 4)	(2, 3, 4)	(3, 4, 5)	0.38
	2300–2900 m^3/ha	(0.33, 0.50, 1)	(1, 1, 1)	(1, 2, 3)	(2, 3, 4)	(3, 4, 5)	0.27
	2900–3600 m^3/ha	(0.25, 0.33, 0.50)	(0.33, 0.50, 1)	(1, 1, 1)	(2, 3, 4)	(2, 3, 4)	0.18
	3600–4100 m^3/ha	(0.25, 0.33, 0.50)	(0.25, 0.33, 0.50)	(0.25, 0.33, 0.50)	(1, 1, 1)	(1, 2, 3)	0.10
	> 4100 m^3/ha	(0.20, 0.25, 0.33)	(0.20, 0.25, 0.33)	(0.25, 0.33, 0.50)	(0.33, 0.50, 1)	(1, 1, 1)	0.07
Geology	Hugli formation	(1, 1, 1)	(1, 1, 1)	(0.33, 0.50, 1)	(0.25, 0.33, 0.50)		0.14
	Chinsurah formation	(1, 1, 1)	(1, 1, 1)	(0.33, 0.50, 1)	(0.25, 0.33, 0.50)		0.14
	Sijua formation	(1, 2, 3)	(1, 2, 3)	(1, 1, 1)	(0.25, 0.33, 0.50)		0.24
	Lalgarh formation	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)	(1, 1, 1)		0.48
Geomorphology	Upland plain	(1, 1, 1)	(1, 2, 3)	(2, 3, 4)	(3, 4, 5)		0.44
	Weathered plain	(0.33, 0.50, 1)	(1, 1, 1)	(2, 3, 4)	(3, 4, 5)		0.33
	Para-deltaic fan surfaces	(0.25, 0.33, 0.50)	(0.25, 0.33, 0.50)	(1, 1, 1)	(1, 2, 3)		0.14
	Low lying flat plain	(0.20, 0.25, 0.33)	(0.20, 0.25, 0.33)	(0.33, 0.50, 1)	(1, 1, 1)		0.09
Pre-monsoon groundwater depth	< 12 m	(1, 1, 1)	(0.33, 0.50, 1)	(0.25, 0.33, 0.50)	(0.25, 0.33, 0.50)	(0.20, 0.25, 0.33)	0.08
	12–14 m	(1, 2, 3)	(1, 1, 1)	(0.33, 0.50, 1)	(0.25, 0.33, 0.50)	(0.20, 0.25, 0.33)	0.11
	14–16 m	(2, 3, 4)	(1, 2, 3)	(1, 1, 1)	(1, 1, 1)	(0.33, 0.50, 1)	0.21
	16–18 m	(2, 3, 4)	(2, 3, 4)	(1, 1, 1)	(1, 1, 1)	(0.33, 0.50, 1)	0.23
	> 18 m	(3, 4, 5)	(3, 4, 5)	(1, 2, 3)	(1, 2, 3)	(1, 1, 1)	0.37
Elevation	< 15 m	(1, 1, 1)	(0.33, 0.50, 1)	(0.25, 0.33, 0.50)	(0.25, 0.33, 0.50)	(0.20, 0.25, 0.33)	0.08
	15–25 m	(1, 2, 3)	(1, 1, 1)	(0.33, 0.50, 1)	(0.25, 0.33, 0.50)	(0.25, 0.33, 0.50)	0.11
	25–35 m	(2, 3, 4)	(1, 2, 3)	(1, 1, 1)	(0.33, 0.50, 1)	(0.25, 0.33, 0.50)	0.17
	35–45 m	(2, 3, 4)	(2, 3, 4)	(1, 2, 3)	(1, 1, 1)	(0.33, 0.50, 1)	0.26
	> 45 m	(3, 4, 5)	(2, 3, 4)	(2, 3, 4)	(1, 2, 3)	(1, 1, 1)	0.38
Land use land cover	Waterbody	(1, 1, 1)	(1, 1, 1)	(0.33, 0.50, 1)	((0.20, 0.25, 0.33)	(0.20, 0.25, 0.33)	0.08
	Vegetation	(1, 1, 1)	(1, 1, 1)	(0.33, 0.50, 1)	(0.25, 0.33, 0.50)	(0.25, 0.33, 0.50)	0.10
	Wet fallow	(1, 2, 3)	(1, 2, 3)	(1, 1, 1)	(0.25, 0.33, 0.50)	(0.25, 0.33, 0.50)	0.14
	Built-up	(3, 4, 5)	(2, 3, 4)	(2, 3, 4)	(1, 1, 1)	(0.33, 0.50, 1)	0.30
	Cultivated land	(3, 4, 5)	(2, 3, 4)	(2, 3, 4)	(1, 2, 3)	(1, 1, 1)	0.38
Soil texture	Sandy loam	(1, 1, 1)	(0.33, 0.50, 1)	(0.25, 0.33, 0.50)	(0.25, 0.33, 0.50)		0.12
	Loam	(1, 2, 3)	(1, 1, 1)	(0.33, 0.50, 1)	(0.25, 0.33, 0.50)		0.18
	Silty clay loam	(2, 3, 4)	(1, 2, 3)	(1, 1, 1)	(1, 1, 1)		0.33
	Silty clay	(2, 3, 4)	(2, 3, 4)	(1, 1, 1)	(1, 1, 1)		0.37
Slope	< 1°	(1, 1, 1)	(0.33, 0.50, 1)	(0.25, 0.33, 0.50)			0.17
	1°–3°	(1, 2, 3)	(1, 1, 1)	(0.33, 0.50, 1)			0.31
	> 3°	(2, 3, 4)	(1, 2, 3)	(1, 1, 1)			0.52

