



Delineation of zones and sites for artificial recharge of groundwater in dry land Barind Tract, Bangladesh using MCDM technique in GIS environment

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Received: 23 May 2021 / Accepted: 2 August 2022 / Published online: 23 August 2022
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Abstract

The present study has been carried out in the dry land Barind Tract, NW Bangladesh to delineate the potential zones for artificial recharge of groundwater and to assess scope for establishing sites for rainwater harvesting (RWH) and runoff water conservation to revert ever depleting groundwater resource through construction of check dam, managed aquifer recharge (MAR) model, percolation tanks, etc. using multi-criteria decision making (MCDM) approach in GIS environment to have a sustainable groundwater resource management plan. The Tract possesses dendritic drainage patterns which indicate scope for loss of major portion of runoff water with less infiltration to recharge the groundwater having its less potentiality for occurrence, but represents good category for surface water conservation. The semi-permeable or poor permeable surface soil lithology (Barind Clay) is less favorable for groundwater recharge, and here, lineament and slope are the most influencing factor for its recharge mechanisms. Here, about 65% of the area falls under ‘moderately suitable’, 1% area under ‘highly suitable’ and about 34% area has unsuitability for artificial recharge of groundwater. The artificial recharge structures like check dams have suggested only for the ‘moderately’ and ‘highly’ suitable zones, and that of artificial recharge through injection well by the MAR and percolation tanks are suggested as only option for the ‘unsuitable’ zone in this dry land. Finally, the present study provides a guideline to water managers, planners and decision maker in this dry land to ascertain availability of water resource that meet community demand through the Integrated Water Resource Management as lauded in the Bangladesh Water Act (2013).

Keywords Artificial groundwater recharge · Zones · Sites · MCDM · GIS · Barind Tract · Bangladesh

Introduction

Water resource management remained at the core of sustainable development in the 1992 Rio World Summit on the United Nations Conference on Environment and Development (UNCED). Thus, this resource must be managed and developed on a sustainable basis. The National Water Management Plan (NWMP) in Bangladesh has considered drought as a major water deficiency issue in the dry land Barind Tract in the country’s northwestern part (Fig. 1)—the

granary where livelihood is at risk more severely when monsoon is curtailed due to loss of food production, scarcity in drinking water, etc. The elevation of the Tract varies from 25 to 47 m above mean sea level (AMSL). The total population is 1,436,980 (average population density: 923 persons/km²) over 2318 km² geographical areas. Generally, the area considered as semiarid lies in the monsoon- and summer-dominant hemisphere. The climate is usually warm and humid. Based on rainfall, humidity, temperature, and wind pressure, the weather condition is classified as pre-monsoon dry summer; monsoon rainy days; and winter cold and dry. The rainfall is comparatively less with an average being about 1410 mm lower than the national average of 2550 mm that mainly (84%) occurs during the monsoon. This area has been designated as drought prone, with its annual average temperature ranges from 25 to 35 °C in the hottest season and 9–15 °C in the coolest season. Therefore,

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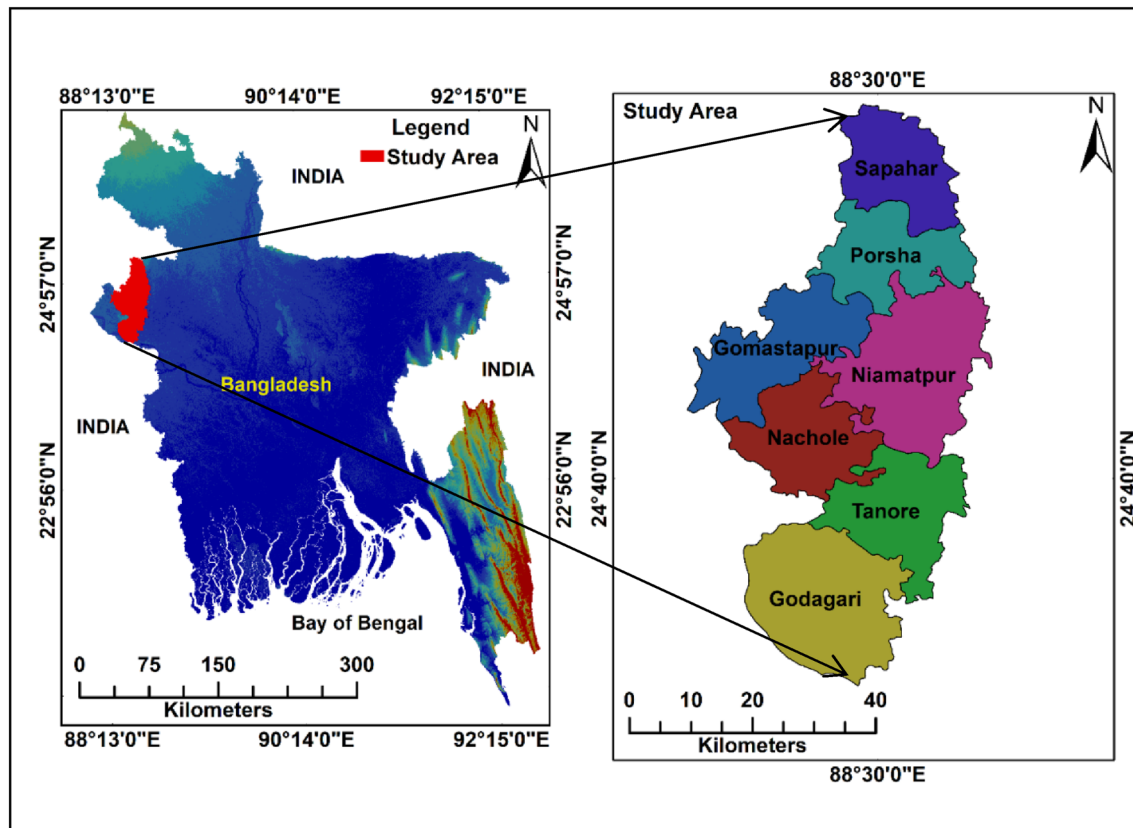


Fig. 1 Location map of Barind Tract in the Northwestern part of Bangladesh

the Tract experiences extremes that are clearly in contrast to the climatic condition of rest of the country (Banglapedia 2003).

