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Original Articles

Assessing the accuracy of GIS-based Multi-Criteria Decision Analysis approaches for mapping groundwater potential

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ABSTRACT

Groundwater is the most important natural resource for reliable and sustainable water supplies throughout the world. However, the over-exploitation of groundwater has led to groundwater depletion over the world. Sustainable development and management of this vital resource under changing environmental conditions is the one of the major challenges of the 21st century. To this end, this study focuses on the evaluation of groundwater prospect following an integrated multi-criteria analysis and geospatial approach. GIS-based Multi-Criteria Decision Analysis (MCDA) techniques viz., Analytic Hierarchy Process (AHP) and Catastrophe theory were used for delineating groundwater potential zones in a Canal Command of Eastern India. Thematic layers (maps depicting features of the factors influencing groundwater) such as 'runoff coefficient', 'drainage density', 'geology', 'slope' and 'proximity to surface water bodies' were considered in this study. Weights were assigned to the themes and their features according to AHP and Catastrophe theories. Thereafter, the themes were integrated in GIS to yield groundwater potential maps based on AHP and Catastrophe techniques. The AHP-based groundwater potential map revealed four zones with varying areal coverage: (a) 'very good' (19% of the study area), (b) 'good' (49%), (c) 'moderate' (28%), and (d) 'poor' (4%). On the other hand, the Catastrophe-based map indicated spatial variation of groundwater potential as: (a) 'very good' (14% of the area), (b) 'good' (63%), (c) 'moderate' (19%), and (d) 'poor' (5%). Thus, both the techniques indicated good groundwater potential in the study area. The validation of the results of these GIS-based MCDA techniques indicated that although both the techniques are suitable for mapping groundwater potential with a reasonably high accuracy (82% for the AHP technique and 74% for the Catastrophe technique), the performance of the AHP technique is somewhat superior to the Catastrophe technique. The findings of this study are very useful to the water managers for cost-effective and efficient planning and development of scarce groundwater resources so as to ensure sustainable water supply in the future.

1. Introduction

Groundwater is one of the most important natural resources that plays a vital role in ensuring reliable water supplies throughout the globe under changing environmental conditions. Due to the accelerated pace of development and intensive agriculture across the globe to meet increasing global food and energy demands, the over-exploitation of groundwater has led to declining groundwater levels and consequent ever-increasing stress on available groundwater resources in several parts of the world (e.g., Doell et al., 2014; Tiwari et al., 2009; Kerr, 2009). Nearly 60% of the irrigated areas in India are dependent on groundwater; the number of power-operated wells and tubewells grew from less than a million to 19 million during the 1960–2000 period (Shah et al., 2003). The water supply of the country will face severe problems in the future due to climate change (Mallick et al., 2015). The irrigation water demand predicted in the year 2010 was 557 km^3 and further projected to increase by 611 km^3 and 807 km^3 in the year 2025 and 2050, respectively. Projected domestic water demand in the year 2010 was 43 km^3 and was further projected to be increased to 111 km^3 in 2050. Further, industrial and environmental demands were projected to increase from 37 km^3 and 5 km^3 to 81 km^3 and 20 km^3, respectively during the period 2010–2050 (MOWR, 1999). Thus, the ever widening gap between water demand and water supply needs to be managed by exploring the additional conventional and non-conventional available water resources.

Surface water resources in West Bengal are estimated to be about 132.9 BCM (billion cubic meters), of which only about 40% can be utilized. The utilizable groundwater in West Bengal is about 17.6 BCM

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(CGWB, 2001). The unbalanced groundwater withdrawal and over exploitation has led to decrease in the groundwater table and also deterioration in the groundwater quality. Damodar Canal Command (DCC) is experiencing acute water scarcity problem during dormant season for both domestic and agricultural purposes. Hence, it is necessary to identify potential groundwater resources using appropriate and reliable scientific methods in West Bengal for augmentation of existing water resources. Conjunctive use can maximize the efficient use of surface water and groundwater resources and makes possible for storage of water resources due to the interrelationship between surface and ground water for use during the dormant season. Groundwater management can ensure efficient management of surplus and deficit water situations, where surplus water can be used for groundwater recharge and water deficit can be managed by extraction of groundwater. Thus, uncertainty in water demand and supply could be minimized through proper management of groundwater and therefore, it is necessary to identify the groundwater potential zones to explore the additional groundwater resources to address water demand and supply gaps in the Damodar Canal Command of West Bengal, India.

Delineation of groundwater potential zones for groundwater extraction has become an important issue in recent years due to excessive pumping of groundwater for meeting water demands in different sectors. Traditional methods for the identification of groundwater potential zones are not only time-consuming and costly but also need skilled manpower (e.g., Israil et al., 2006; Jha et al., 2010). GIS is a robust tool to handle a large amount of spatial data, and it can be successfully used for natural resources management (Bandyopadhyay et al., 2007; Jha and Chowdary, 2007; Chowdhury et al., 2009). Geospatial techniques have been proved to be an effective tool in the identification of groundwater potential zones (e.g., Murthy, 2000; Jaiswal et al., 2003; Rao and Jugran, 2003; Saraf et al., 2004; Chowdhury et al., 2009; Rose and Krishnan, 2009; Elewa and Qaddah, 2011; Jha et al., 2010; Machiwal et al., 2011; Rekha et al., 2011; Singh, et al., 2011; Gumma and Pavelic, 2013; Elmahdy and Mohamed, 2015; Sahoo et al., 2015). Most of these researchers used approaches that involved the assignment of weights to the selected themes and respective features of individual themes that influence groundwater potential in an area.

The review of literature revealed that an integrated remote sensing and GIS-based Multi-Criteria Decision Analysis (MCDA) approach using Analytic Hierarchy Process (AHP) technique were used for assessing groundwater potential in West Medinipur district of West Bengal, India (Chowdhury et al., 2009; Jha et al., 2010). Murthy and Mamo (2009) identified groundwater potential zones in Moyale-Teltele sub-basin, South Ethiopia using MCDA method. Agarwal and Garg (2016) delineated groundwater potential and recharge zones in Loni and Morahi watersheds, Unnao and Rae Bareli districts, Uttar Pradesh, India using remote sensing and GIS-based multi-criteria decision making techniques. Geospatial and AHP techniques were adopted for the evaluation of groundwater potential zones in the coal mining affected hard-rock terrain of Ramgarh and parts of Hazaribagh district, Jharkhand state, India (Kumar and Krishna, 2016). Further, Mandal et al. (2016) evaluated groundwater potential zones of coastal groundwater basin in the Balasore district of Odisha, India using remote sensing and multi-criteria decision making techniques. GIS, remote sensing and AHP techniques were applied for the delineation of groundwater potential zones in the Comoro watershed, Timor Leste using eight thematic layers namely drainage density, land use, lineament, lithology, rainfall, slope, soil and topography elevation (Pinto et al., 2017). On the other hand, some researchers applied geospatial and MCDA techniques for mapping recharge zones in different parts of the world (Chenini et al., 2010; Chowdhury et al., 2010; Rahman et al., 2012; Rahimi et al., 2014; Agarwal and Garg, 2016).

In the present study, well recognized GIS-based Multi-Criteria Decision Analysis (MCDA) technique such as Saaty's (1980) Analytic Hierarchy Process (AHP) and an emerging technique Catastrophe theory-based MCDA were used for mapping groundwater potential zones. Catastrophe theory was developed by French scientist Rene Thom in 1960s (Al-Abadi and Shahid, 2015). It is a special branch of dynamical systems theory (Kozak and Benham, 1974; Ghorbani et al., 2010). It is useful for the classification of various phenomena characterized by sudden shifts in behaviour arising from small changes in circumstances (Kam, 1992) and the phenomena of discontinuity (Benham and Kozak, 1976; Wang et al., 2011). The Catastrophe theory has environmental applications also. Yun-feng et al. (2007) adopted Catastrophe model for the prediction of water bloom in the Lake Chaohu, China. Zhang et al. (2009) applied Catastrophe progression method to predicting coal and gas outburst, while Wang et al. (2011) assessed pollution of near-shore coastal water using Catastrophe theory. In the recent past, the Catastrophe theory has been used to evaluate water security and adaptation strategy in the context of environmental change (Yang et al., 2012; Xiao-jun et al., 2014). Recently, Jenifer and Jha (2017) compared three methods viz., Analytic Hierarchy Process (AHP), Catastrophe and Entropy for evaluating groundwater prospect of hard-rock aquifer systems in Tiruchirappalli district, Tamil Nadu, India. On the other hand, limited studies on groundwater potential mapping using Catastrophe theory have been reported to date (Ahmed et al., 2015; Al-Abadi and Shahid, 2015; Sadeghfam et al., 2016) and the knowledge about the efficacy of the Catastrophe theory for mapping groundwater prospect compared to the conventional GIS-based MCDA technique in diverse hydrogeologic settings is fairly limited.

Although the study area "Damodar Canal Command of West Bengal" in Eastern India receives adequate rainfall, both domestic and irrigation sectors suffer from water scarcity problem during non-monsoon seasons due to short monsoon season (rainy season), large spatio-temporal variability of rainfall, and capricious nature of the monsoon. In view of growing water scarcity and environmental problems under changing climatic conditions at global, national and regional levels in general and in developing countries in particular, the present study was conducted with the objectives of: (a) delineation of groundwater potential zones in the study area using GIS-based Multi-Criteria Decision Analysis (MCDA) approaches such as AHP and Catastrophe techniques, and (b) to assess the efficacy of these two GIS-based MCDA approaches. Also, a novel method has been employed in this study for the validation of groundwater-potential results obtained by these MCDA approaches. The results of this study are very helpful to the water managers for formulating cost-effective and efficient plans and management strategies for sustainable groundwater withdrawal, which in turn can ensure dependable water supply for agriculture and domestic sectors as well as improved livelihoods and environmental security in the region.