Receiver Operating Characteristics (ROC) curve. The discharge rate of groundwater has been taken for the ROC analysis, which can be used as a proxy for vulnerability to over-exploitation.

ROC curve is a widely accepted technique for this type of assessment. It helps to assess independently the model's predictive capability of a specific probability threshold which might be selected to classify a pixel as a potential vulnerable or non-vulnerable area. The AUC value can be computed by the trapezoidal rule of integral calculus (Dou et al. 2019).

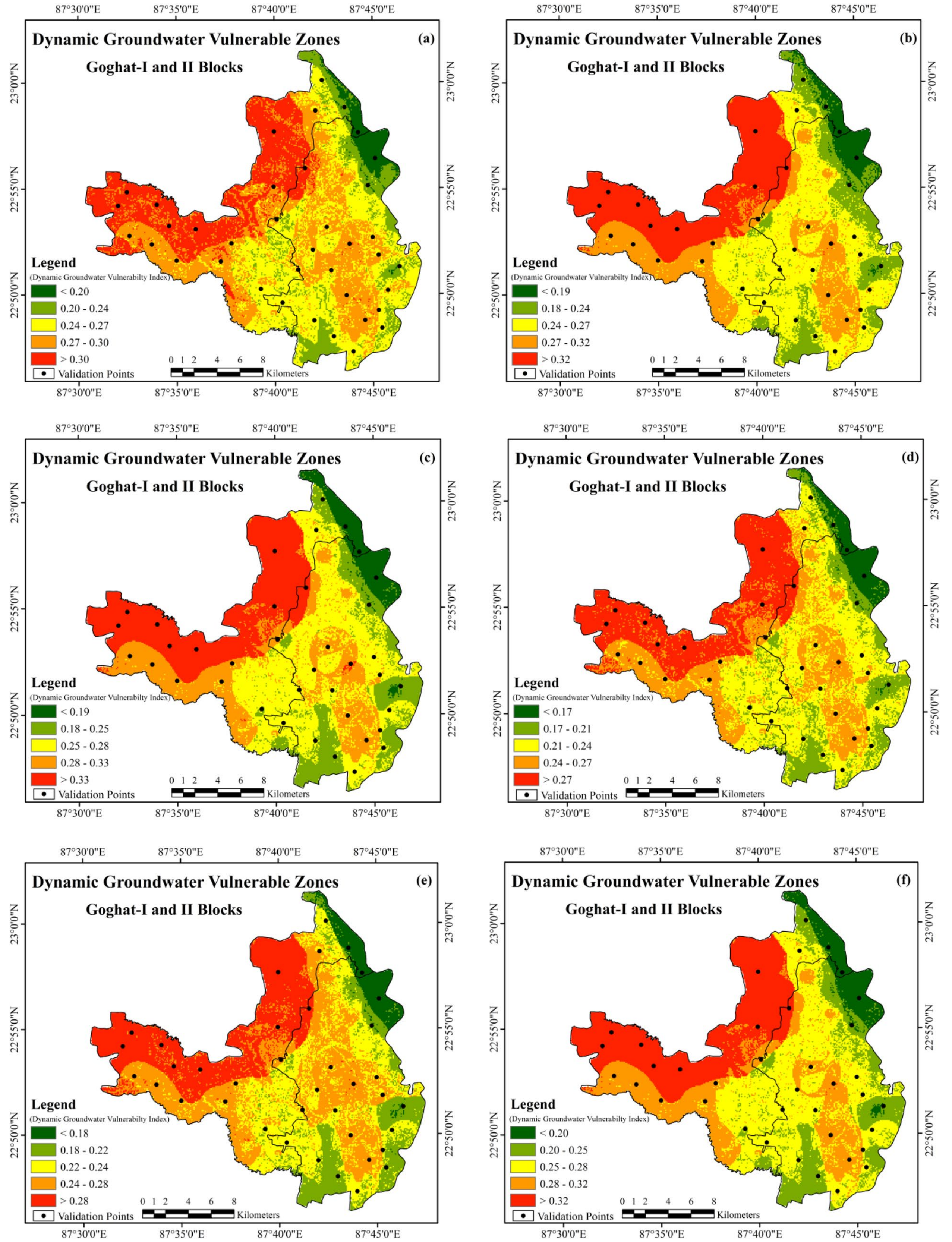

Fig. 4 Assessment of groundwater vulnerability to over-exploitation using—**a** MCDA, **b** AHP, **c** fuzzy logic, **d** ensemble of MCDA and AHP, **e** ensemble of MCDA and fuzzy logic, **f** ensemble of AHP and fuzzy logic

Table 8 Areal extension of different vulnerable classes for different methods

Vulnerability of dynamic groundwater resource	Areal extent (%)					
	MCDA	AHP	Fuzzy logic	Ensemble of MCDA and AHP	Ensemble of MCDA and fuzzy logic	Ensemble of AHP and fuzzy logic
Very low	3.88	5.06	6.18	5.10	5.64	6.45
Low	10.85	14.44	14.08	12.93	13.56	14.55
Moderate	32.14	34.89	33.50	33.81	26.94	33.89
High	30.82	20.93	21.22	24.94	30.10	20.41
Very high	22.31	24.68	25.02	23.22	23.76	24.70

Table 9 Groundwater consumption for irrigation in Goghat-I and II blocks

Block	Crop	Hours of groundwater irrigation/Bigha	Discharge/h (L)	Groundwater consumption/Bigha (L)	Groundwater consumption/ha ('000 L)	Cropping area (ha)	Groundwater consumption ('000 cubic metres)
Goghat-I	Aman paddy	10	12,000	120,000	897	12,992	11,654
	Potato	14	18,000	252,000	1884	4724	8900
	Boro paddy	45	9000	405,000	3027	5491	16,621
	Mustard	4	18,000	72,000	538	345	186
	Sesame	4	9000	36,000	269	2878	774
	Total						38,135
Goghat-II	Aman paddy	14	10,286	144,004	1076	11,242	12,096
	Potato	16	18,000	288,000	2153	3350	7213
	Boro paddy	52	9000	468,000	3498	4271	14,940
	Mustard	4	18,000	72,000	538	966	520