The Tract is covered with Clay-silt layers (Barind Clay) of semi-impervious nature of Recent–Pleistocene age with thickness 8.0–47.5 m (average 19.5 m) and is underlain by potential water bearing horizon or aquifer of very fine to medium-coarse sand texture of Plio-Pleistocene of 3.0–42.5 m. The study area possesses mainly single aquifer with multiple nature only in the southeastern and partly northern corner (BAEC 1989). Morgan and McIntire (1959) stated that the Tract is one of the older uplifted Pleistocene terraces in the Bengal basin, and physiographically, the dissected Tract is surrounded by floodplains of rivers of Purnabhaba, Mahananda, Atrai and Padma (Ganges) with number of perennial streams/canals (*Kharies*) along with a number of stream and inter stream deposits (recent sediments). The exposed Pleistocene deposits in the Tract are known as the Barind Clay and are underlined by thick coarser sediments of the Early Pleistocene to Late Paleocene comprising aquifer zone. The Barind Clay is hydrogeologically semi-impervious, and is composed of Clay-silt aquitard [low infiltration rate: 1–2 mm/day (UNDP 1982) having a thickness 8.0–47.5 m] of semi-impervious nature. The aquifer system

is single to multiple layered (two–three) of Plio-Pleistocene age (thickness: 5.0–42.5 m) (Jahan et al. 2007) having suitability mostly for drinking and household purposes and limited scope for irrigation uses (Jahan and Ahmed 1997). The thickness of the Barind Clay horizons and depth of piezometric surface indicate the presence of groundwater pressure-head in most places of the Tract. The major aquifer system is structure-controlled, and several faults and fractures around the Tract influence the groundwater flow directions and create boundary condition for aquifers in the area.

As the demand of groundwater irrigation increases day by day along with meteorological and agricultural drought intensity, the stress on this resource increases and becoming acute due to its over-exploitation with the extension of irrigated agriculture. The recent declining trend of the piezometric surface is at higher rate than earlier, and after 2002–2004, GWT did not return to its original level (Jahan et al. 2021). Moreover, the changing climatic scenario along with yearly irregular frequency and intensity of rainfall makes it difficult for planned water resource. Therefore, there is an urgent need of management of water resources in the area for the sustainability of livelihood and ecosystem.

However, there is a huge scope to study on water resource management issues especially in developing countries where

water resources for agriculture is at risk due to unplanned development, low economic capacity to solve the problems, and lack of adaptation measures. As a result, the ecosystems are falling at fragile condition that would become irrecoverable without taking action at right time. Therefore, water resource management and abstraction planning have been assessed in the present study by delineating groundwater recharge zones and artificial recharge sites to formulate an efficient groundwater management plan using a MCDM approach in GIS environment. Finally, this study will help to identify the scope for RWH sites including suggestions for construction of water conservation structures like cross/check dam and Managed Aquifer Recharge (MAR) facilities for efficient groundwater management in the dry land Tract.

Concepts and methodology

Five thematic layers namely geomorphology, lithology, drainage density, slope and aquifer transmissivity were taken into consideration to delineate artificial recharge zones, and different features/classes of the individual themes have been identified and weights have been assigned according to their relative importance in groundwater recharge in the area following the Saaty’s Analytic Hierarchy Process (AHP) (Saaty 1980).

The plan for water conservation measures based on satellite images and several watersheds or drainage basins of different stream order have identified. Ten watersheds (watersheds I, II, III, IV, V, VI, VII, VIII, IX and X) (Fig. 2) have been taken into consideration because of their higher (1st–6th) order such as I–III and V–VI, and that 1st–5th orders in watershed VII–X. For analyzing morphometric parameters of the watersheds, topographical sheets from the Survey of Bangladesh (SoB) are geometrically rectified and then geo-referenced using the Universal Transverse Mercator (UTM) coordinator system projection and the World Geodetic System (WGS84) datum considering the Ground Control Points (GCPs). Using data preparation option of Erdas Imagine Software, the watershed areas are delineated from SRTM-DEM and topographical sheets of SoB. Accordingly, Landsat 8 Satellite (December, 2016) image is used to produce and update the drainage maps, slope of the watersheds using Spatial Analyst Tool of ARC GIS 10.5.

In the present study, lithology as parent material of soil has considered as an important factor. Here, geomorphological data are extracted from USGS, and slope values are obtained from SRTM-DEM using spatial analyst tool. The drainage map is prepared using toposheets of SoB and DEM from which drainage density is determined by spatial analyst tool. Here, all analyses are rectified and then geo-referenced by Universal Transverse Mercator (UTM) coordinate

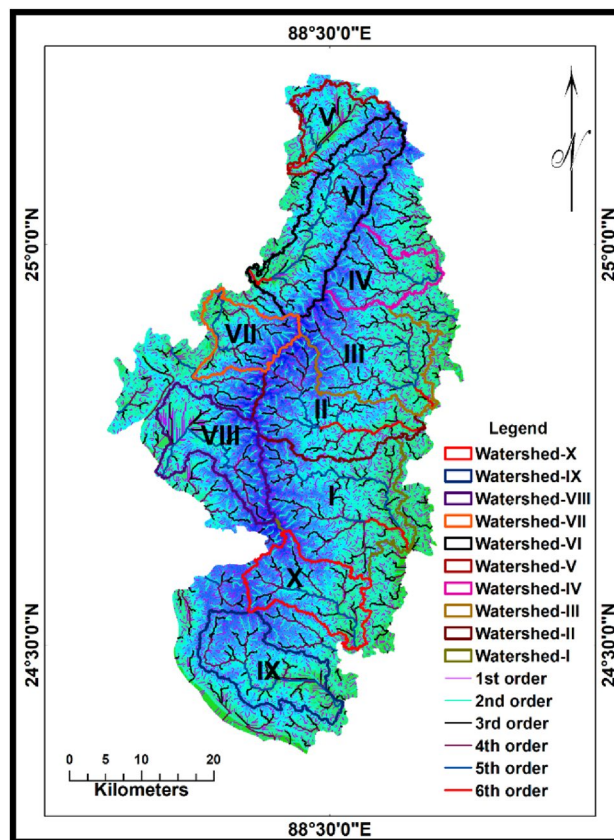


Fig. 2 Drainage map along with studied watersheds and stream order in the study area

Table 1 Weights of the five thematic layers used for artificial recharge

Themes	Assigned weight (%)	Normalized weight
Geomorphology	30	0.30
Lithology	22	0.22
Drainage density	15	0.15
Slope	23	0.23
Aquifer transmissivity	10	0.10

projection and the World Geodetic System (WGS84) datum considering the Ground Control Points (GCPs).

