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Delineating the groundwater potential zones in Bangladesh

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ABSTRACT

The objective of this research is to identify groundwater potential zones for Bangladesh. Fourteen influential factors associated with topography, geology and meteorological concerns were applied for this study. Weights for factors and sub-factors within a factor were calculated based on pairwise comparisons. The groundwater potential zones were delineated through GIS-based weighted overlays of factor maps. According to the pairwise comparison, the consistency ratios for factors and sub-factors were within the allowable range (i.e., less than 0.10). General soil type (eigenvalue 0.17), geology (eigenvalue 0.16), and geomorphology (eigenvalue 0.15) were the most important factors in determining groundwater potential zoning. The groundwater potential index has maximum and minimum values of 45.99 and 10.34, respectively. According to the groundwater potential map, relatively higher groundwater potential zones were found in the southern parts of Bangladesh and along major rivers. The study's findings will be useful to government authorities in making evidence-based decisions about national water policy and planning.

Key words: analytical hierarchical process, Bangladesh, GIS, groundwater, remote sensing

HIGHLIGHTS

- The research attempts to identify the groundwater potential zones of Bangladesh.
- Fourteen factors associated with topography, geology and meteorological conditions were considered.
- General soil type, geology and geomorphology were the most influential factors for explaining groundwater potential zoning.
- The southern part of Bangladesh and the areas close to the major rivers have relatively higher groundwater potential.

1. INTRODUCTION

Although Goal-6 of the Sustainable Development Goals (SDGs) outlined by the UN in 2015 stresses the importance of clean water and sanitation, practically all the SDGs are related to water in some way or other (Bhattacharya & Bundschuh 2015). With the water-energy-climate-food-ecosystem nexus becoming increasingly and far more intricately intertwined than ever before, efficient management of finite water resources is and will continue to be vital for realizing these goals in the coming years. This has been manifested in the UN resolution declaring 2018–2028 as the International Decade for Action on 'Water for Sustainable Development' (Water Action Decade 2018). However, the global trend of rapid urbanization and industrialization owing to population growth coupled with the effects of climate change are putting excessive stress on the existing sources of both surface and groundwater around the world. Apart from the water that is stored as ice, groundwater is the world's greatest freshwater source and accounts for one-third of the global consumption of freshwater (Bovolo *et al.* 2009; Famiglietti 2014; Gorelick & Zheng 2015). Nevertheless, poor management of groundwater has led to detrimental effects including deterioration of water quality, subsidence of water level and lower yield of crops (Wagner 1995; Schoups *et al.* 2006; Praveena *et al.* 2012).

Bangladesh is blessed with a relatively wider range of water sources due to its riverine nature and tropical climate. Despite having challenges like arsenic, iron, manganese and microbial contamination (Saha *et al.* 2019; Quino Lima *et al.* 2021), groundwater is considered safer to drink than surface water (Singh *et al.* 2012). Nevertheless, the country faces acute water crisis throughout the year, especially during the dry season, due to over-extraction of groundwater, unchecked surface water pollution, impacts of climate change induced disasters and salinity intrusion, among others (Abedin *et al.* 2019; Hadi 2019). Moreover, increased human activities including deforestation, escalated agricultural practice and developmental activities leading to more impervious surfaces have only served to aggravate the situation (Peace Research Institute Oslo 2013). As a result, a huge proportion of the population is regularly being exposed to the vulnerabilities associated with water scarcity and degrading quality of available water. Hence the necessity of identifying potential groundwater sources and their efficient management cannot be overemphasized.

The conventional techniques used to map groundwater potential zones are predominantly dependent on ground surveys which are typically expensive and time demanding (Israil *et al.* 2006; Jha *et al.* 2010, 2007; Arulbalaji *et al.* 2019). According to a plethora of literatures, there are various probabilistic models such as frequency ratio (Ozdemir 2011; Razandi *et al.* 2015), multi-criteria decision analysis (Chowdhury *et al.* 2008; Mukherjee *et al.* 2013), certainty factor (Razandi *et al.* 2015), logistic regression (Pourghasemi & Beheshtirad 2015), artificial neural network model (Lee *et al.* 2012), decision tree (Chenini & Ben Mammou 2010), Shannon's entropy (Naghibi *et al.* 2015), and machine learning models (e.g. random forest (RF), maximum entropy (ME)) (Rahmati *et al.* 2016) which are in practice to map and delineate groundwater, potential zones. Again, to see the trend and variation in spatial distribution of groundwater, different spatial clustering and geostatistical techniques (e.g. Moran's I, LISA cluster, Gi statistics) have been employed around the world (Chaudhuri & Ale 2014; Saha *et al.* 2019; Ijumulana *et al.* 2020; Quino Lima *et al.* 2021). Among them GIS and remote sensing techniques are increasingly being used to locate, delineate, and portray groundwater potential zones (see for example, Srinivasa Rao & Jugran 2003; Magesh *et al.* 2012; Ghorbani Nejad *et al.* 2017; Al-Djazouli *et al.* 2020; Saravanan *et al.* 2020) for fast and effective estimation of natural resources and geospatial data in a cost effective manner before opting for any meticulous and expensive surveying methods (Lambrechts & Sinha 2016). This study delineated groundwater potential zones integrating the Analytical Hierarchy Process (AHP) and geospatial techniques together. AHP is considered to be a powerful instrument for dealing with complex decision-making, related to groundwater regime. This tool is used to break down complicated decisions into multiple pairwise comparisons and synthesize the findings afterward. Additionally, there is room for a consistency check of the findings to eliminate any further bias in the decision-making process (Fatti 1989).