	Sesame	4	9000	36,000	269	4626	1244
	Total						36,013

(1 ha = 7.4749306 Bigha, 1 cubic metre = 1000 L)

Table 10 Consumption of groundwater for domestic purposes

Block	Projected population of 2014	Domestic water consumption in 2014 for 60 L per capita per day ('000 cubic metres)
Goghat-I	144,785	3171
Goghat-II	166,146	3639

$$\mathrm{AUC} = \sum_{k=1}^{n} (X_{k+1} - X_k)\left(S_{k+1} - S_k - S_k/2\right).$$

AUC is the area under curve, X_k indicates 1-specificity and S_k is the sensitivity. AUC values obtained in this study are 0.862, 0.842, 0.817, 0.822, 0.810 and 0.810 for the outputs of MCDA, AHP, fuzzy logic, ensemble of MCDA-AHP,

Table 11 Scenario of groundwater recharge and abstraction in Goghat-I and II blocks

Block	Year: 2014		
	Net groundwater recharge ('000 cubic metres)	Total Groundwater draft ('000 cubic metres)	Stage of groundwater development (%)
Goghat-I	49,298.0	41,306.0	83.79
Goghat-II	43,590.7	39,652.0	90.96

MCDA-fuzzy logic and AHP-fuzzy logic methods respectively (Fig. 7). AUC values of greater than 0.80 generally indicate that the output from a model is reliable. Consequently, the vulnerability assessment methods used in this study are considered to be reliable.

Conclusions

The vulnerability of groundwater to over-exploitation has been assessed in two groundwater management areas such as Goghat-I and II blocks in West Bengal in India. The assessment was undertaken using a number of methods including MCDA, AHP, fuzzy logic, ensembles of MCDA-AHP, MCDA-fuzzy logic and AHP-fuzzy logic, which produced similar results. This assessment indicated that most of the study area is highly vulnerable to water level decline due to excessive groundwater use. Vulnerable areas should be given special attention through monitoring and protection. The assessment methodologies that were developed in this study should benefit in developing strategies for better management of this precious groundwater resources in other regions.