Based on hydrogeologic significance in artificial groundwater recharge, weights of the five thematic layers (geomorphology, lithology, drainage density, slope and aquifer transmissivity) are 30, 22, 15, 23 and 10%, respectively (Table 1). The weights to different thematic maps and their features have assigned on Saaty’s nine point scale (1–9) based on relatives influences on groundwater condition. Qualitative evaluation of the scale has done on the basis of higher the weight more the influencing theme or features. The normalization

process reduces the subjectivity associated with the assigned weights of the thematic maps and their features. The pairwise comparison matrix for the five themes and calculations of normalized weights by the Saaty’s analytic hierarchy process is shown in Table 2. The normalized weights of different individual themes are also calculated and shown in Table 3. To demarcate groundwater recharge zones, all five thematic layers after assigning weights have been integrated (overlaid) step by step using ArcMap 10.5 software.

GWPI has been calculated using weighted linear combination method (Malczewski 1999) given by the following equation:

$$GWPI = \sum_{j=1}^m \sum_{i=1}^n (W_j \times X_i), \tag{1}$$

where GWPI is the groundwater potential index, L is the lithology, GM is the geomorphology, DD is the drainage, SL is the slope, AT is the aquifer thickness, X_i is the normalized weight of the i th class/feature of the theme and W_j is the normalized weight of the j th theme, m is the total number of themes, and n is the total number of classes in a theme.

Table 2 Pair-wise comparison for the five themes and calculation of normalized weights by Saaty’s AHP

Themes	Themes					Geometric mean	Normalized weight
	GM	L	DD	Slope	AT		
GM	30/30	30/22	30/15	30/23	30/10	1.61	0.30
L	22/30	22/22	22/15	22/23	22/10	1.18	0.22
DD	15/30	15/22	15/15	15/23	15/10	0.80	0.15
Slope	23/30	23/22	23/15	23/23	23/10	1.23	0.23
AT	10/30	10/22	10/15	10/23	10/10	0.54	0.10
Total						5.35	1.00

Table 3 Assigned and normalized weights for individual features of themes for artificial recharge zoning

Themes	Feature	Recharge prospect	Assigned weight	Normalized weight
Geomorphology	Smooth plain	Very good	5	0.33
	Irregular plain	Good	4	0.27
	Moderately irregular plain	Moderate	3	0.2
	Highly irregular plain	Poor	2	0.13
	Very highly irregular plain	Very poor	1	0.07
Lithology	Alluvial sand	Good	5	0.42
	Water marshy clay	Moderate	4	0.33
	Marshy clay	Poor	2	0.17
	Barind Clay Residuum	Very poor	1	0.08
Slope (%)	0–3	Very good	5	0.42
	> 3–8	Good	4	0.33
	> 8–15	Moderate	2	0.17
	> 15–22	Poor	1	0.08
	Drainage density	0.0–0.58	Very good	5
0.58–1.17		Good	4	0.27
1.17–1.75		Moderate	3	0.2
1.75–2.45		Poor	2	0.13
2.45–3.11		Very poor	1	0.07
Aquifer transmissivity, m ² /day	< 500	Poor	2	0.13
	500–1000	Moderate	3	0.2
	1000–1500	Good	4	0.27
	> 1500	Very good	5	0.33

Similarly, to calculate groundwater recharge index (GWRI), selected thematic maps overlaid into GIS software and GWRI has been calculated using the following equation.

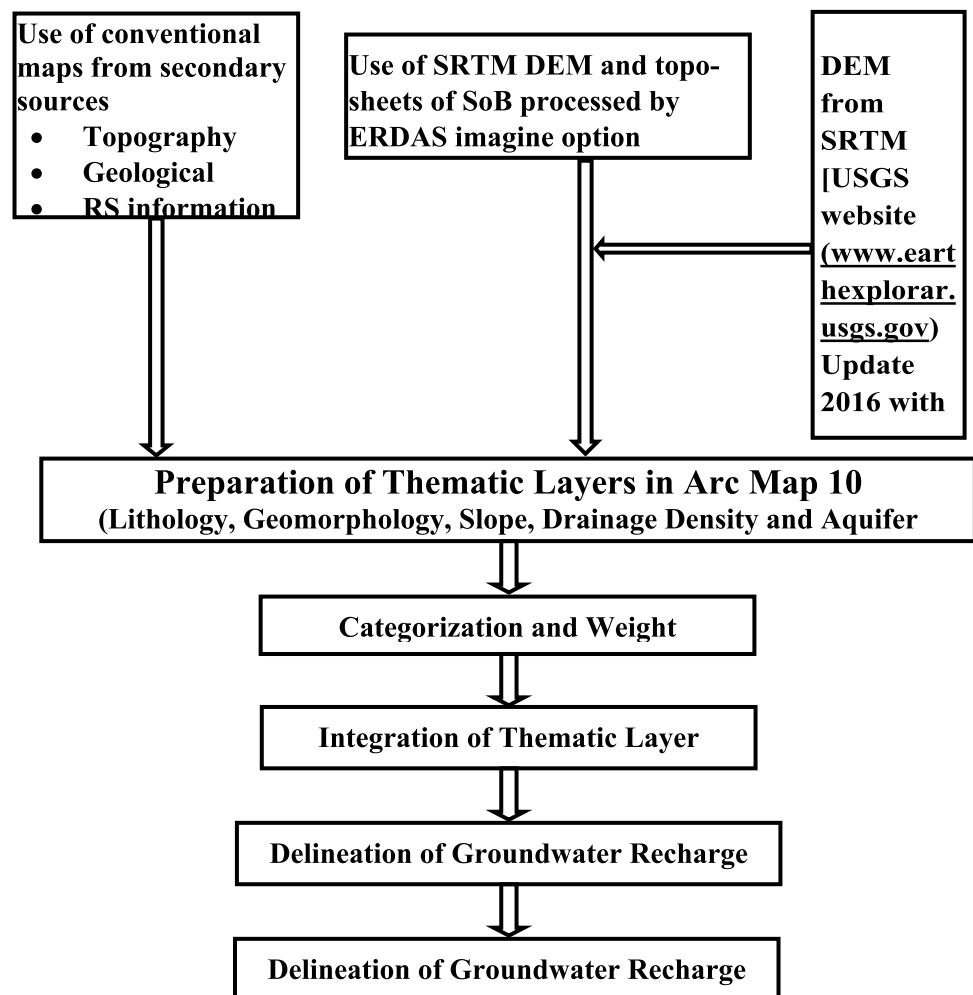
The whole normalized weights of distinctive polygons in the integrated layer had been derived from the following equation to calculate the groundwater recharge index (GWRI) and have been given in the following equation:

$$GWRI = (L_w L_{wi} + GM_w GM_{wi} + DD_w DD_{wi} + SL_w SL_{wi} + AT_w AT_{wi}), \quad (2)$$

where GWRI is the groundwater recharge index, L is the lithology, GM is the geomorphology, DD is the drainage density, SL is the slope, AT is the aquifer transmissivity, 'w' is the normalized weight of a theme, and 'wi' is the normalized weight of the individual elements of a theme.

Finally, all these thematic layers have been integrated using weighted overlay of Arc Map 10.5. In addition, a lineament map of the area has been prepared by the factor enhancement of the Landsat ETM+ panchromatic band (band 8) using Geomatica 2016 and Arc Map 10.5. A drainage map of the Tract with a 100 m buffer around the second and third-order streams was also prepared. Strahler's system of stream ordering (Strahler 1957) has been used in which the smallest fingertip tributaries have been designated as 1st order and when two first-order channels join, a channel segment of 2nd order is formed (and so on). These thematic maps have been used for the selection of possible artificial recharge sites check dam, MAR, percolation tanks in the study area. The flowchart of methodology for identification of artificial recharge zones and sites in the present study is shown in Fig. 3.

Fig. 3 Flowchart of methodology for identification of artificial recharge zones and sites in present study



Results and discussion

The watersheds exhibit dendritic drainage pattern with homogenous subsurface strata. The values of the stream order (W) varies from 1st to 6th orders for watersheds where the 1st order streams have maximum total length of the stream segment and decreases as the stream order increases. The drainage map exhibiting stream order of the studied watersheds is shown in Fig. 2. Calculated values of drainage density (DD) in major part of watersheds range from 1.0 to 3.0 indicating presence of surface lithology of poor permeability in drainage course, and favor poor to less potentiality for groundwater resource, and favors poor to less potentiality for groundwater percolation and accumulation. Relationship between top soil lithology and hydrological analysis of watersheds reveal coarse drainage density and generally represent semi-permeable or poor permeable surface soil lithology with moderate vegetation. The drainage density map of the watersheds is shown in Fig. 4.

In the Tract, the east-facing slope is comparatively less hot as it gets sun light before noon than that of west-facing slope with warmer climatic condition. Therefore, it has major effects on the distribution of vegetation type in the

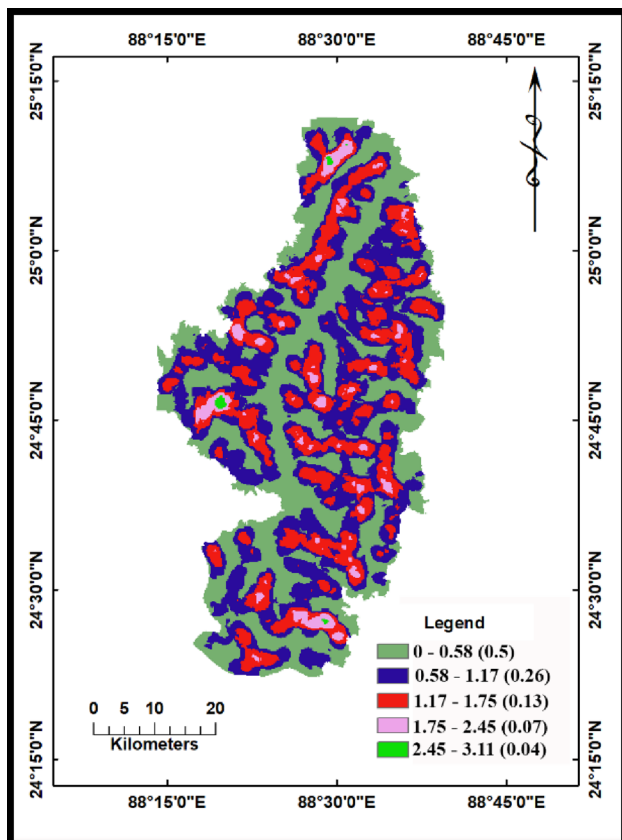


Fig. 4 Drainage density map with stream order in the study area

watershed area. Major part of the watersheds come under flat to gentle slope with undulating nature and can be classified as ‘good’ category (Berhanu et al. 2013) for its relevance for water resource management. If the surface runoff is conserved in *Kharies* (Canals) which will favor the infiltration capacity with maximum time of percolation of runoff water. Therefore, the watershed has good potentiality for construction of check dams, rubber dam, percolation tank, artificial recharge for groundwater, etc. The slope map of the study area is given in Fig. 5.

Geomorphologically, highly irregular to irregular plain (Fig. 6) in the Tract has less influence in occurrence of groundwater (Dey 2014). The Tract possess sub-dendritic drainage pattern and are normally characterized through a tree-like branching system with less homogeneity and uniformity. Here, the drainage pattern indicates scope of loss of major component of runoff water with less infiltration capacity of surface soil to recharge the groundwater and suggests that the area has less potentiality for groundwater occurrence and development.