2. The study area

The Damodar Canal Command (DCC) located in the upper Damodar River basin, south-central part of West Bengal, India (Fig. 1). The study area is situated between 22°31′25″ N and 23°42′48″ N latitude, 87°15′14″ E and 88°26′22″ E longitude. The total geographical area of the study command is ~7470 km^2 with an elevation ranges from 1 to 98 m (MSL). The DCC comprises of forty administrative units called 'blocks' falling under four districts namely Burdwan district (20 blocks), Hooghly district (12 blocks), Howrah district (4 blocks) and Bankura district (4 blocks). The study area has the sub-humid climate with four distinct seasons: (a) summer season (March–May), (b) monsoon season (June–September), (c) post-monsoon/autumn season (October–November), and (d) winter season (December-February). The average annual rainfall of the study area is 1913 mm and the rainfall period usually spans from mid-June to the end of October. The study area is classified into two agro-climatic zones, viz., Gangetic alluvial zone (Amta–I, Amta–II, Arambag, Balagarh, Chinsurah–Magra, Chnditala–I, Dhaniakhali, Haripal, Jagatballavpur, Jangipara, Pandua, Polba-Dadpur, Pursura, Singur, Tarakeswar and Udayanarayanpur), and Red and Laterite zone (Ausgram–I, Ausgram–II, Barjora, Bhatar, Burdwan–I, Burdwan–II, Galsi–I, Galsi–II, Indus, Jamalpur, Kalna–I, Kalna–II,

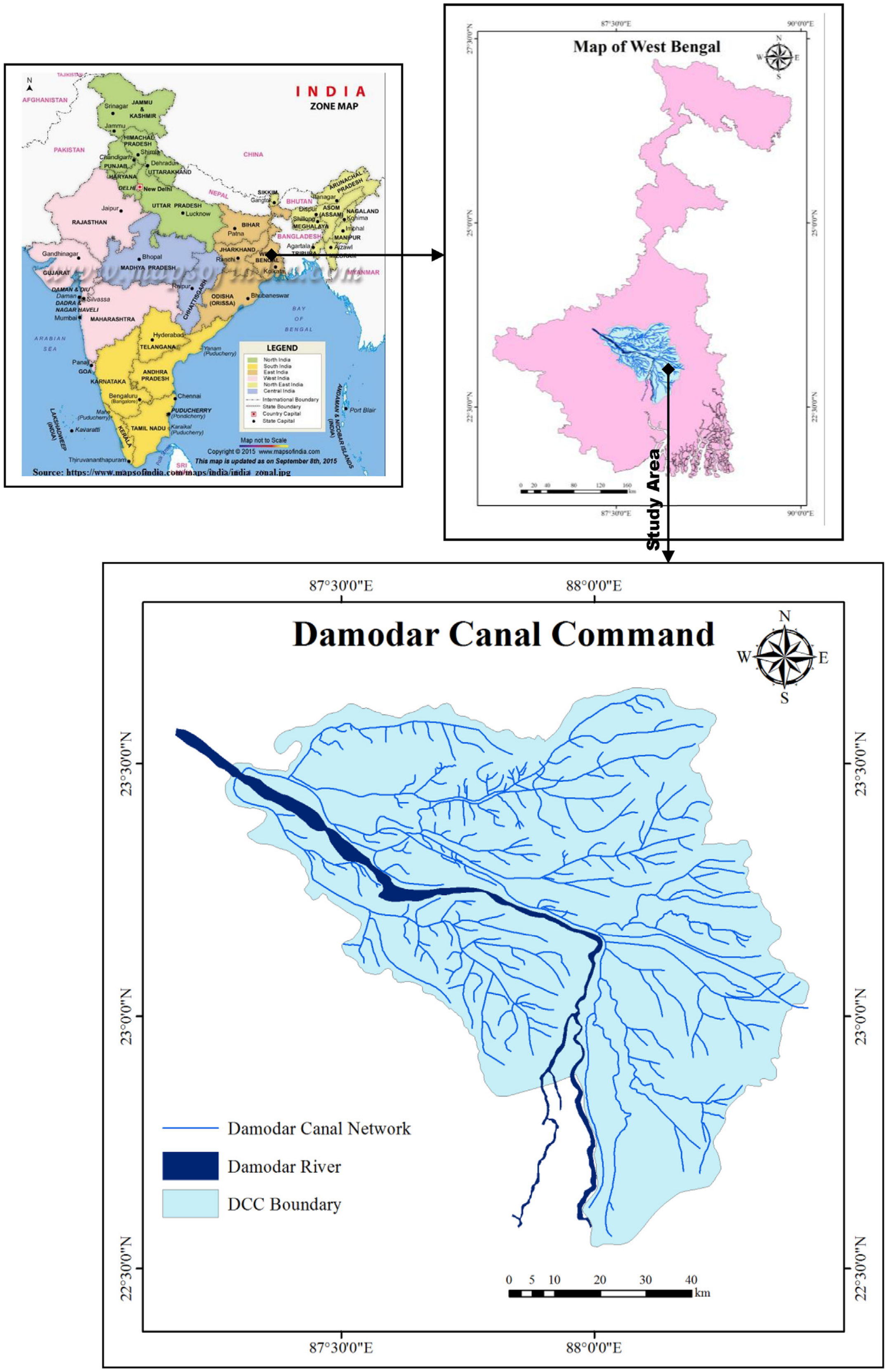

Fig. 1. Location map of the study area.

Kanksa, Katwa–I, Katwa–II, Khandaghosh, Mangolkote, Manteswar, Memari–I, Memari–II, Patrasayar, Raina–I, Raina–II and Sonamukhi). Major soil textural classes of the study area are silt loam, clay, and sandy loam. Major cropping patterns of the study area are rice, potato and sesame. Rice occupy nearly 80% of the total agricultural area and three seasons of rice are grown namely *Aman* paddy (monsoon), *Aus* paddy (pre-monsoon) and *Boro* paddy (non-monsoon). Besides rice crop, other major crops cultivated in the study area are potato, sesame, and mustard. The jute and wheat crops are also cultivated in limited areas. Average cropping intensity of the study area during the last decade was about 190%. Canal water is the major source of irrigation along with other sources of irrigation from groundwater, river-lift irrigation, and tanks.

3. Materials and methods

3.1. Data collection

Conventional and remote sensing data pertaining to the study area were collected from various government agencies. Meteorological data of 14 rain gauge stations available in the study area were obtained from the Climate Forecast System Reanalysis website (http://globalweather.tamu.edu/) for the 35-year period (1979–2013). Soil map generated by National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) at 1:250,000 scale was used in the present study. Land use/land cover map and proximity to surface water bodies at 1:50,000 for the year 2005 were collected from Regional Remote Sensing Centre-East, NRSC, ISRO, Kolkata. SRTM Digital Elevation Model at 90 m × 90 m spatial resolution was obtained from the CGIAR Consortium for Spatial Information (http://srtm.csi.cgiar.org). Geology map at 1:250,000 scale was collected from Geological Survey of India (GSI), Kolkata, West Bengal, India. Pre-monsoon and post-monsoon groundwater depth data of the study area for the period 1990–2014 and the specific yield data were collected from Central Ground Water Board (CGWB) (http://gis2.nic.in/cgwb/) and State Water Investigation Directorate (SWID), Government of West Bengal, India.

3.2. Thematic layers used in the study

Groundwater potential zoning is a multi-objective and multi-criteria problem. Thematic layers such as 'runoff coefficient', 'drainage density', 'geology', 'slope' and 'proximity to surface water bodies' were considered for AHP and Catastrophe methods in the present study based on the literature survey (Table 1). The derived thematic layer 'runoff coefficient' (representing the combined influence of land use/land cover, soil, and rainfall thematic layers) was successfully used in earlier studies for the identification of rainwater harvesting potential zones (Jha et al., 2014; Singh et al., 2017) and hence, the 'runoff coefficient' thematic layer was used in this study for the identification of groundwater potential zones which facilitated the use of desired thematic layers (factors) for both the AHP and Catastrophe methods. Runoff coefficient is a dimensionless value that indicates the fraction of rainfall that generates runoff. Its value varies from 0.05 for sandy soils to 0.95 for concrete surfaces (Singh, 1992). Runoff coefficient map of the study area was generated by overlaying the runoff potential map of a given year and corresponding rainfall map in the GIS environment. The 'runoff coefficient' map of the 'normal year' (2004) was used for the delineation of groundwater potential zones in the study area. It is worth mentioning that the thematic map of 'runoff coefficient' accounts for rainfall, soil, and land use/land cover factors that affect runoff. For the Catastrophe technique, different geologic features were quantified using properties of soil based on specific yield (GWREC, 1997). DEM reconditioning, i.e., removal of sink and fill was carried out for the creation of depression less DEM, which was used for generation of slope map and drainage network in ArcGIS software. Stream network and micro-watershed were delineated using SRTM DEM (90 m × 90 m spatial resolution) in ArcGIS software. Subsequently, drainage density at a micro-watershed level was computed using stream length and micro-watershed area of the study area using ArcHydro extension in ArcGIS software. The details of the thematic layers along with their sources are given in Table 2.

Table 2
Thematic layers used and their sources.