The groundwater potential is influenced by a variety of topographical factors, and various studies employed a varied set of factors linked to topography, hydrology, soil, and so on (Kaur *et al.* 2020; Pal *et al.* 2020). The researches related to groundwater potential mostly addressed a region, a river basin or an administrative part of a country. However, studies attempting to identify, delineate and map groundwater potential zones at a nation-wide scale are rare. This research aimed to identify groundwater potential zones for Bangladesh. Fourteen influential factors related to topography, geology and meteorology were used for zoning groundwater potential. A knowledge-based multi-criteria technique with GIS coupled with AHP method was used for identifying and mapping the groundwater potentiality of Bangladesh. To the best of the authors' knowledge, national level study on groundwater potential zones in the context of Bangladesh is rare and, hence, the findings of this research will be beneficial for government officials for evidence-based decision-making regarding national water policy and planning.

2. METHODS & MATERIALS

Bangladesh was the focus of the study, which applied mostly secondary data from relevant institutions, such as the Geology Survey of Bangladesh for geological and soil data, the United States Geological Survey for topography and land use/land cover data, and the Bangladesh Meteorological Department for meteorological data. A knowledge-based multi-criteria technique was central to investigate the potential groundwater zones in Bangladesh. AHP is a multi-criteria technique (Saaty 1977; Saaty 1987) that is applied in this research. For the analysis of groundwater potential zones, 14 factors were taken: (a) six topographic factors (i.e., slope, roughness, curvature, drainage density, Topographic Wetness Index (TWI) and Topographic Position Index (TPI)), (b) four geological factors (i.e., geology, geomorphology, general soil type and lineament density) and (c) four land use and meteorological factors (land use/land cover, rainfall, temperature and relative humidity).

AHP links substantial and insubstantial aspects in order to produce a ratio and abstract scale of priorities, which is needed to arrive at complex decision-making where data availability is limited (Al Khalil 2002; Sólnes 2003). Given this fact, this study developed pairwise comparison matrices for both factors and sub-factors under each factor. Weights were assigned to several factors and their particular sub-factors based on the review of pertinent literature (Pinto *et al.* 2017; Kumar & Krishna 2018; Arulbalaji *et al.* 2019; Achu *et al.* 2020; Bera *et al.* 2020), field experience, and expert judgment, which were normalized using Saaty's AHP approach. This process included interviews and group discussions with 30 national and international resource persons who work as groundwater experts, researchers, and academicians in Bangladesh's water-related sectors. As proposed by Saaty (1980) and Malczewski (1997), the normalization that reduces the bias of the given weights of the factors and sub-factors was further checked for consistency.

Again, the study developed pairwise comparison matrices for both factors and sub-factors under a factor. The factor hierarchy using pairwise comparisons aids in the discovery and correction of conceptual contradictions in AHP (Poudyal *et al.* 2010; Feizizadeh & Blaschke 2013). A 9-point continuous scale (Lane & Verdini 1989; Lootsma 1989) (i.e., 1/9, 1/8, 1/7, 1/6, 1/5, 1/4, 1/3, 1/2, 1, 2, 3, 4, 5, 6, 7, 8, 9) was used for weight rating. The eigenvalues and Consistency Ratio (CR) were calculated using the specified weight ranking. The following Equations (1) and (2) was used to calculate CR (Reis *et al.* 2012; Franek & Kresta 2014).

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{1}$$

where, CI=Consistency Index; RI=Mean Consistency Index

$$\mathrm{CI} = \frac{y_{\max} - n}{(n-1)} \tag{2}$$

where, $y_{\max}$ = largest eigenvalue; n = size of the comparison matrix.

The CR values of less than 10% were approved (Saaty 1977). Finally, weighted overlays of factor maps based on factor eigenvalues and sub-factor eigenvalues were performed to develop GIS-based groundwater potential index. Based on groundwater potential index values, the entire research region was divided into five classes: (a) very high (greater than 80$^{\text{th}}$ percentiles); (b) high (80–60$^{\text{th}}$ percentiles); (c) moderate (60–40$^{\text{th}}$ percentiles); (d) low (40–20$^{\text{th}}$ percentiles) and (e) very low (less than 20$^{\text{th}}$ percentile). The result was validated using groundwater table data.

3. RESULTS & DISCUSSION

3.1. Description of topographical factors

The slope of the ground surface is a crucial topography feature that reflects how steep the ground surface is (Riley *et al.* 1999; Arulbalaji *et al.* 2019). The surface runoff and infiltration of precipitation are directly determined by the slope's gradient (Yeh *et al.* 2009; Singh *et al.* 2013). Areas with larger slopes don't get enough time to penetrate and replenish the depleting zone with rain water, since the water flows off the top of a steeper slope quickly, resulting in a lower volume of groundwater recharge (Yeh *et al.* 2009; De Reu *et al.* 2013). Figure 1(a) illustrates the slope of the study area. The values were divided into four classes: flat (less than 2), gentle (2–7), moderate (7–12) and steep (more than 12). Most of the areas of the region are flat (82.20%) in nature and the high lands of the study area's south-eastern corner consist of moderate to steeper slopes. Higher weights were given to flat and gentle slopes, while lower weights were assigned to moderate and steep slopes.

Roughness index represents the undulation of the topographic surface by comparing the difference in elevation among the adjacent raster cells in the Digital Elevation Model (DEM) (Riley *et al.* 1999; Nair *et al.* 2017). The roughness index indicates how much undulation there is. The roughness map (Figure 1(b)) was reclassified into four categories: less than 0.3, 0.3–0.5, 0.5–0.7 and more than 0.7. Higher weights were given for lower values of roughness and vice versa.

Curvature is a measurement of the nature of the surface profile, which can be either concave upwards or convex upwards (Riley *et al.* 1999; Nair *et al.* 2017; Arulbalaji *et al.* 2019). Groundwater tends to decelerate and accumulate in a convex profile and concave upward profile, respectively (Nair *et al.* 2017). The value of curvature ranges from less than −0.3 to more than 0.7 (Figure 1(c)) which was further reclassified into four classes: less than −0.3, −0.3–0.1, 0.1–0.7 and more than 0.7. For higher values of curvature, higher weights were assigned and vice versa.