The Barind Clay as top most lithological unit mostly covers the Tract, followed by alluvial sand, marshy clay, water bodies, etc. Based on the hydraulic properties, the lithological classes are ranked as: alluvial sand > water marsh clay > marshy clay > Barind Clay. Lithology map and rates for lithological classes in the area are shown in Fig. 7. The

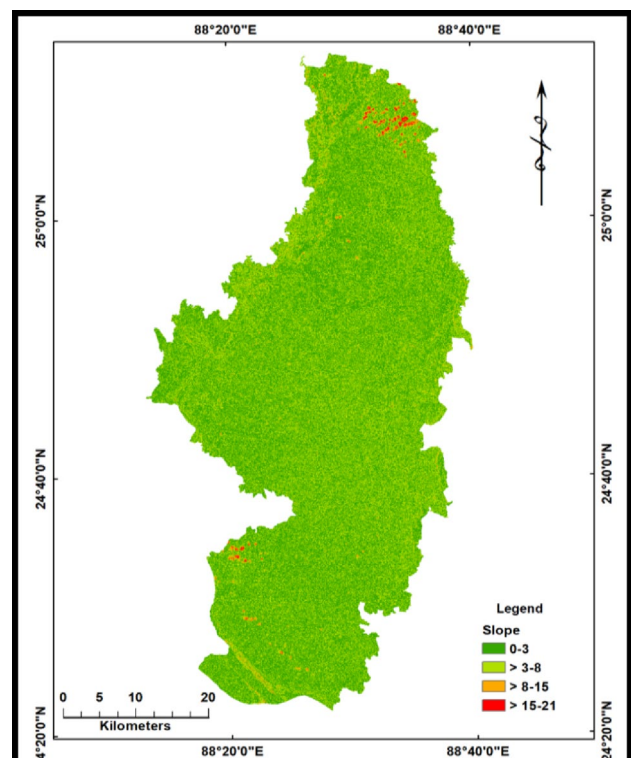


Fig. 5 Slope map of the study area

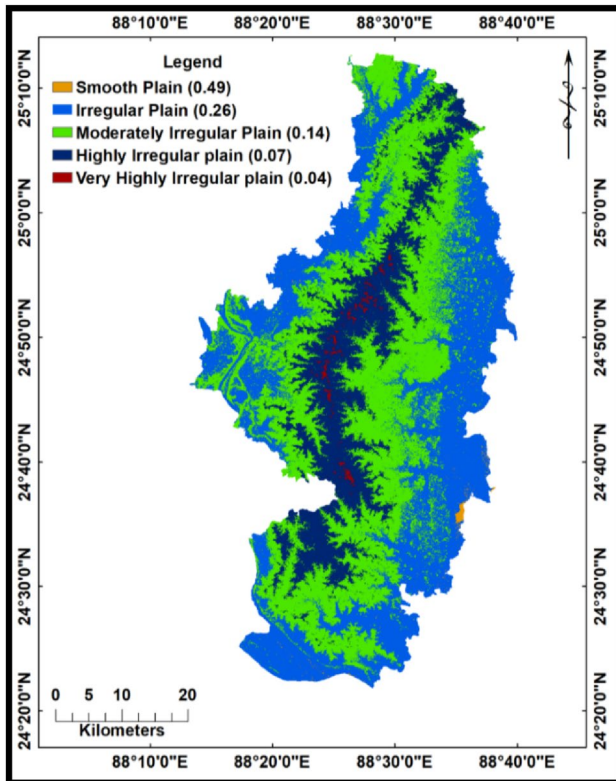


Fig. 6 Geomorphological map of the study area

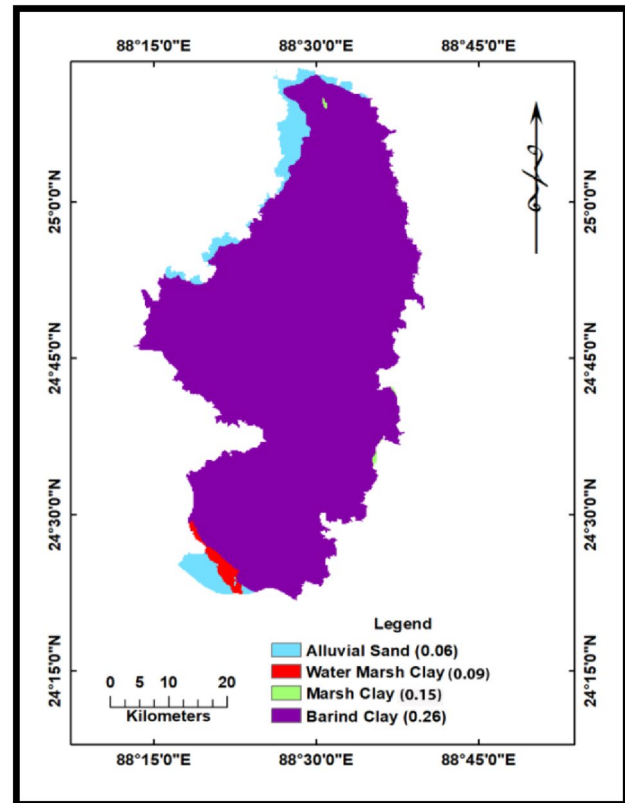


Fig. 7 Lithological map of the study area

aquifer properties such as hydraulic conductivity (K) and specific yield (S) values in the area as obtained from pumping test results (Jahan and Ahmed 1997) are 12–56 m/day and 0.06–0.30, respectively.