Thematic Layer	Source
1. Land Use/Land Cover	Regional Remote Sensing Centre–East, NRSC, ISRO, Kolkata,
2. Soil	NBSS&LUP, Nagpur
3. Runoff Coefficient	Generated using rainfall data, and Soil and Land Use/Land Cover maps
4. Drainage Density	Generated from SRTM DEM (90 m × 90 m spatial resolution)
5. Geology	Geological Survey of India, Kolkata, West Bengal
6. Slope	SRTM DEM (90 m × 90 m spatial resolution)
7. Proximity to Surface Water Bodies	Extracted from Land Use/Land Cover map

3.3. Multi-Criteria Decision Analysis using AHP technique

The commonly used GIS-based MCDA (Multi-Criteria Decision Analysis) method, 'AHP technique' was used for delineating groundwater potential zones (GWPZ) by integrating the pertinent spatial data in GIS. Suitable weights based on the Saaty's AHP scale were assigned to the themes and respective theme features (Table 3) according to the relative importance of themes and their features in groundwater existence. This task was completed based on the experts' opinions, salient literature, and local experience. Principal eigenvalue (λ_{max}) was computed by Eigen vector technique. Thereafter, Consistency Index (CI) and Consistency Ratio (CR) were calculated using the equations given below (Saaty, 1980; Saaty, 1990; Saaty, 2000; Saaty, 2008):

$$\text{Consistency Index(CI)} = \frac{\lambda_{max}-n}{n-1} \quad (1)$$

where n is the number of factors used in the analysis.

Table 1
Literature reviewed related to the thematic layers selected in this study for groundwater potential mapping.

Thematic Layer Used	Literature Reviewed
1. Runoff Coefficient	Jha et al. (2014), Singh et al. (2017)
2. Land Use/Land Cover	Rose and Krishnan (2009), Rekha et al. (2011), Gumma and Pavelic (2013), Mallick et al. (2015)
3. Drainage Density	Rose and Krishnan (2009), Gumma and Pavelic (2013), Elmahdy and Mohamed (2015), Mallick et al. (2015), Rahmati et al. (2015)
4. Soil	Machiwal et al. (2011), Singh et al. (2011), Gumma and Pavelic (2013), Mallick et al. (2015)
5. Geology	Rose and Krishnan (2009), Rekha et al. (2011), Machiwal et al. (2011), Oh et al. (2011), Singh et al. (2011), Gumma and Pavelic (2013), Elmahdy and Mohamed (2015), Mallick et al. (2015), Rahmati et al. (2015)
6. Slope	Rose and Krishnan (2009), Rekha et al. (2011), Machiwal et al. (2011), Singh et al. (2011), Gumma and Pavelic (2013), Elmahdy and Mohamed (2015), Rahmati et al. (2015)
7. Proximity to Surface Water Bodies	Machiwal et al. (2011), Oh et al. (2011), Mallick et al. (2015)

Table 3
AHP scale and its interpretation (Eastman, 2003).

Less Important				Equally Important	More Important			
Extremely	Very Strongly	Strongly	Moderately		Moderately	Strongly	Very Strongly	Extremely
1/9	1/7	1/5	1/3	1	3	5	7	9

Table 4
Weights of the thematic layers used for groundwater potential mapping.

Thematic Layer	Assigned Weight
1. Runoff Coefficient (RC)	8
2. Drainage Density (DD)	7
3. Geology (GL)	6
4. Slope (SL)	6
5. Proximity to Surface Water Bodies (SW)	4

Table 5
Pair-wise comparison matrix of the five thematic layers.

Theme	RC	DD	GL	SL	SW	Geometric Mean	Normalized Weight
RC	8/8	8/7	8/6	8/6	8/4	1.32367	0.25806
DD	7/8	7/7	7/6	7/6	7/4	1.15821	0.22581
GL	6/8	6/7	6/6	6/6	6/4	0.99275	0.19355
SL	6/8	6/7	6/6	6/6	6/4	0.99275	0.19355
SW	4/8	4/7	4/6	4/6	4/4	0.66184	0.12903
Column Total =						5.12922	1.00

$$\text{Consistency Ratio(CR)} = \frac{CI}{RCI} \tag{2}$$

where RCI = Random Consistency Index, whose values were obtained from the standard table provided in Saaty (1980).

If CR value is less than 10%, then the assigned weights are considered consistent, otherwise the weights need to be re-evaluated (Saaty, 1980). The assigned weights of the thematic layers for the AHP technique and the pair-wise comparison matrix for the five thematic layers are presented in Tables 4 and 5, respectively. Similarly, normalized weights for different features corresponding to respective themes were also computed.

3.4. Multi-Criteria Decision Analysis using Catastrophe technique

In the Catastrophe theory, the dependency of state variables on control variables is determined by the Catastrophe Fuzzy Membership functions, and the theory follows an analytic hierarchy, utility function, and fuzzy evaluation to obtain Catastrophe Fuzzy Membership functions by normalized treatment of the bifurcation set (Wang et al., 2011). Particularly, the importance of indices is evaluated rather than the weights assigned by the researchers (Zhang et al., 2009). In order to solve complicated problems using Catastrophe theory, the dynamic system must be divided into sub-systems, and each subsystem should have indicators consisting of a number which will be used for evaluation. Thus, the original numeric data are first normalized using Catastrophe theory and Fuzzy mathematics and the normalized values range between 0 and 1 (Sadeghfam et al., 2016). Various Catastrophe models with corresponding potential functions are given in Table 6. The normalization formulae which describe all possible discontinuities controlled by no more than four variables are given in Table 7.

Table 7
Normalization formulae for the Catastrophe theory (Cheng et al., 1996).

Sl. No.	Category	Control Variable	Normalization Formula
1	Cusp	2	$x_a = a^{0.5}$ *and* $x_b = b^{0.33}$
2	Swallowtail	3	$x_a = a^{0.5}$, $x_b = b^{0.33}$, *and* $x_c = c^{0.25}$
3	Butterfly	4	$x_a = a^{0.5}$, $x_b = b^{0.33}$, $x_c = c^{0.25}$, *and* $x_d = d^{0.20}$
4	Wigwam	5	$x_a = a^{0.5}$, $x_b = b^{0.33}$, $x_c = c^{0.25}$, $x_d = d^{0.20}$, *and* $x_e = e^{0.17}$

Delineation of groundwater potential zones using Catastrophe technique involves four major steps namely (Ahmed et al., 2015): (i) selection of influential thematic layers for groundwater potential; (ii) standardization of the data; (iii) normalization of the data using Catastrophe models; and (iv) delineation of groundwater potential zones in GIS. These steps are briefly described below.

3.4.1. Standardization of data

Different thematic layers or indices have different units of measurement and standardization process converts them into dimensionless. The standardization formulas used for the study were 'larger the better' and 'smaller the better' as suggested by Li et al. (2010). The equation used for the standardization of 'larger the better' indices are:

$$y_i = \frac{x_i - x_{i(\min)}}{x_{i(\max)} - x_{i(\min)}} \tag{3}$$

The equation used for standardization of 'smaller the better' indices are:

$$y_i = \frac{x_{i(\max)} - x_i}{x_{i(\max)} - x_{i(\min)}} \tag{4}$$

where y_i = standardized values; i is the index or attribute; x_i is the original value of i; and $x_{i(\max)}$ and $x_{i\ (\min)}$ are maximum and minimum values.

3.4.2. Normalization using Catastrophe model

The normalization is carried out using the Catastrophe theory using the normalization formulas given in Table 7. The Catastrophe progression of each control variable is computed from the initial fuzzy

Table 6
Different types of Catastrophe models (Ahmed et al., 2015).

Sl. No.	Catastrophe Model	Control Parameter	State Variable	Potential Function
1	Fold	1	1	$V_a(x) = 1/3x^3 + ax$
2	Cusp	2	1	$V_{ab}(x) = 1/4x^4 + 1/2ax^2 + bx$
3	Dovetail	3	1	$V_{abc}(x) = 1/5x^5 + 1/3ax^3 + 1/2bx^2 + cx$
4	Butterfly	4	1	$V_{abcd}(x) = 1/6x^6 + 1/4ax^4 + 1/3bx^3 + 1/2cx^2 + dx$
5	Oval umbilici point	3	2	$V_{abc}(x,y) = 3 - xy^2 + a(x^2 + y^2) + bx + cy$
6	Elliptic umbilici point	3	2	$V_{abc}(x,y) = x^3 - xy^2 + a(x^2 + y^2) + bx + cy$
7	Parabolic umbilici point	4	2	$V_{abc}(x,y) = x^2y + y^4 + ax^2 + by^2 + cx + dy$