The rate of groundwater recharge is controlled by the drainage system's characteristics. Hence, it is necessary to evaluate the drainage characteristics prior to evaluating groundwater potential (Singh *et al.* 2013). Low drainage density encourages increased groundwater percolation and accumulation (Yeh *et al.* 2016). The drainage density (Figure 1(d)) was categorized into four different categories as very low (less than 0.2), low (0.2–0.4), moderate (0.4–0.6) and high (more than 0.6). Higher weights have been assigned for low density and lower weights have been given for high density.

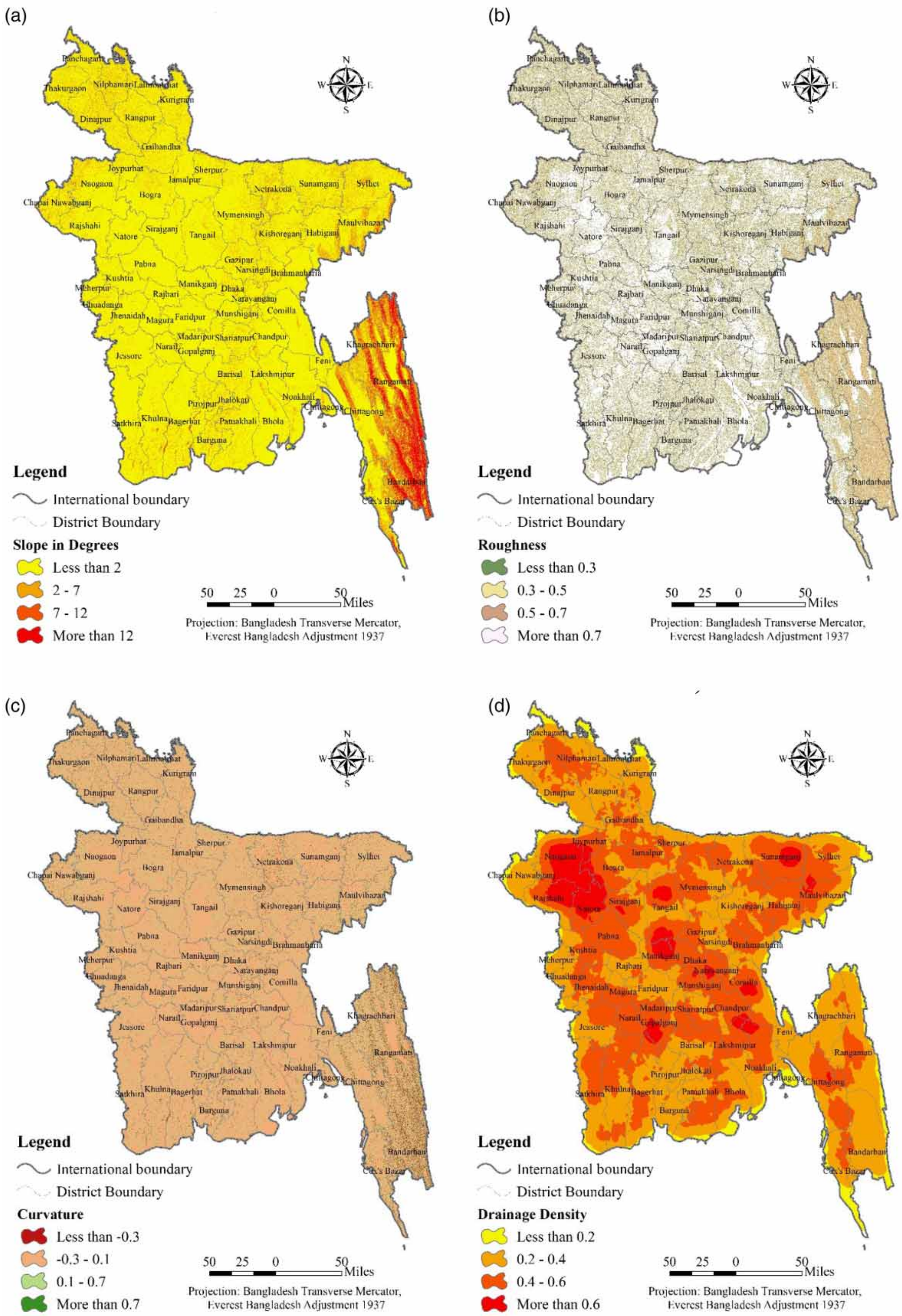


Figure 1 | Topographic factor maps: (a) slope; (b) roughness; (c) curvature; (d) drainage density; (e) Topographic Wetness Index (TWI); (f) Topographic Position Index (TPI). (*continued*)

TWI is commonly used to calculate topographic control over hydrological processes (Mokarram *et al.* 2015; Arulbalaji *et al.* 2019). It represents the potential for groundwater infiltration due to topographic effects. Thus, the greater the TWI value, the greater the groundwater potential. Figure 1(e) illustrates the TWI map where the values are reclassified into four classes: less than 8, 8–11, 11–15 and more than 15. For greater TWI, greater weights were assigned, and vice versa.