Lineament density map is computed from lineaments produced through factor enhancement of the Landsat ETM+ panchromatic band (band 8) and varies from 0.00 to 0.017 km/km². Based on totally identical classification (Sener et al. 2005; Hammouri et al. 2012), the lineament density map is classified into five categories (Fig. 8). The part of the Tract has a slope value of 0–8% representing flat to gentle and cannot be distinct as so ‘top’ category for groundwater occurrence because of less favorable infiltration ability of top soil with admire to time of percolation of runoff water on the alternative aspect. As the major part of the Tract comes under cultivated land, the agricultural practice needs support for groundwater abstraction and its sustainable management. According to Hasan (2021), groundwater potential (GP) zonation map of the Tract has classified as 15 km² (2%)—high; 91 km² (4%)—moderate; 1826 km² (77%)—poor; and 405 km² (17%)—very poor class of GP. Therefore, from the statistics of map-removal sensitivity analysis and statistics of single-parameter sensitivity analysis, it is evident that lithology, lineament and slope are the most influencing factor for GP, and where lineament density

is high, GP is also high and vice-versa. On the other hand, in case of lithology, area with Barind Clay shows poor GP (Hasan, 2021).

The artificial groundwater recharge zonation map was prepared using 5 thematic layers namely lithology, geomorphology, drainage density, slope and aquifer transmissivity. The transmissivity values (Jahan and Ahmed 1997) vary from 259 to 2228 m²/day, and accordingly based on these transmissivity values the Tract has classified as ‘Low’ (< 500 m²/day), ‘Moderate’ (500–1000 m²/day) and ‘High’ (> 1000 m²/day) as shown in Fig. 9. The contour map for the period of 1980–2019 mean pre-monsoon (represented by May month) depth of piezometric surface over the Barind Tract ranges from 16 to 18 m bgl, and that of mean post-monsoon ranges from 4 to 8 m bgl. Thus, there is a considerable seasonal fluctuation of depth of piezometric surface in the study area. The map generated through superimposing artificial groundwater recharge (AGR) zone map, drainage map of 2nd- and 3rd-order streams and lineament map with a 100-m buffer helped to detect favorable sites (crossing of 2nd- and 3rd-order streams and lineament) for check dam. This is also true for the unsuitable area in the central part of the area. As far as the artificial recharge structures are concerned, primarily check dams are advocated at the recognized sites for artificial recharge in the study area. Since

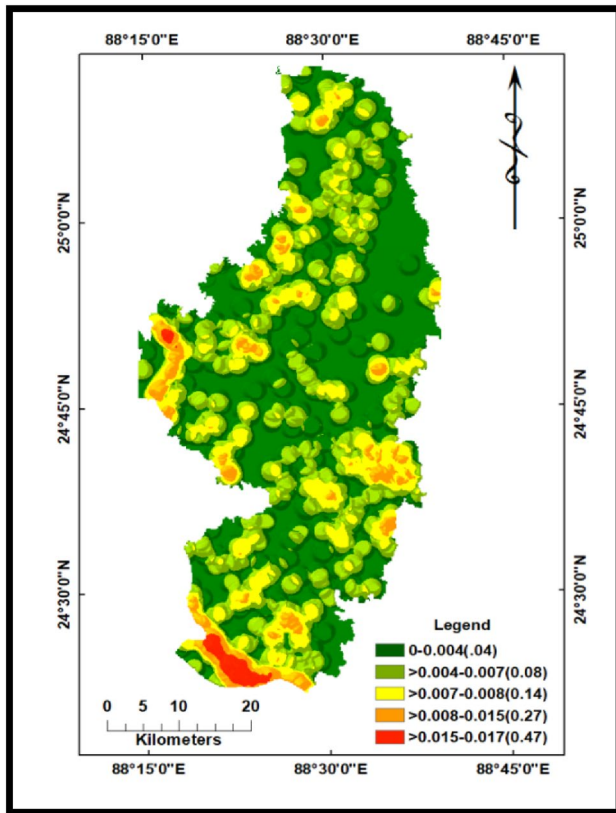


Fig. 8 Lineament density map of the study area

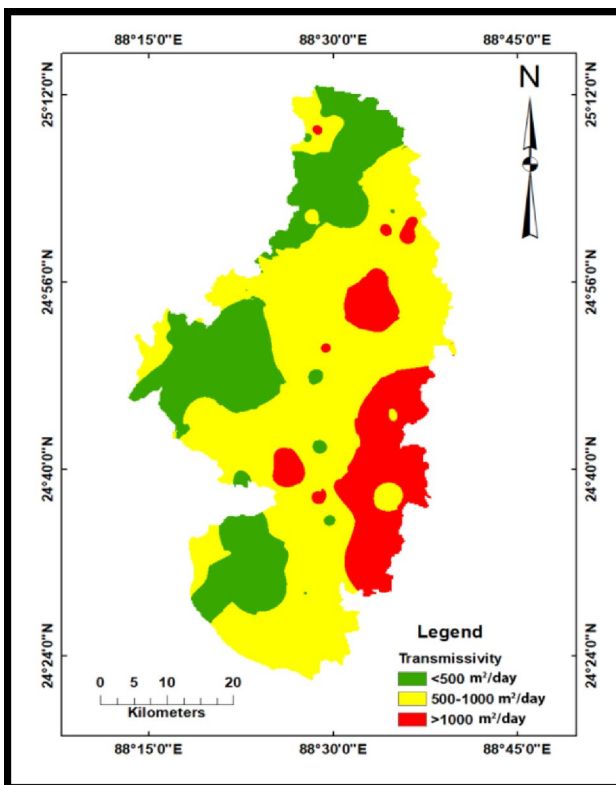


Fig. 9 Thematic layer of aquifer transmissivity of the study area

the lineaments frequently act as good conduits for ground-water flow coupled with relatively permeable stream beds, the endorsed check dams in suitable and may be unsuitable AGR zones are anticipated to assist recharge the aquifer of the Barind Tract.