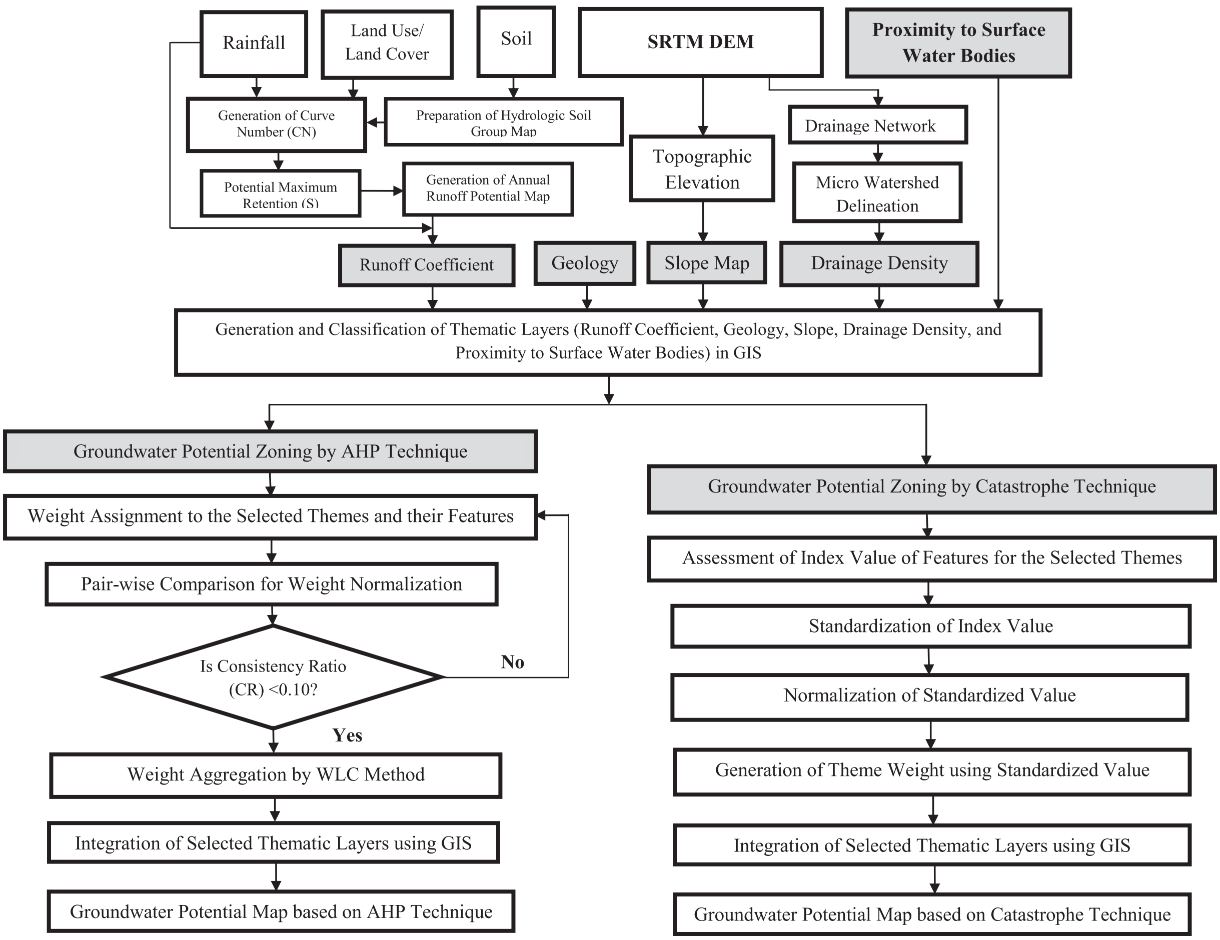

Fig. 2. Flowchart for delineating groundwater potential zones using AHP and Catastrophe techniques.

subordinate (Ahmed et al., 2015). In normalization process, two principles are applied namely a complementary and a non-complementary principles (Wang et al., 2011; Zhang et al., 2009). In complementary principle, control variables of a system such as a, b, c, and d offset each other. Hence, the control variable of a system is the average value, i.e., $x = (x_a + x_b + x_c + x_d)/4$ (Zhang et al., 2009). Conversely, control variables cannot be offset each other in case of non-complementary principle. Therefore, state variable will be the smallest value of a system, i.e., $x = \min \{x_a, x_b, x_c, x_d\}$. In this study, the complementary principle was used to compute the Catastrophe progression of each control variable.

3.5. Delineation of groundwater potential zones using AHP and Catastrophe techniques

In this study, 'rainfall', 'land use/land cover' and 'soil hydrologic group' layers were used for creating derived theme 'runoff coefficient', and hence only 'runoff coefficient', 'drainage density', 'geology', 'slope' and 'proximity to surface water bodies' layers were used to generate the groundwater potential map. All these thematic layers along with their normalized weights were integrated in ArcGIS software. The flowchart of the methodology followed for AHP, and Catastrophe techniques is shown in Fig. 2. The weights of the theme and the features of corresponding layers were aggregated in GIS using Weighted Linear Combination (WLC) method as follows:

$$GWPI = RC_{wt} \times RC_{wf} + DD_{wt} \times DD_{wf} + GL_{wt} \times GL_{wf} + SL_{wt} \times SL_{wf} + SW_{wt} \times SW_{wf} \quad (5)$$

where $GWPI$ = 'Groundwater Potential Index' for a particular polygon, RC = runoff coefficient, DD = drainage density, GL = geology, SL = slope, SW = proximity to surface water bodies, $_{wt}$ = normalized weight of a theme, and $_{wf}$ = normalized weight of the individual features of a theme.

3.6. Calculation of dynamic groundwater reserve

A new approach considering the concept of 'Dynamic Groundwater Reserve (DGWR)' has been adopted in this study for the validation of groundwater prospect zones obtained using AHP and Catastrophe techniques. DGWR indicates 'exploitable groundwater reserve' or 'utilizable groundwater reserve' and it can be estimated by averaging the long-term annual recharge under conditions of maximum groundwater use (GWREC, 1997). The dynamic groundwater reserve can be fully extracted to meet annual water demands without causing detrimental effects on the available groundwater resource and environment. The monsoon season lasts up to October and usually additional groundwater is not required for irrigation. Conversely, groundwater is extracted for irrigation during November to May of the next year as soil moisture gradually declines during this period. Therefore, the dynamic groundwater reserve (DGWR) can be estimated as follows (GWREC, 1997):

$$DGWR = (D_{WTE} - D_{WTO}) \times A \times S_y \quad (6)$$

where D_{WTE} = depth to water table in the pre-monsoon season of next year [L], D_{WTO} = depth to water table in the post-monsoon season of the current year [L], A = aquifer area of influence [L^2], and S_y = specific yield of the aquifer [fraction].

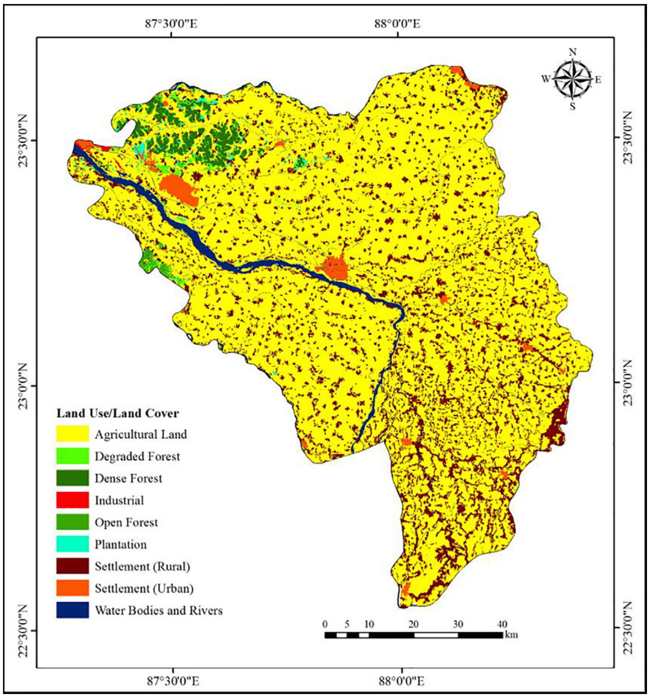

Fig. 3. Land use/land cover map of the study area.

4. Results and discussion

4.1. Thematic layers

4.1.1. Land use/land cover

Spatial distribution of land use/land cover in the study area is shown in Fig. 3. Evidently, the agricultural area occupies a major portion of the study area (77.42%) followed by settlements (16%), river and water bodies (2.81%) and dense forest (1.79%).

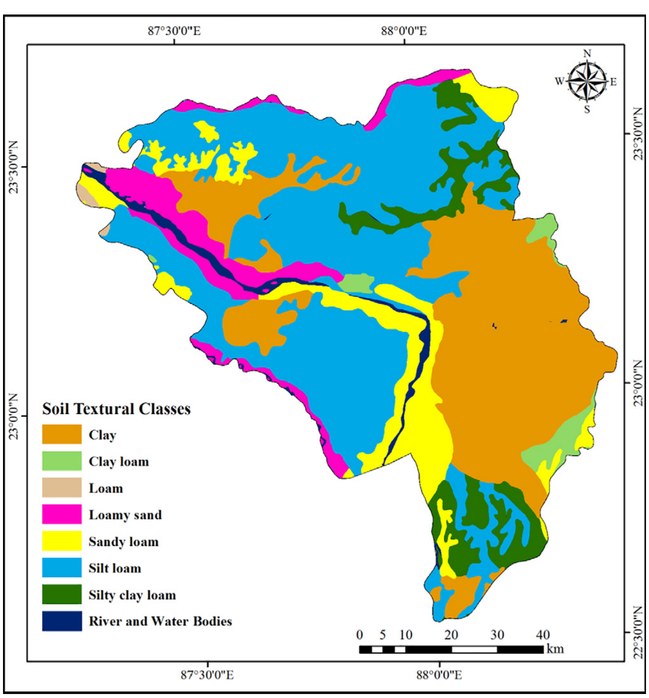

Fig. 4. Soil map of the study area.

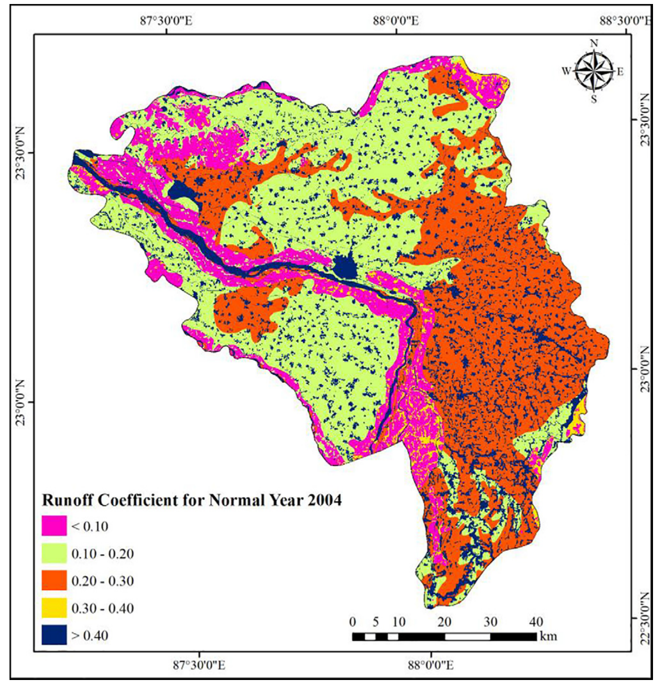

Fig. 5. Runoff coefficient map for the 'normal year'.