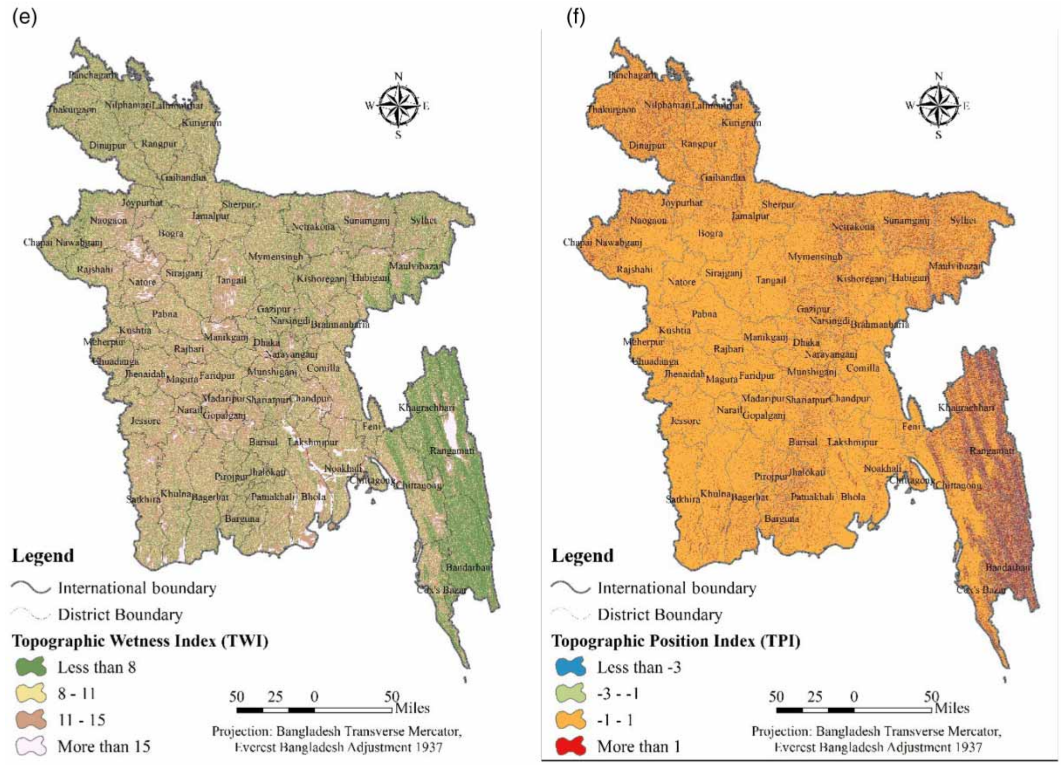


Figure 1 | Continued

TPI is a widely used method for automating landform categorization and measuring topographic slope locations (De Reu *et al.* 2013). TPI comes in handy to explain physical processes (hill, ridges, valley, flat plains, etc.) (Jenness 2006). TPI value close to zero stands for flat ground surface (Nair *et al.* 2017; Arulbalaji *et al.* 2019). The values of TPI were reclassified into four categories: less than −3, −3 to −1, −1 to 1 and more than 1 (Figure 1(f)). For groundwater potential high weights were given to areas with low values of TPI and vice versa.

3.2. Description of geological factors

The geological composition of an area, to a large extent, determines groundwater recharge and prevalence (Kaur *et al.* 2020). As the largest delta in the world, Bangladesh is almost entirely formed of alluvium with the exception of the Chittagong Hill Tracts region (Miocene and Pliocene) and some parts of central and north-western Bangladesh (Pleistocene) (Figure 2(a)). As the presence of alluvium is conducive for the reposition of groundwater (Patra *et al.* 2018), higher weight was assigned to it compared to other geological formations.

Geomorphology not only explains the landform and topography of an area, but also provides vital information on processes like surface runoff, infiltration, geo-chemical changes, groundwater movement, freezing and thawing (Singh *et al.* 2010; Rajaveni *et al.* 2017). While precipitation on waterbodies and plain stretches of land is suitable for more efficient infiltration to groundwater, mountainous regions account for most of the runoff with minimum infiltration (Duan *et al.* 2016). As a result, higher weights were assigned to waterbodies, terraces and plain lands compared to the hilly areas for this study. Figure 2(b) classifies the geomorphology of Bangladesh into four major categories, namely waterbodies/terraces (21.98%), basin/valley/ridges (60.10%), high/medium/low hills (9.68%) and flat land (8.25%).

The infiltration and percolation rates of water entering aquifers are substantially determined by an area's soil profile (Tolche 2021). Prevalence of a combination of differently textured soil types, like fine sand or sandy-loam, is beneficial for groundwater recharge (Costache *et al.* 2019). Consequently, higher weights were assigned to combined soil types compared to single type soils, especially clay. From Figure 2(c), it is evident that clay and brown/grey soil constitutes the majority of the soil types occurring in Bangladesh. The combination of silt, loam and clay type of soil can mostly be found along the major rivers and their adjoining regions. While the eastern part of Bangladesh mainly consists of brown/grey soil, the central and western regions are mostly characterized by clay.