After acquiring the normal weights of all five thematic layers based on hydrological significance (geomorphology, lithology, drainage density, slope and aquifer transmissivity), and the elements of individual thematic layers, all the thematic layers have been integrated with one another using Arc Map 10.5 software in order to demarcate artificial recharge zones in the Tract. In the first step, the geomorphology layer has integrated with the geology layer. The weight of every polygon of the integrated layer has derived by including the weights of polygons of these two layers. This manner has continued for the final three thematic layers to achieve a final integrated layer. In the second step, the ultimate normalized weights of each polygon in the final integrated layer have been derived through summing up the normalized weights of polygons from individual layers, and the highest derived sum of the normalized weights in the final integrated layer has divided into three equal classes, as a consequence dividing the whole study area into three artificial groundwater recharge zones, viz., the ‘highly suitable’ zone having a groundwater recharge index (GWRI) value of higher than 0.5, ‘moderately suitable’ zone (GWRI=0.25–0.5) and ‘unsuitable’ zone (GWRI < 0.25), and accordingly, the zonation map of artificial recharge has been obtained (Fig. 10). Flat topography (slope = 0–2%), higher depth of pre-monsoon piezometric surface, suitable geomorphologic (smooth to irregular plain) elements which are existing in the element of highly suitable to moderately suitable zones in the Tract supply favorable stipulations for groundwater recharge, thereby making the area suitable for artificial recharge. About 65% of the area falls beneath the ‘moderately suitable’ zone, 1% area falls beneath the ‘highly suitable’ groundwater recharge zone and about 34% area is unsuitable for artificial recharge of groundwater. The unsuitability of this portion for artificial recharge is in agreement with the available geology, geomorphology and slope. The thickness of the Barind Clay—a semi-impervious layer and depth of piezometric surface indicate presence of pressure-head, and represents semi-confined aquifer in the Tract. 39-year (1980–2019) mean pre-monsoon (represented by May month) depth of piezometric surface over the study area reveals that the depth varies from 16 to > 18 m in major portion. On the other hand, the mean post-monsoon (represented by October month) depth of piezometric surface reveals that the depth varies in major portion of the area 6 to > 12 m. On the other hand, the Tract is covered by Clay-silt layer (Barind Clay) of semi-impervious nature with average thickness of 19.5 m and thickness by potential water bearing aquifer. Moreover, there is a considerable seasonal

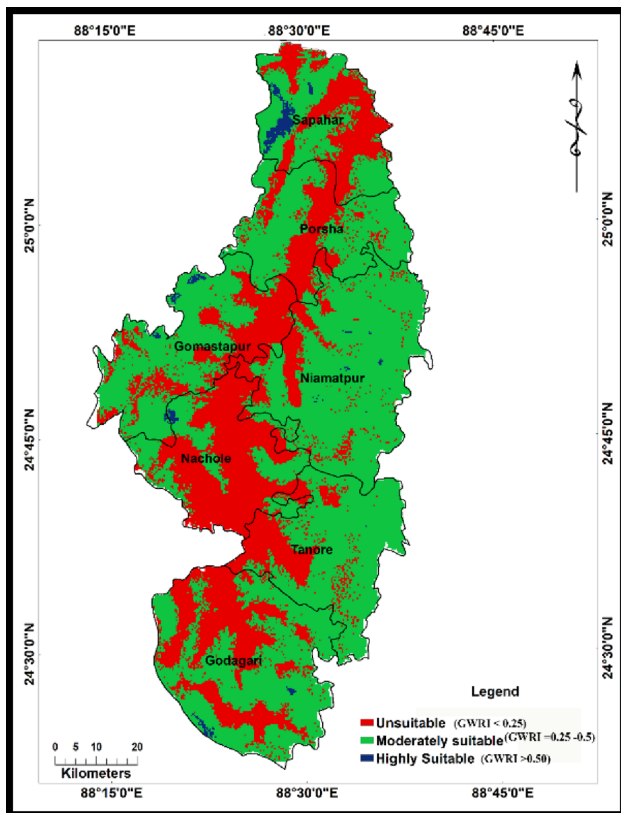


Fig. 10 Artificial recharge zone map of the study area

fluctuation of piezometric surface over the Tract. Therefore, it may be said that the area has been indicating available scope for artificial recharge.

Moreover, the identified “moderately suitable” artificial recharge zone has deep pre-monsoon groundwater level, i.e., > 14 m. Relatively high depth of piezometric surface in this zone suggests favorable sites for artificial recharge indicating greater availability of dynamic groundwater storage during the non-monsoon (dry) period. However, suitable water harvesting structures will be required for artificial recharge operations during the post-monsoon period. The average post-monsoon depth to piezometric surface in majority of the area is between 4 and 10 m which indicate available scope for artificial recharge even after the monsoon season.

For identification of AGR sites in the Tract, the drainage map with a 100-m buffer around the 2nd- and 3rd-order streams and the lineament map with a 100-m buffer around them have been superimposed on the AGR zonation map. The areas where the drainage line intersects with the lineament lines are regarded as favorable sites for AGR. The Barind Clay in the study area has semi-impermeable aquitard having thickness of 8.0–47.5 m where sites for check dams identified are not favorable. Areas with a thin layer of Clay could also be identified as site