4.1.2. Soil

Major soil textural classes of the study area are found to be 'silt loam', 'clay' and 'sandy loam' (Fig. 4). Silt loam occupies 41% of the study area in northern, south western and southern portion of the study area. Soil textural classes such as 'clay' and 'sandy loam' occupy 31% and 11% of the study area, respectively in the western, eastern and central parts of the study area. The 'silty clay loam' texture partially occupies northern and southern portions of the command encompassing an area of 7%.

4.1.3. Runoff coefficient

As mentioned in the methodology, the runoff coefficient of the study area was estimated for the 'normal rainfall year' (2004). The runoff coefficient of the study area can be grouped into four classes: (i) 'very high' runoff coefficient (> 0.4), (ii) 'high' runoff coefficient (0.3–0.4), (iii) 'moderate' runoff coefficient (0.2–0.3), (iv) 'low' runoff coefficient (< 0.2), and (v) 'very low' runoff coefficient (< 0.1) as shown in Fig. 5. It is apparent that most of the study area falls under 'low' and 'moderate' runoff coefficient classes covering 36.6% and 31.3% of the study area, respectively. Runoff coefficient under 'very high' category covers 16% of the study area, while 'very low' runoff coefficient category covers an area of 1033.40 km^2 (13.80%). A small portion of the study area falls under 'high' runoff coefficient covering 2.3% of the study area.

4.1.4. Drainage density

Drainage density in the study area ranges from 0.01 to 4.86 $km\ km^{-2}$ (Fig. 6). The drainage density of the study area can be grouped into five classes: (a) 'very low' (< 0.25 $km\ km^{-2}$), (b) 'low' (0.25–0.50 $km\ km^{-2}$), (c) 'moderate' (0.50–0.75 $km\ km^{-2}$), (d) 'high' (0.75–1.00 $km\ km^{-2}$), and 'very high' (> 1.00 $km\ km^{-2}$). Drainage density under 'low' and 'very low' categories occupy 57.3% and 32.2%, respectively. The area under 'moderate' density category covers 558.5 km^2 (about 7.5%), while categories 'high' and 'very high' together occupy nearly 3% of the study area. Thus, the drainage density of the study area mostly falls under 'low' and 'very low' categories, thereby indicating that there is a better possibility of groundwater occurrence in these zones.

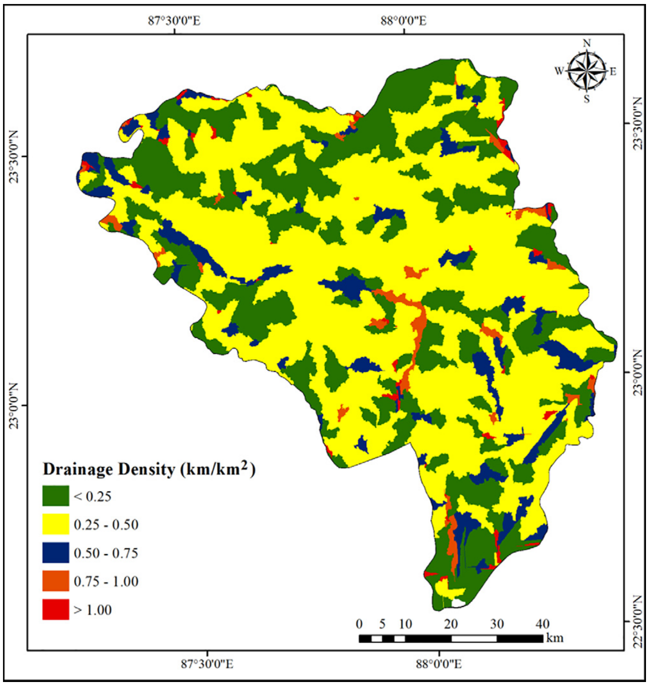

Fig. 6. Drainage density map of the study area.

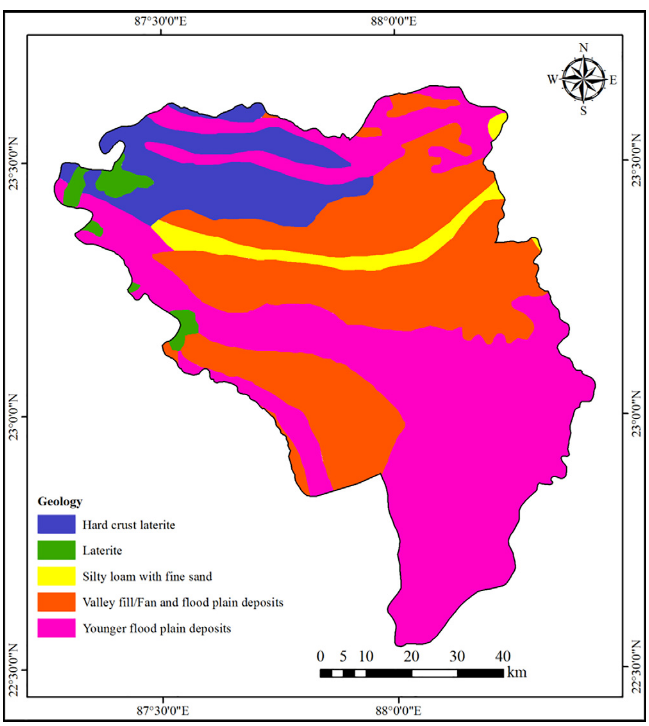

Fig. 7. Geology map of the study area.

4.1.5. Geology

Spatial distribution of major geological classes in the study area is shown in Fig. 7. Younger floodplain deposits are most widely spread in southern, northern and south western parts of the study area covering 48%. Valley fill and floodplain deposits occupy central and south western portions encompassing 35.5% of the study area. Nearly 11.5% of the study area (north-western part) is occupied by hard crust laterite. For the Catastrophe method, the properties of different features of geology were quantified based on the rainfall infiltration factor (GWREC, 1997). The values of rainfall infiltration factor for the study

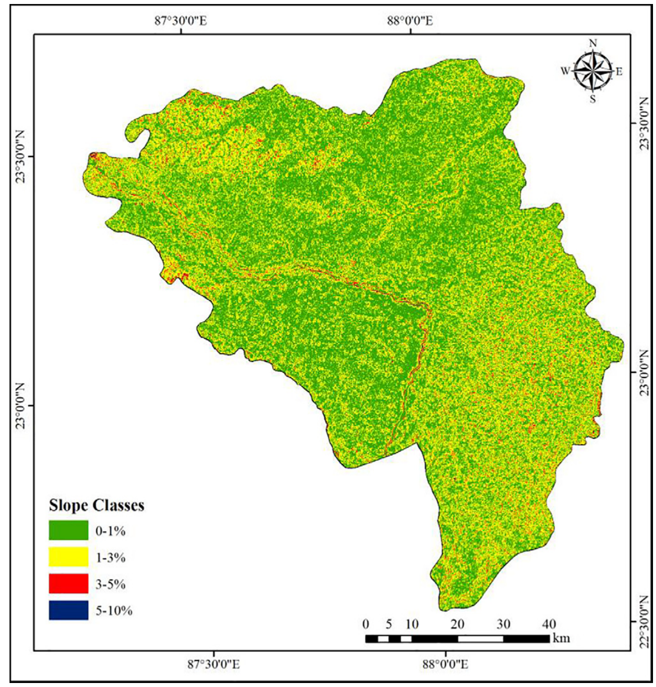

Fig. 8. Slope map of the study area.

area range from 0.065 to 0.225.

4.1.6. Slope

The topographic slope of the study area can be categorized into four classes: (a) 'nearly level' (0–1%), (b) 'gentle' (1–3%), (c) 'moderately gentle' (3–5%), and (d) 'steep' (5–10%) and their spatial distributions are shown in Fig. 8. Nearly, 58% of the study area is an under 'nearly level' category, while 'gentle' slope category covers an area of 39.5%.

4.1.7. Proximity to surface water bodies

'Proximity to surface water bodies' can be categorized into three

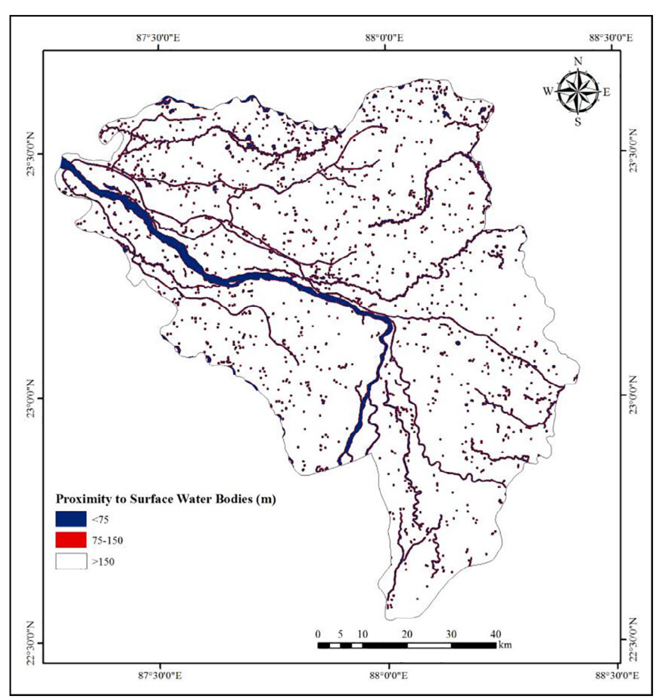

Fig. 9. Proximity to surface water bodies map of the study area.