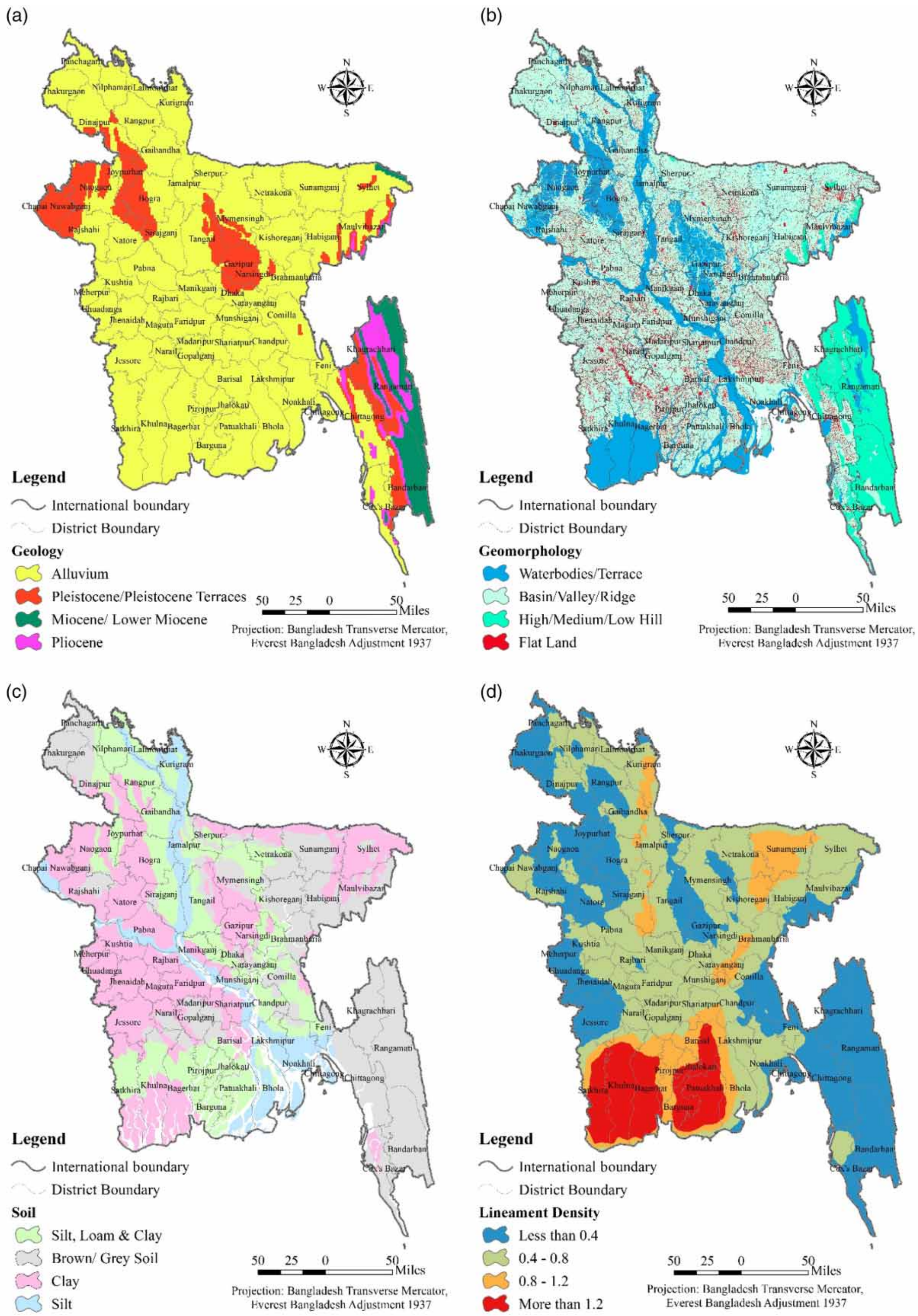


Figure 2 | Geological factor maps: (a) geology; (b) geomorphology; (c) general soil type; (d) lineament density.

Faulting and fracturing zones are represented by lineaments which are responsible for secondary porosity and permeability of the ground surface (Yeh *et al.* 2016). Near high-density lineament areas, the potential for groundwater is high and vice versa (Nair *et al.* 2017). In Figure 2(d), lineament density of the study area was divided into four classes: less than 0.4, 0.4–0.8, 0.8–1.2 and more than 1.2. For groundwater potential, higher weights were given for high density and lower weights were given for low density classes.

3.3. Descriptions of land use/land cover and meteorological factors

The pattern of land use/land cover (LULC) of a particular area gives important evidence regarding groundwater quantity and quality. Researchers across various geographical contexts have established that with increasing level of urbanization (rise in built-up areas), population growth and increased agricultural practices, the level of groundwater, its quality and recharge potential degrades over time (Scanlon *et al.* 2005; Melesse & Abtew 2015; Elmahdy *et al.* 2020). Figure 3(a) shows that more than 50% of the land area of Bangladesh is subjected to high intensity development, except for the Chittagong Hill Tracts region to the south-east, suggesting that the potential for groundwater recharge through infiltration in this vast area is lower compared to other regions. Correspondingly, higher weights were assigned to water bodies and relatively pristine land masses like forest areas.

Rainfall is the most vital water source in the hydrological cycle and one of the most crucial factors associated with groundwater recharge and availability. The annual rainfall distribution map of Bangladesh, depicted in Figure 3(b), reclassifies the rainfall (mm) into four categories (i.e., less than 2000, 2000–3000, 3000–4000 and more than 4000). Rainfall of high intensity but shorter duration results in lower infiltration rates and higher runoffs while that of low intensity and longer duration influence higher infiltration and lower runoffs (Arulbalaji *et al.* 2019). Consequently, higher weights were given to higher amounts of rainfall and vice versa.

Temperature and humidity are two of the deciding phenomena for precipitation and are hence important for considering groundwater potential of a particular area. Increased surface temperature may have an impact on the sub-surface water quantity (Jakeman *et al.* 2016; Salem *et al.* 2017; Jannis *et al.* 2021), whereas reduced humidity over a longer duration might result in extended periods of droughts, leading to over-extraction of groundwater and/or scarcity (Li *et al.* 2020). Accordingly, higher weights were assigned to lower temperatures and higher humidity for this study. Figure 3(c) and 3(d) illustrate the distribution of temperature and relative humidity in the study area.

3.4. Weights for factors and the sub-factor within a factor

Table 1 shows the weights, consistency ratio and eigenvalues for different sub-factors. As found by the pairwise comparison matrices, 14 consistency ratios were smaller then 0.10. According to the consistency ratios, eigenvalues for different sub-factors were preferable for groundwater potential calculation. For the factors under topographical category, slope less than 2, roughness less than 0.3, curvature more than 0.7, drainage density less than 0.2, TWI more than 15 and TPI less than −3 sub-factors have the highest eigenvalues at 0.55, 0.56, 0.59, 0.64, 0.58 and 0.57, respectively. For geological factors, alluvium in geology, waterbodies/terrace in geomorphology, silt in general soil type and lineament density more than 1.2 sub-factors have the highest eigenvalues at 0.57, 0.51, 0.50 and 0.60, respectively. In the land use and meteorological factor category, water in LULC, rainfall more than 4000, temperature less than 25.25 and relative humidity less than 77 sub-factors have relatively higher eigenvalues at 0.59, 0.47, 0.37 and 0.41, respectively. Higher eigenvalues of sub-factors have higher influence on the groundwater potential.