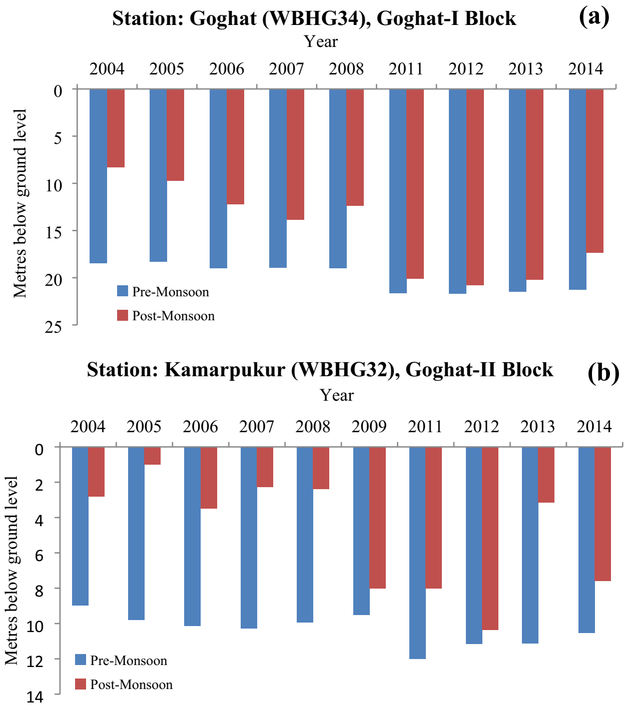

Fig. 5 Decline of groundwater levels over time in **a** Goghat-I **b** Goghat-II blocks

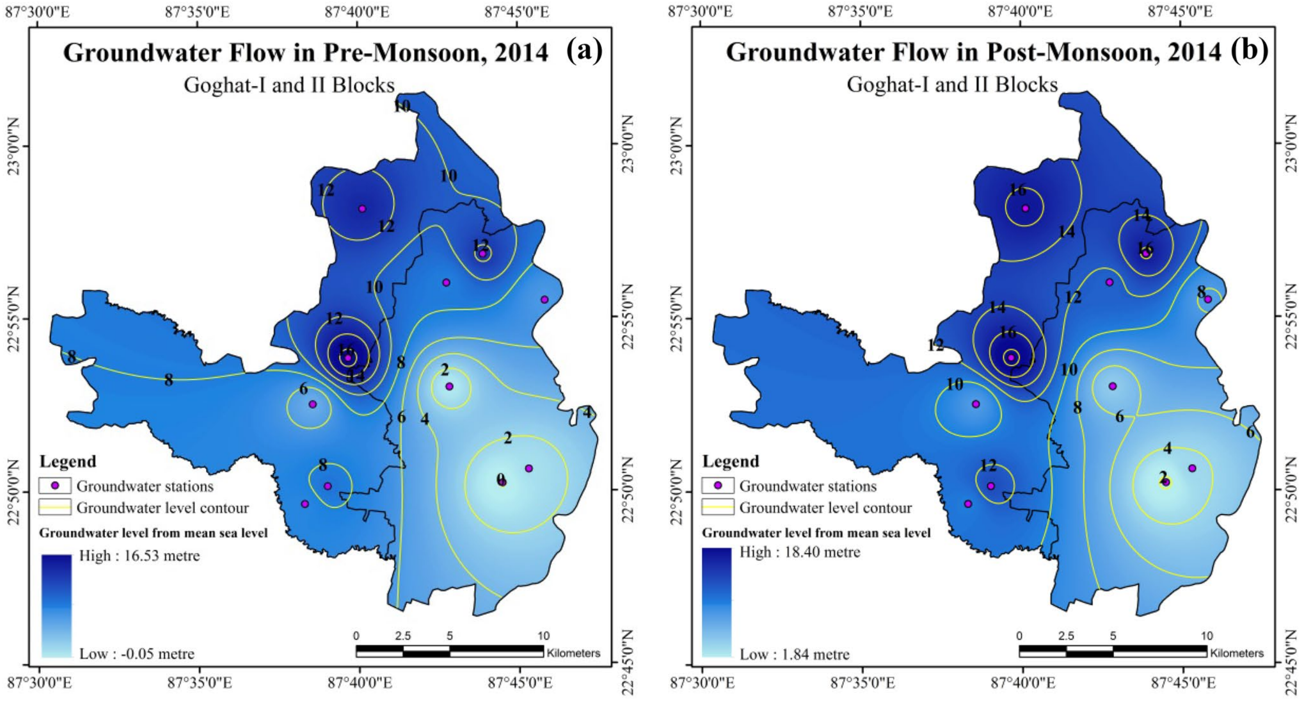

Fig. 6 Natural groundwater flow in the Goghat-I and II blocks—**a** during the pre-monsoon season, and **b** the post-monsoon season of 2014