Table 8
Assigned and computed normalized weights of the five thematic layers for the AHP-based MCDA approach.

Thematic Layer	Assigned Weight	Normalized Weight
1. Runoff Coefficient	8	0.25806
2. Drainage Density	7	0.22581
3. Geology	6	0.19355
4. Slope	6	0.19355
5. Proximity to Surface Water Bodies	4	0.12903

Table 9
Assigned and computed normalized weights of different features of the five thematic layers for the AHP-based MCDA approach.

Thematic Layer	Feature Class	Groundwater Prospect	Assigned Weight	Normalized Weight
1. Runoff Coefficient	< 0.1	Very Good	8	0.327
	0.1–0.2	Good	7	0.286
	0.3–0.2	Good	5	0.204
	0.4–0.3	Moderate	3	0.122
	> 0.4	Poor	1.5	0.061
2. Drainage Density	< 0.25 km km^{-2}	Very Good	8	0.327
	0.25–0.50 km km^{-2}	Good	7	0.286
	0.50–0.75 km km^{-2}	Good	5	0.204
	0.75–1.00 km km^{-2}	Moderate	3	0.122
	> 1.00 km km^{-2}	Poor	1.5	0.061
3. Geology	Younger Floodplain Deposits	Very Good	8	0.333
	Valley Fill and Floodplain Deposits	Good	7	0.292
	Silty Loam with Fine Sand	Moderate	5	0.208
	Laterite	Poor	3	0.125
	Hard Crust Laterite	Very Poor	1	0.042
4. Slope	0–1% (Nearly level)	Very Good	8	0.348
	1–3% (Gentle)	Good	7	0.304
	3–5% (Moderate gentle)	Moderate	5	0.217
	5–10% (Steep)	Poor	3	0.130
5. Proximity to Surface Water Bodies	< 75 m	Good	8	0.500
	75–150 m	Moderate	6	0.375
	> 150 m	Poor	2	0.125

classes: (a) < 75 m, (b) 75–150 m, and (c) > 150 m (Fig. 9). The 'proximity to surface water bodies' classes < 75 m, 75–150 m and > 150 m occupy 6.7%, 4.3% and 89% of the study area, respectively.

4.2. Groundwater potential map using AHP technique

Weights were assigned to all the five thematic layers and their features based on their influence on the occurrence of groundwater in using Saaty's 1–9 scale (Saaty, 1980). Analytic Hierarchy Process and eigenvector techniques were used to convert all the weights assigned to the thematic layers and features into normalized weights. The details of the weights assigned to all the thematic layers and their features are given in Tables 8 and 9. The consistency ratio (CR) of all the thematic layers and their feature weights were thoroughly checked and were found to be less than the threshold limit of 0.10 as recommended by Saaty (1980).

Groundwater Potential Index (GWPI) was computed by aggregating all the themes in GIS using Eq. (5), Tables 8 and 9. The study area was divided into four zones using Quantile method available in ArcGIS© software, i.e., 'very good' (GWPI > 0.25), 'good' (GWPI = 0.22–0.25), 'moderate' (GWPI = 0.18–0.22), and 'poor' (GWPI = < 0.18) groundwater potential zones (Fig. 10). About 24% of the study area shows 'very good' groundwater potential, which is dominant in the central and

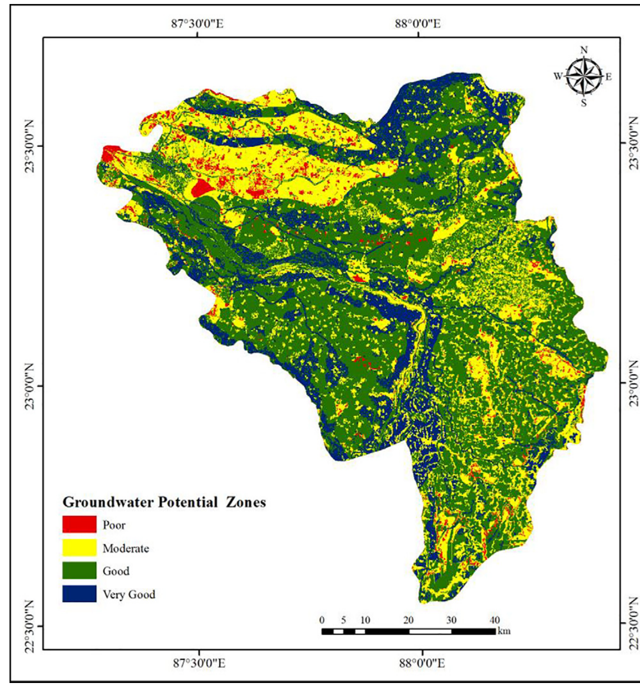

Fig. 10. Groundwater potential map of the study area using AHP-based MCDA approach.

northern portions of the study area, with some patches in the southern portion. The 'good' groundwater potential zone occupies nearly 53% of the study area except for north western portion. The 'moderate' and 'poor' groundwater potential zones respectively cover 20% and 3% of the study area. It is worth mentioning that the groundwater potential under 'good' and 'very good' categories together constitute 77% of the study area, which indicates that the study area has very good potential of groundwater. If this vital resource is judiciously exploited, it can overcome current water scarcity problems in the study area as well as can ensure dependable water supply in the future.

4.3. Groundwater potential map using Catastrophe technique

Groundwater potential index (GWPI) by the Catastrophe technique was computed using Eq. (5) and Table 10. Spatial distribution of groundwater potential zones derived using this technique is shown in Fig. 11. The Catastrophe technique content analysis is readily understandable and is easy and straight forward. Particularly, this approach does not require experts' opinion for assigning weights to the thematic features. In this case also, five thematic layers namely 'runoff coefficient', 'drainage density', 'geology', 'slope' and 'proximity to surface water bodies' were used for groundwater potential mapping. Based on the GWPI values obtained in this case, the study area was classified into four groundwater potential zones using Quantile method available in ArcGIS© software: 'very good' (GWPI > 3.31), 'good' (GWPI = 3.05–3.31), 'moderate' (GWPI = 2.52–3.05), and ('poor' (GWPI = < 2.52). Groundwater potential under 'good' category occupies nearly 48% of the study area. Nearly 25% of the study area is under 'very good' groundwater potential zone, located in the south western, south eastern, northern and central portions of the study area. 'Moderate' groundwater potential zone is found in north western and sparsely spread all over the study area to an extent of 22% and while about 5% of the study area is under 'poor' category.

4.4. Comparative evaluation of AHP and Catastrophe techniques

The results of the AHP and Catastrophe techniques revealed that the

Table 10
Weights of the different thematic layers and their features for the Catastrophe theory-based MCDA approach.

Thematic Layer	Feature Class	Groundwater Prospect	Index Value	Normalized Value	Theme Weight
1. Runoff Coefficient	< 0.1	Very Good	0.05	1.000	0.720
	0.1–0.2	Good	0.15	0.922	
	0.2–0.3	Good	0.25	0.867	
	0.3–0.4	Moderate	0.35	0.810	
	> 0.4	Poor	0.51	0.000	
2. Drainage Density	< 0.25 km km^{-2}	Very Good	0.13	1.000	0.772
	0.25–0.50 km km^{-2}	Good	0.375	0.970	
	0.50–0.75 km km^{-2}	Good	0.625	0.953	
	0.75–1.00 km km^{-2}	Moderate	0.875	0.940	
	> 1.00 km km^{-2}	Poor	2.93	0.000	
3.Geology (Specific Yield)	Younger Floodplain Deposits	Very Good	0.15	1.000	0.671
	Valley Fill and Floodplain Deposits	Good	0.12	0.916	
	Silty Loam with Fine Sand	Moderate	0.085	0.841	
	Laterite	Poor	0.03	0.599	
	Hard Crust Laterite	Very Poor	0.02	0.000	
4. Slope	0–1% (Nearly level)	Very Good	0.5	1.000	0.691
	1–3% (Gentle)	Good	2	0.923	
	3–5% (Moderate gentle)	Moderate	4	0.841	
	5–10% (Steep)	Poor	7.5	0.000	
5. Proximity to Surface Water Bodies	< 75 m	Good	37.5	1.000	0.564
	75–150 m	Moderate	112.5	0.693	
	> 150 m	Poor	150	0.000	

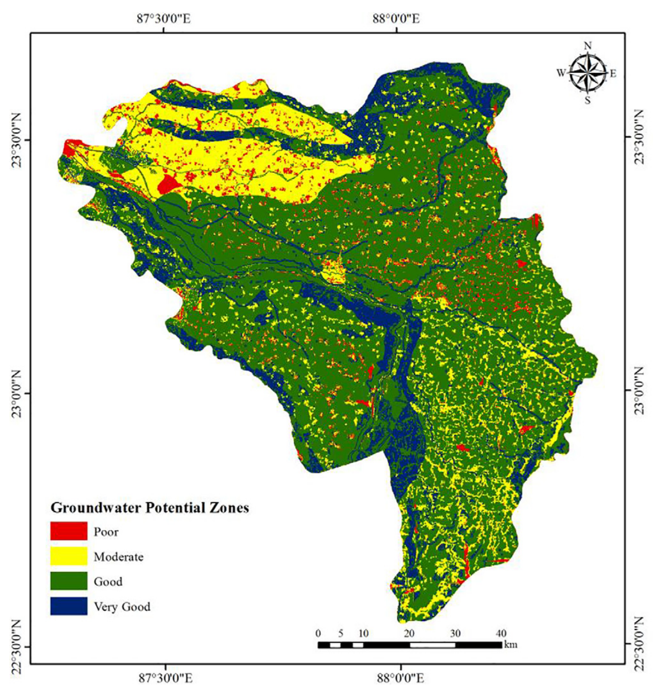

Fig. 11. Groundwater potential map of the study area using Catastrophe theory-based MCDA approach.