The pairwise comparison matrix among the 14 influential factors is shown in Table 2. For the factors, the consistency ratio was 0.09, which was within the acceptable range. General soil type, geology, and geomorphology have relatively higher eigenvalues, 0.17, 0.16 and 0.15, respectively. The combined influence for these three factors was about 48%. LULC and drainage density have equal influence on groundwater potential (i.e., eigenvalue 0.11). Relatively lower eigenvalue was found for slope, relative humidity, roughness, curvature, TWI and TPI.

3.5. Groundwater potential zones

Groundwater is a renewable resource that can be replenished. Owing to human activities and unbalanced development, the recharge of this crucial, life-sustaining substance has been substantially reduced. Since the availability of groundwater varies across time and geographical location, a comprehensive evaluation of the groundwater resource is of dominant importance for better planning and sustainable development (Arulbalaji *et al.* 2019).

The highest and lowest groundwater potential index values were 45.99 and 10.34, respectively. The resulting groundwater potential map was reclassified into five groundwater potential zones (i.e., very high, high, moderate, low, and very low) (Figure 4). The result illustrates that very high and high groundwater potential zones were mostly found in the areas to the south, near the Bay of Bengal, and areas adjacent to major rivers running across the study region. The two categories of

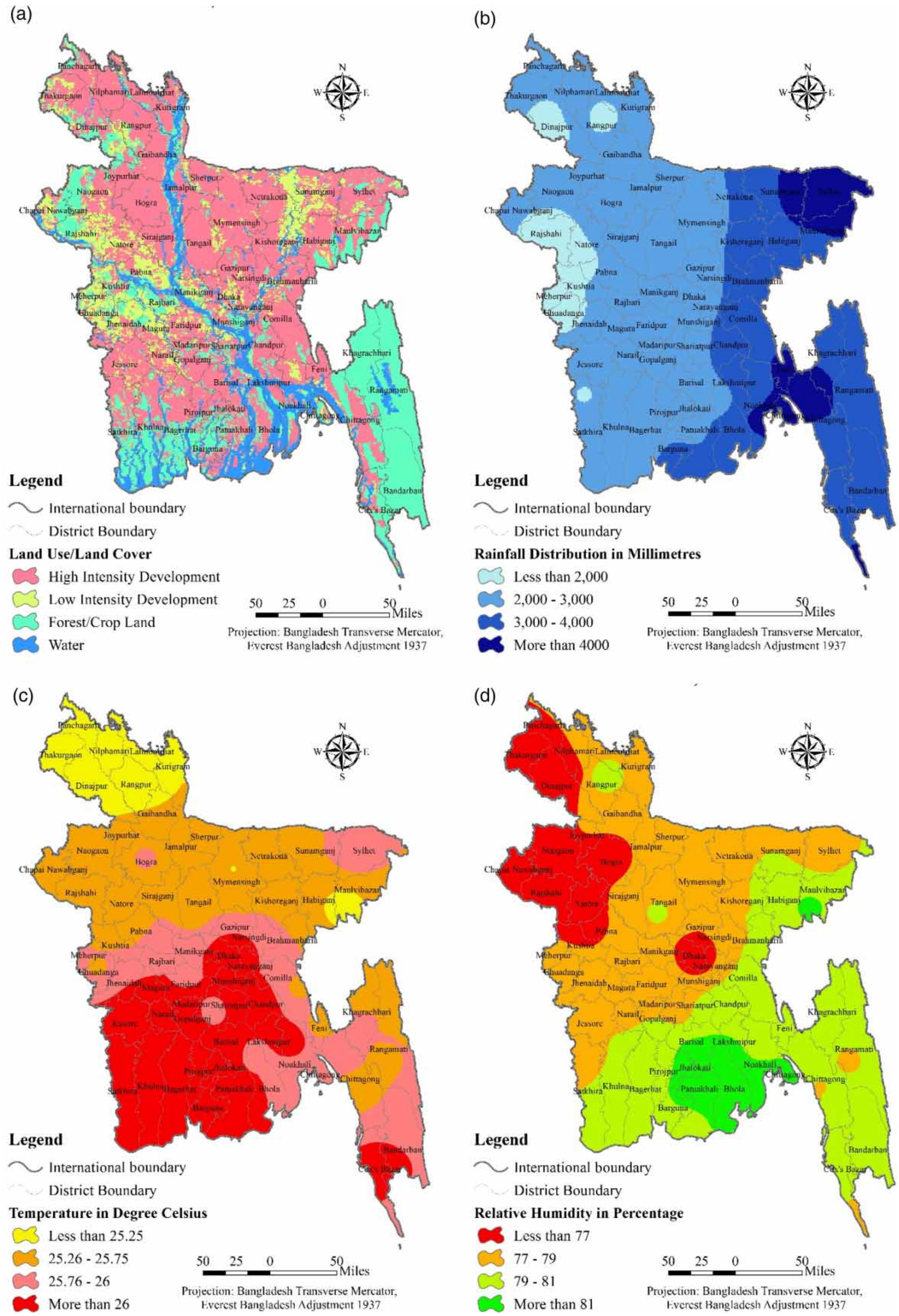


Figure 3 | Land use/land cover and meteorological factor maps: (a) land use/land cover; (b) rainfall; (c) temperature; (d) relative humidity.

groundwater potential (i.e., very high and high) were typically found in areas with considerable rainfall and silty clay loam soil type, which has considerable infiltration potential. Zones with moderate groundwater potential were generally found in valleys, locations with low-intensity development, and a high drainage density. The remaining two zones (i.e., very low and low) were mostly found in the hilly areas in highlands, with a lower presence in the lowlands. Factors like steeper slopes, low