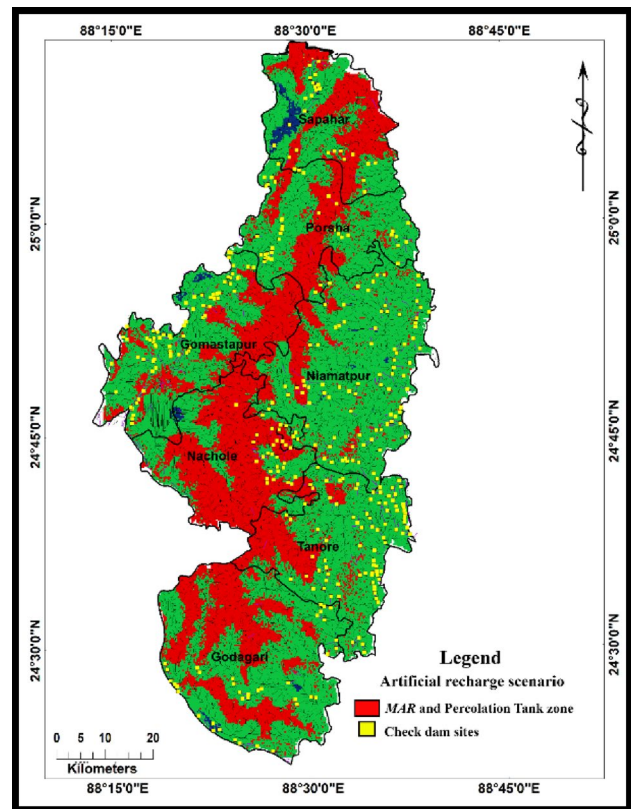


Fig. 11 Favorable artificial recharge scenarios in the study area

for check dams. Thus, the recognized potential sites for AGR in the Tract have been presented in Fig. 11. As far as the artificial recharge structures are concerned in the context of AGR recognized sites, primarily check dams (permanent or semi-permanent types), percolation tanks and rain/runoff injected recharge facilities such as MAR are advocated in the area. MAR is the purposeful recharge of water to aquifers for subsequent recovery or environmental benefit. Normally, this is achieved through injection wells, infiltration basins and galleries for rainwater, storm water, reclaimed water, mains water and water from other aquifers that is subsequently recovered for all types of uses (Dilon et al. 2009). On the other hand, the percolation tank is an artificially created surface water body so that surface runoff is made to percolate and recharge the ground water storage. Since the lineaments frequently act as good conduits for groundwater flow coupled with relatively permeable stream beds, the endorsed check dams are anticipated to assist recharge the aquifer of the area. It is anticipated that the check dams would prevent the water flowing down to join the greater order streams. The area where there are very few drainage and where lineament not crossing the second- and third-order stream are considered as favorable artificial recharge sites for MAR model and percolation tank.

Conclusions

- The integrated approach of RS and GIS with MCDM approach of the Tract has given the time saving and cost-effective results. The area possesses dendritic drainage patterns and represents good category for surface water conservation with scope for groundwater recharge due to the variation of slope of the studied watersheds. The coarse drainage density represents semi-permeable or poorly permeable surface soil lithology. The major part of the elongated watersheds has flat to gentle slope offering long time for infiltration as flatter peak of runoff water flow prevail for longer duration. The drainage pattern in the area indicates scope of loss of major portion of runoff water with its less infiltration to recharge the groundwater, and indicating as less potentiality for groundwater occurrence and development. The surface lithology is characterized mostly by Barind Clay being less favorable for groundwater recharge, and here lineament and slope are the most influencing factor for its recharge mechanisms.
- Regarding the AGR potentiality of the concern, 1% of the area falls under the 'highly suitable', 65% area under the 'moderately suitable', and 34% area under 'unsuitable' zones. The suitability map for artificial recharge sites suggests locations for artificial recharge structures like check dams (permanent or semi-permanent types) in the 'moderately suitable' and 'highly suitable' zones of the Tract. Artificial recharge structures like MAR facilities and percolation tanks are suggested for the 'unsuitable' zones as the only option. However, the precise area and techno-economic feasibility of such recharge structures have to be found out via detailed field investigations.
- Despite the inherent limitations of MCDM approach using GIS in RS environment, it is a valuable practical tool for the areas/regions (especially developing countries) where data scarcity (in terms of quantity and quality) is often an obstacle for solving real-world water problems minimizing time, labor and money.

References

- BAEC (Bangladesh) (1989) A study on aquifer condition and groundwater quality of the Barind in Rajshahi, Institute of Nuclear Science and Technology, Atomic Energy Establishment, Ganakbari, Savar, Dhaka
- Banglapedia (2003) National encyclopedia of Bangladesh. Asiatic Society of Bangladesh, Dhaka
- Berhanu B, Melesse AM, Seleshi Y (2013) GIS-based hydrological zones and soil geo-database of Ethiopia. *CATENA* 104:21–31
- Dey S (2014) Delineation of ground water prospect zones using remote sensing, GIS techniques—a case study of Baghmundi development block of Puruliya district, West Bengal. *Int J Geol Earth Environ Sci* 4(2):62–72 (ISSN: 2277-2081 (online))
- Dilon P, Gale I, Contreras S, Pavelic P, Evans P, Ward I (2009) Managing aquifer recharge and discharge to sustain irrigation livelihoods under water scarcity and climate change. In: IAHS & IAH conference, Hyderabad, India, vol 330. IAHS-AISH Publication, pp 1–12
- Hammouri N, El-Naqa A, Barakat M (2012) An integrated approach to groundwater exploration using remote sensing and geographic information system. *J Water Resour Prot* 4:717–724
- Hasan, T.M. (2021) Study on Groundwater Resource Potentiality and Prospect of Artificial Groundwater Recharge in Barind Tract, Bangladesh: A Multi-criteria Decision Making Approach in GIS Environment, MS Thesis (Unpublished), University of Rajshahi, Bangladesh
- Jahan CS, Ahmed M (1997) Flow of groundwater in the Barind area, Bangladesh: implication of structural framework. *J Geol Soc India* 50:743–752
- Jahan CS, Islam MA, Mazumder QH, Asaduzzaman M, Islam MM, Islam MO, Sultana A (2007) Evaluation of depositional environment and aquifer condition in the Barind area, Bangladesh, using gamma ray well log data. *J Geol Soc India* 70:1070–1076
- Jahan CS, Rahaman MF, Mazumder QH, Hossain MI (2021) MAR model: a blessing adaptation for hard-to-reach livelihood in thirsty Barind Tract, Bangladesh. In: Mukerjee (ed) *GLOBAL GROUNDWATER source, scarcity, sustainability, security and solution*. Elsevier Publications
- Morgan JP, McIntire WG (1959) Quaternary geology of the Bengal Basin, East Pakistan and India. *Geol Soc Am Bull* 70:319–342
- Saaty TL (1980) *The analytic hierarchy process*. McGraw-Hill, New York
- Sener E, Davraz A, Ozcelik M (2005) An integration of GIS and remote sensing in groundwater investigations: a case study in Burdur, Turkey. *Hydrogeol J* 13(5–6):826–834
- Strahler AN (1957) Quantitative analysis of watershed geomorphology. *Trans Am Geophys Union* 38:913–920
- UNDP (United Nations Development Programme) (1982) *Groundwater survey: the hydrogeological conditions of Bangladesh, united nations development programme (UNDP), technical report DP/UN/BGD-74-009/1*, New York, p 113

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