'good' category of groundwater potential zones is the highest among the all classes of groundwater potential zones occupying 49 and 63% of the study area, respectively (Fig. 12). The category 'moderate' follows after the 'good' category for both the techniques with areal extents of 28 and 19%, respectively. The 'very good' category covers 19% of the study area in case of AHP, while it is 14% for the Catastrophe technique. The 'poor' category is the lowest among all the classes and occupies 4% (AHP technique) and 5% (Catastrophe technique) of the study area (Fig. 12). After summing the categories of 'good' and 'very good' classes of groundwater potential, the AHP technique results in 68% of the study area and the Catastrophe technique yields 77%. Thus, both the techniques suggest that a majority of the study area has very good groundwater prospect.

4.5. Validation of groundwater potential maps

As mentioned in the methodology, in this study, a novel approach considering Dynamic Groundwater Reserve (DGWR) was used for validating groundwater potential zones identified by AHP and Catastrophe techniques. The Dynamic Groundwater Reserves of the study area computed using field data were grouped into four classes as shown in Table 11. Out of the total number of observation wells, 4.1% of the wells fall under 'poor' DGWR, 51.2% of the wells under 'moderate' DGWR, 33.3% of the wells are in 'good' category of DGWR, and the remaining 11.4% of the wells are in the 'very good' category. The location-specific dynamic groundwater reserve of the study area was overlaid on the groundwater potential maps obtained by the AHP and Catastrophe techniques, and each well was evaluated for its potential concerning groundwater potential (GWP) zones/classes identified by these two techniques.

Evaluation of dynamic groundwater reserves for 123 locations (observation wells) located within the study area was carried out as shown in Table A1 (Appendix A). Nearly 101 and 91 wells are found to match with the groundwater potential (GWP) zones yielded by AHP and Catastrophe techniques, respectively (Appendix A). Thus, the accuracy of groundwater potential mapping by the AHP technique is 82% and that by the Catastrophe technique is 74%. Based on the validation results, it can be inferred that both AHP and Catastrophe techniques are capable of delineating groundwater potential zones with reasonably high accuracies, though the performance of the AHP technique is superior to that of the Catastrophe technique. Nevertheless, the Catastrophe technique is relatively easy to apply as well as it avoids subjectivity in assigning weights and eliminates the necessity of consulting experts for weights and their subsequent processing as required for the application of AHP technique. The groundwater potential zone maps generated in this study can provide guidelines for the cost-effective selection of suitable locations for the extraction of groundwater in the study area. Also, the identification of groundwater potential zones is useful to optimal conjunctive use planning for the efficient utilization of available groundwater and surface water resources in the study area.

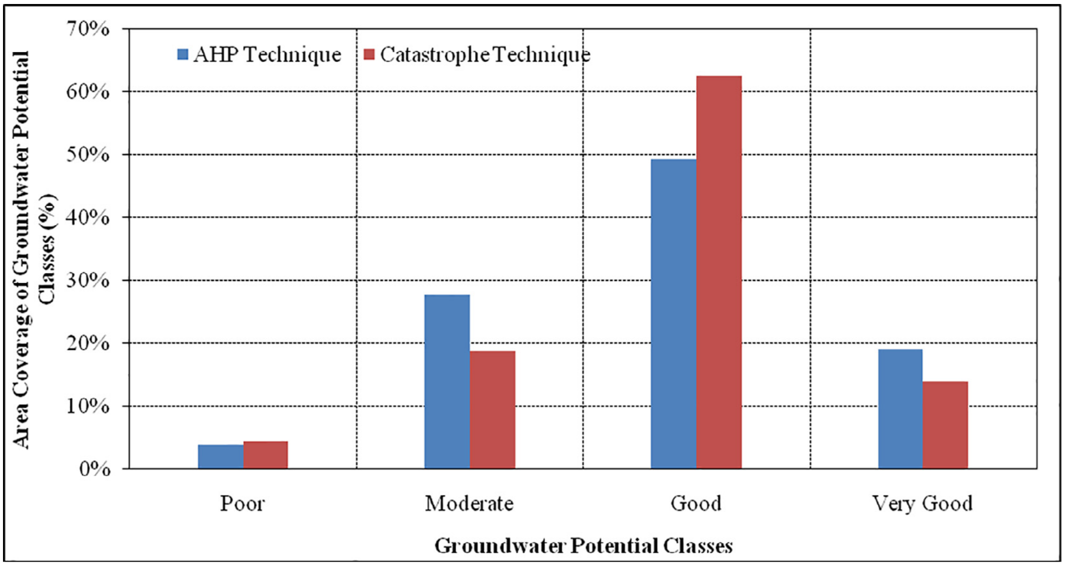

Fig. 12. Comparative evaluation of the results yielded by AHP and Catastrophe techniques.

Table 11
Classification of 'Dynamic Groundwater Reserve' in the study area.

Groundwater Prospect Class	Annual Dynamic Groundwater Reserve
1. Poor	< 30
2. Moderate	30–60
3. Good	60–90
4. Very Good	> 90

5. Conclusions

This study deals with the performance assessment of two different GIS-based Multi-Criteria Decision Analysis (MCDA) approaches namely commonly used 'Analytic Hierarchy Process (AHP)' and an emerging technique 'Catastrophe Theory' for mapping groundwater potential in a Canal Command of Eastern India. Unlike past studies, derived thematic layer 'runoff coefficient' and other pertinent thematic layers such as 'drainage density', 'geology', 'slope' and 'proximity to surface water bodies' were used for delineating groundwater potential zones. In the AHP-based MCDA approach, the weights of themes and their features were assigned according to the Saaty's AHP theory, while in the case of Catastrophe theory-based MCDA approach, the index value of the features were computed according to the Catastrophe theory. Finally, the validation of the results obtained by these GIS-based MCDA techniques was carried out using a novel approach. Based on the results of this study, the following conclusions are drawn:

1. The groundwater potential zones delineated by the AHP technique are: (a) 'very good' (covering 19% of the study area), (b) 'good' (49%), (c) 'moderate' (28%), and (d) 'poor' (4%).
2. The groundwater potential zones delineated by the Catastrophe technique are: (a) 'very good' (covering 14% of the study area), (b) 'good' (63%), (c) 'moderate' (19%), and (d) 'poor' (5%).
3. The validation of the results of AHP and Catastrophe techniques revealed that the AHP technique has an accuracy of 82%, whereas the Catastrophe technique has an accuracy of 74%. Thus, the performance of the AHP technique is fairly superior to that of the Catastrophe technique.
4. Overall, it can be inferred that although both the GIS-based MCDA approaches are suitable for groundwater potential mapping with a reasonable accuracy, the implementation of the Catastrophe technique is relatively easy and it is free from subjectivity in assigning weights to the themes and their features.

Several techniques exist for the identification of groundwater potential zones using geospatial techniques and Multi-Criteria Decision Analysis (MCDA). However, cost-effective, simpler but scientifically sound and reliable approaches are required for their adoption by field engineers and water managers. In this study, GIS-based AHP and Catastrophe techniques were found to have greater prediction capability, and they are easy to use and cost-effective. The methodology demonstrated in this study can be easily replicated in other parts of the Indian subcontinent as well as in other regions of the world. The findings of such studies provide valuable information for water planners/managers and decision makers for the sustainable management of dwindling groundwater resources. Finally, the efficacy of emerging GIS-based MCDA techniques needs to be rigorously evaluated under different hydrologic, agro-climatic and hydrogeologic conditions before adopting it as a universal solution tool for real-world water problems.

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Appendix A.

Table A1

Table A1
Comparison of AHP and Catastrophe results with the Dynamic Groundwater Reserves (DGWR) of 123 locations over the study area.