Table 1 | Pairwise comparison matrix, consistency ratio and weights of the sub-factors

Factors	(1)	(2)	(3)	(4)	Eigenvalues
Slope					
(1) Less than 2	1				0.54
(2) 2–7	1/3	1			0.31
(3) 7–12	1/5	1/5	1		0.10
(4) More than 12	1/7	1/7	1/3	1	0.05
Consistency Ratio=0.08					
Roughness					
(1) Less than 0.3	1				0.58
(2) 0.3–0.5	1/3	1			0.25
(3) 0.5–0.7	1/5	1/3	1		0.12
(4) More than 0.7	1/9	1/5	1/4	1	0.05
Consistency Ratio=0.05					
Curvature					
(1) Less than (−0.3)	1				0.06
(2) (−0.3)−0.1	3	1			0.12
(3) 0.1–0.7	4	3	1		0.23
(4) More than 0.7	6	5	4	1	0.59
Consistency Ratio=0.08					
Drainage Density					
(1) Less than 0.2	1				0.64
(2) 0.2–0.4	1/5	1			0.21
(3) 0.4–0.6	1/6	1/3	1		0.09
(4) More than 0.6	1/7	1/4	1/2	1	0.06
Consistency Ratio=0.06					
Topographic Wetness Index (TWI)					
(1) Less than 8	1				0.04
(2) 8–11	3	1			0.10
(3) 11–15	7	4	1		0.28
(4) More than 15	9	6	3	1	0.58
Consistency Ratio=0.05					
Topographic Position Index (TPI)					
(1) Less than (−3)	1				0.57
(2) (−3)–(−1)	1/3	1	3	6	0.27
(3) (−1)−1	1/5	1/3	1		0.12
(4) More than 1	1/8	1/6	1/4	1	0.04
Consistency Ratio=0.05					
Geology					
(1) Alluvium	1				0.57
(2) Terraces/ Pleistocene Terraces	1/3	1			0.27
(3) Miocene/ Lower Miocene	1/6	1/4	1		0.08
(4) Pliocene	1/6	1/4	1	1	0.08
Consistency Ratio=0.02					

(*Continued.*)

Table 1 | Continued

Factors	(1)	(2)	(3)	(4)	Eigenvalues
Geomorphology					
(1) Waterbodies/Terrace	1				0.51
(2) Basin/Valley/Ridge	1/2	1			0.23
(3) High/Medium/Low Hill	1/9	1/5	1		0.05
(4) Flat Land	1/3	1	5	1	0.21
Consistency Ratio=0.01					
Soil					
(1) Silt, Loam & Clay	1				0.30
(2) Brown/Grey Soil	1/7	1			0.05
(3) Clay	1/2	3	1		0.15
(4) Silt	2	9	3	1	0.50
Consistency Ratio=0.01					
Lineament Density					
(1) Less than 0.4	1				0.06
(2) 0.4–0.8	3	1			0.12
(3) 0.8–1.2	5	2	1		0.22
(4) More than 1.2	7	5	4	1	0.60
Consistency Ratio=0.04					
Land Use/ Land Cover					
(1) High Intensity Development	1				0.04
(2) Low Intensity Development	2	1			0.08
(3) Forest/ Crop Land	7	5	1		0.29
(4) Water	9	7	3	1	0.59
Consistency Ratio=0.04					
Rainfall					
(1) Less than 2000	1				0.10
(2) 2000–3000	2	1			0.15
(3) 3000–4000	3	2	1		0.28
(4) More than 4000	4	3	2	1	0.47
Consistency Ratio=0.01					
Temperature					
(1) Less than 25.25	1				0.37
(2) 25.25–25.75	1	1			0.28
(3) 25.75–26	1/2	1	1		0.23
(4) More than 26	1/3	1/2	1/2	1	0.12
Consistency Ratio=0.02					
Relative Humidity					
(1) Less than 77	1				0.42
(2) 77–79	1/2	1			0.29
(3) 79–81	1/2	1/2	1		0.19
(4) More than 81	1/3	1/3	1/2	1	0.10
Consistency Ratio=0.03					

Table 2 | Pairwise comparison matrix, consistency ratio and weights of the factors

Factors	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	Eigenvalues
(1) Slope	1														0.03
(2) Roughness	1/3	1													0.02
(3) Curvature	1/4	1	1												0.02
(4) Drainage Density	3	6	5	1											0.11
(5) Topographic Wetness Index (TWI)	1/5	1/3	1/2	1/5	1										0.02
(6) Topographic Position Index (TPI)	1/5	1/3	1/2	1/5	1	1									0.01
(7) Geology	4	6	5	4	7	7	1								0.16
(8) Geomorphology	4	6	5	4	7	7	1	1							0.15
(9) Soil	4	5	4	3	6	6	2	2	1						0.17
(10) Lineament Density	4	5	5	1/2	5	5	1/5	1/5	1/4	1					0.07
(11) Land Use/Land Cover	5	7	5	1/3	5	5	1/2	1/2	1	3	1				0.11
(12) Rainfall	5	4	4	1/3	3	4	1/4	1/3	1/4	1/2	1/3	1			0.06
(13) Temperature	3	3	3	1/4	3	3	1/5	1/4	1/5	1/3	1/4	1/3	1		0.04
(14) Relative Humidity	2	3	3	1/5	4	3	1/6	1/5	1/6	1/4	1/5	1/4	1/5	1	0.03
Consistency Ratio=0.09															

lineament density, moderate to high drainage density, high-intensity development, and forest lands, contribute to low and extremely low groundwater potential zones.