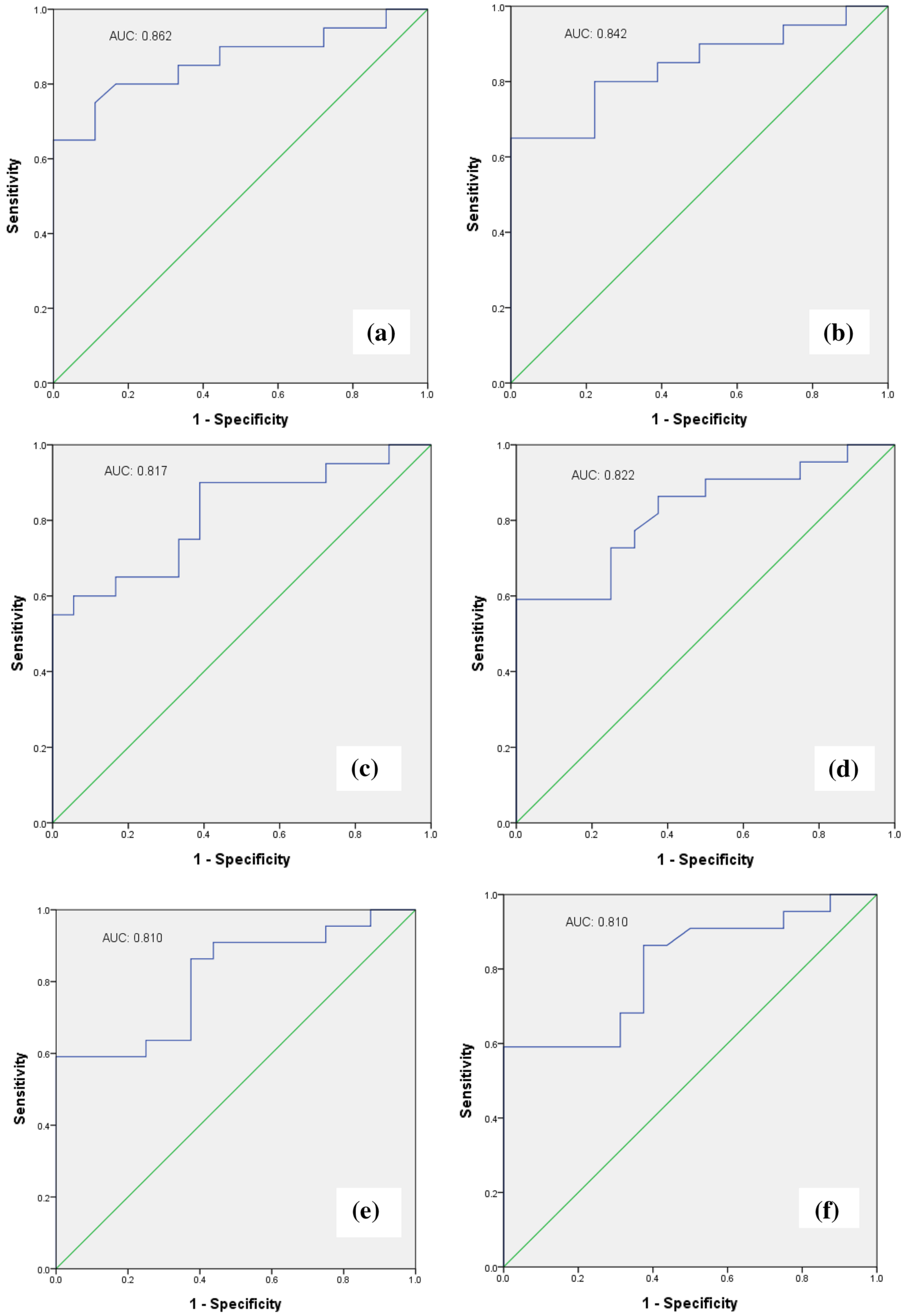

Fig. 7 Model Validation through the ROC curve—**a** MCDA, **b** AHP, **c** fuzzy logic, **d** ensemble of MCDA-AHP, **e** ensemble of MCDA-fuzzy logic, **f** ensemble of AHP-fuzzy logic

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