Sl. No.	Location	Latitude	Longitude	DGWR Class	GWP Classes Obtained by Catastrophe Technique	GWP Classes Obtained by AHP Technique
1	Udaynarayanpur	22.625246	88.008976	Good	Good	Good
2	Arambag B.D. Office	22.888120	87.785230	Good	Good	Good
3	Mandra, Plot of Gautam Mukherjee	22.932430	87.785300	Good	Good	Good
4	Arambagh Pz	22.870153	87.790948	Moderate	Moderate	Moderate
5	Ausgram –I	23.474955	87.679424	Moderate	Moderate	Moderate
6	Ramnagar ARS (3W-D)	23.458000	87.550000	Moderate	Moderate	Moderate
7	Barddhaman I	23.459266	87.618647	Poor	Poor	Poor
8	Ausgram –II	23.500761	87.512372	Moderate	Moderate	Moderate
9	Balagarh	23.063301	88.379041	Good	Good	Good
10	Near H/o G. Sutradhar, Pratappur(15)/ Ronale jora	23.442000	87.291000	Poor	Poor	Poor
11	Barabelun Bus Stand	23.409267	87.981950	Moderate	Moderate	Moderate
12	Bhatar Seed Farm	23.403667	87.919467	Moderate	Moderate	Moderate
13	Gramdihi Samity	23.412950	87.788767	Moderate	Moderate	Moderate
14	Kaluttak F.P. School	23.448200	87.904617	Moderate	Moderate	Moderate
15	Karjona High School	23.356350	87.890400	Moderate	Good	Good
16	Kubajpur F.P. School	23.364567	87.979700	Moderate	Moderate	Moderate
17	Kulnagar F.P. School	23.403250	87.941000	Poor	Poor	Poor
18	Nutangram F.P. School	23.399917	87.895767	Moderate	Moderate	Moderate
19	Orgram High School	23.435600	87.763700	Moderate	Poor	Moderate
20	Salkuni F.P. School	23.448383	87.797600	Moderate	Moderate	Moderate
21	Sripur F.P. School	23.464483	87.844217	Moderate	Moderate	Moderate
22	Parhat F.P. School	23.337000	87.868000	Moderate	Moderate	Moderate
23	Mahinagar F.P. School	23.357900	87.797533	Moderate	Moderate	Moderate
24	Bhatar	23.396815	87.868052	Moderate	Moderate	Moderate
25	Bidchala F.P. School	23.272083	87.845467	Good	Good	Good
26	Burdwan DM Office (North)	23.239583	87.869950	Moderate	Moderate	Moderate
27	Bhandardi G.P.O.	23.351283	88.022383	Moderate	Poor	Moderate
28	Kamalpur khalpar FP	23.213050	87.825283	Good	Good	Moderate
29	Burdwan – II	23.265203	87.847128	Moderate	Poor	Moderate
30	Barsul B.D.O. Office	23.183467	87.961200	Moderate	Poor	Moderate
31	Natu G.P. office	23.168033	87.942850	Good	Good	Good
32	Haripur F.P. School	23.175017	87.929233	Good	Good	Good
33	Amra	23.208672	87.949501	Moderate	Good	Moderate
34	Burdwan – I	23.223777	87.943125	Very Good	Good	Good
35	Janai Pz (chanditala)	22.713279	88.243740	Very Good	Very Good	Very Good
36	Kumirmora1	22.696929	88.227869	Good	Good	Moderate
37	Aknapur Pry. School	22.906630	88.048850	Good	Very Good	Good
38	Dhanikhali	22.970767	88.100281	Moderate	Good	Good
39	Jotbehar Primary School, (102) (New)	23.074498	87.639613	Very Good	Good	Good
40	Khosbag bus stop	23.160232	87.603464	Good	Good	Good
41	Kharsi. High School(7)	23.074368	87.751784	Very Good	Good	Very Good
42	Mondalpur	23.049454	87.706532	Good	Good	Good
43	Jagatballavpur	22.679420	88.117028	Moderate	Moderate	Moderate
44	Masagram High School	23.120600	88.028250	Moderate	Good	Good
45	Mahisgaria F.P. School	22.989267	88.035950	Good	Good	Moderate
46	Haibatpur	23.149779	87.991052	Very Good	Very Good	Very Good
47	Purba Mallickpur P. Sch.	22.782130	88.146050	Very Good	Good	Very Good
48	Chanditala-II	22.703861	88.171352	Good	Good	Good
49	Simlon F.P. School	23.278700	88.249869	Good	Good	Good
50	Kalna – I	23.256930	88.240404	Moderate	Good	Moderate
51	Kaigaria F.P. School	23.146617	88.341167	Good	Good	Good
52	Kalna –II	23.146758	88.269429	Good	Good	Good
53	Durgapur Barage	23.485992	87.312067	Moderate	Good	Good
54	Kanksa	23.470880	87.454446	Moderate	Moderate	Poor
55	Kanksa	23.489005	87.435508	Moderate	Moderate	Moderate
56	Nanagar	23.630950	88.095383	Good	Good	Good
57	Srikhanda Farm	23.605000	88.068617	Good	Good	Good
58	Karajgram F.P. School	23.573333	88.140283	Good	Good	Good
59	Dainhat Municipility	23.611111	88.165833	Good	Very Good	Good
60	Kaithan1	23.515776	88.087153	Very Good	Good	Good
61	Katwa Town	23.637053	88.095397	Very Good	Very Good	Very Good
62	Benga F.P. School	23.591200	88.187767	Good	Good	Moderate
63	Karui Nutangram School	23.532533	88.115267	Moderate	Moderate	Moderate
64	Induti	23.072778	87.777944	Good	Moderate	Moderate
65	Nutanhat Farm	23.533350	87.905800	Good	Very Good	Very Good
66	Jhilu F.P. School	23.543150	87.934117	Moderate	Moderate	Moderate
67	Bhalurgram F.P. School	23.586517	88.001383	Moderate	Moderate	Moderate
68	Kaichar F.P. School	23.545062	87.998262	Moderate	Moderate	Moderate
69	Majigram Bus Stand	23.588250	87.976278	Good	Good	Good
70	Kalyanpur High School	23.533967	87.851367	Good	Good	Good
71	Boinchi F.P. School	23.589733	88.036417	Moderate	Moderate	Moderate
72	Balarampur Sub Center	23.554217	88.040667	Moderate	Moderate	Moderate

(*continued on next page*)

Table A1 (*continued*)

Sl. No.	Location	Latitude	Longitude	DGWR Class	GWP Classes Obtained by Catastrophe Technique	GWP Classes Obtained by AHP Technique
73	Koichor	23.544234	87.999665	Moderate	Moderate	Moderate
74	Mulgram F.P. School	23.365000	88.085517	Moderate	Poor	Moderate
75	Piplon Library	23.355583	88.141700	Moderate	Moderate	Moderate
76	Madhayamgram Society	23.305550	88.139300	Moderate	Poor	Moderate
77	Barandala F.P. School	23.359633	88.187550	Moderate	Moderate	Moderate
78	Kulut F.P. School	23.405300	88.150750	Moderate	Moderate	Poor
79	Monteswar BDO	23.416267	88.108683	Moderate	Poor	Moderate
80	Monteswar BDO	23.416111	88.108611	Moderate	Poor	Moderate
81	Lohar sibtala	23.449033	88.100550	Moderate	Poor	Moderate
82	Manteswar	23.369253	88.114996	Moderate	Good	Good
83	Purbasthali – I	23.432995	88.207645	Good	Good	Moderate
84	Palla Road	23.175333	88.007567	Moderate	Good	Moderate
85	Block Office Memari-I	23.181933	88.094483	Moderate	Moderate	Moderate
86	Amodpur G.P. Office	23.200500	88.091767	Good	Good	Good
87	Ajhapur I	23.140637	88.053392	Moderate	Moderate	Moderate
88	Ajhapur	23.140741	88.049673	Moderate	Moderate	Moderate
89	Kuchut High School	23.249817	88.047967	Moderate	Good	Moderate
90	Kaleswar F.P. School	23.257100	88.056083	Moderate	Moderate	Moderate
91	Bohar Hospital	23.270100	88.193167	Moderate	Moderate	Moderate
92	B.D.O. Office Paharhati	23.252317	88.097667	Moderate	Moderate	Poor
93	Khanyan B.U.S. Pathagar	23.049380	88.319830	Good	Good	Good
94	Pandua P.W.D.Ins.Bunglow	23.079070	88.278650	Moderate	Moderate	Good
95	B. M. Health Centre	23.112830	88.220120	Good	Good	Good
96	Bhopur Pry. Health Centre	23.140820	88.206550	Moderate	Moderate	Moderate
97	Pirgram Pry. School	23.146670	88.221830	Moderate	Moderate	Poor
98	Jamna G.P.O.	23.150220	88.231080	Good	Good	Good
99	Iisoba-Mandlai High School	23.094830	88.319380	Moderate	Moderate	Moderate
100	Dumurdaha Angenwari School	23.049400	88.319830	Moderate	Moderate	Good
101	Singarkone II	23.151139	88.232134	Good	Good	Good
102	Pandua	23.083905	88.283600	Moderate	Moderate	Moderate
103	Khanyan	23.048827	88.315387	Poor	Poor	Poor
104	Pandua	23.054593	88.228979	Good	Good	Good
105	Agri. Farm(Alipore Stn), Betur(78)	23.184654	87.575325	Moderate	Moderate	Moderate
106	Patrasayer(stn)	23.189404	87.545147	Moderate	Moderate	Moderate
107	Patrasayer	23.232839	87.538297	Good	Good	Good
108	Polba2	22.936160	88.352684	Moderate	Good	Moderate
109	Dihibandhpur H. Centre	22.890620	87.939900	Very Good	Very Good	Very Good
110	Bhangamore Pry. School	22.943430	87.959280	Good	Good	Moderate
111	Soaluk Azad Jr.P. School	22.926180	87.945000	Good	Good	Good
112	Kelepara Pry. School	22.910020	87.943200	Very Good	Good	Very Good
113	Keshab Chak G.P.O.	22.889550	87.968150	Good	Good	Good
114	Raina – I	23.084683	87.858697	Good	Good	Good
115	Uchalon GPO, Dommara	22.996200	87.777850	Good	Good	Good
116	Chabukpur Pry. School	23.016972	87.925306	Very Good	Good	Very Good
117	Raina – II	22.966837	87.844442	Good	Good	Good
118	Atisara Saratv Smriti Sangha	22.824030	88.262120	Good	Good	Good
119	Gopal Prasadpur	22.838874	88.239937	Very Good	Very Good	Very Good
120	Dhansimla Level Crossing (151)	23.267926	87.464585	Poor	Good	Poor
121	Jaynagar Pry. School	22.857970	88.042480	Very Good	Very Good	Very Good
122	Dhalyan Pry. School	22.892266	87.998601	Very Good	Very Good	Very Good
123	Tarakeswar	22.878590	88.014302	Moderate	Good	Moderate

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