There are eight hydrological regions in Bangladesh, namely North West (NW), North Central (NC), North East (NE), South West (SW), South Central (SC), South East (SE), River and Estuary (RE), and Easter Hills (EH), which are used for water modeling, management, irrigation, and so on. Each region has its distinct characteristics, which result in the substantial spatial variability of groundwater. Even the groundwater scenario varies greatly in various regions with time. Figure 5 shows the overall status of groundwater potential zones in different hydrogeological zones of Bangladesh. SW region claims the highest percentage (5%) of groundwater potential zones among the regions next to SC (4%), while NW avails the highest level of high and moderate groundwater potentiality. This region also has the highest status of low groundwater potentiality zones next to SW while the class of very low groundwater potentiality is the highest in the EH. Figure 6 shows the status of groundwater potential zones in each hydrological region. RE regions observe the highest percentage of groundwater potential zone next to SC. RE region includes the major rivers of the country and the Meghna River estuary and its surroundings, where the water table is comparatively low and the availability of water assists in recharging groundwater all through the year. SC region is characterized by low topography with substantial surface water bodies along with the tidal effects, which keep around half of the region as a very high groundwater potential zone. This region suffers from drainage congestion, which directly assists the groundwater recharge. But unfortunately, the groundwater table is frequently contaminated by salinity intrusion. The status of high groundwater potential zones is seen in SE, SC, and NW regions which are characterized by comparatively lower topography. NE region avails the status of moderate groundwater potential zones next to NC and SE. Flooding and drainage congestion is a normal phenomenon in the NE region. NE is also marked by the low groundwater potential zone among the regions. EH is characterized by a hilly region with comparatively higher topography and high groundwater table and has a very low status of groundwater potentiality.

3.6. Validation of results

The groundwater potential zones found in this study were further cross-validated based on the groundwater observation data from a secondary source. Bangladesh Water Development Board (BWDB) has a rich network of 1253 groundwater observation wells (piezometric wells), which encompasses almost all the sub-districts and districts to collect and monitor groundwater table data on a weekly basis throughout the year. Among them, groundwater table data from a total of 64 observation wells spreading across the study area was selected randomly in this research for 2018. Data from more groundwater observation wells could have better results in the validation process. However, due to data scarcity, it was not possible to

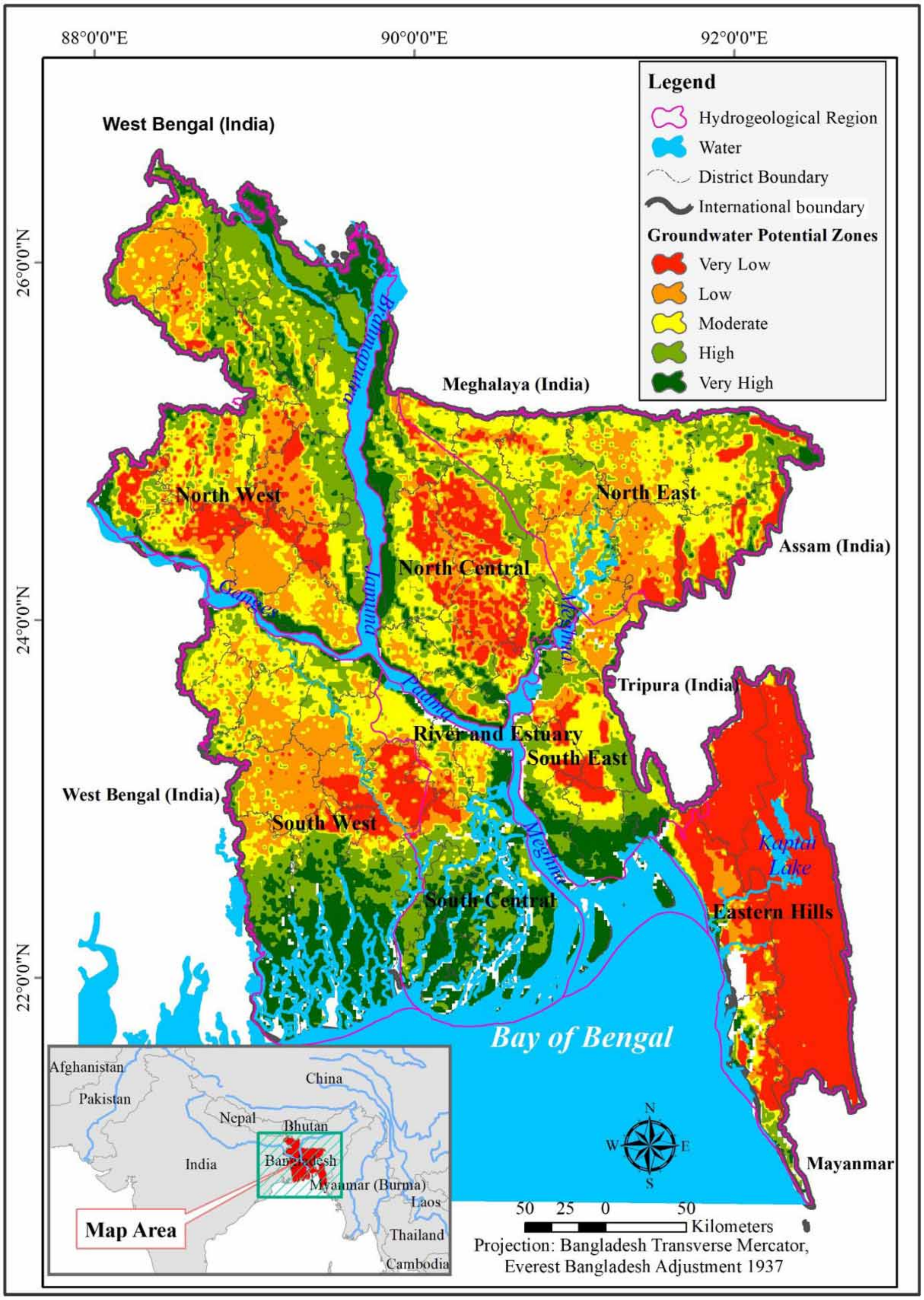
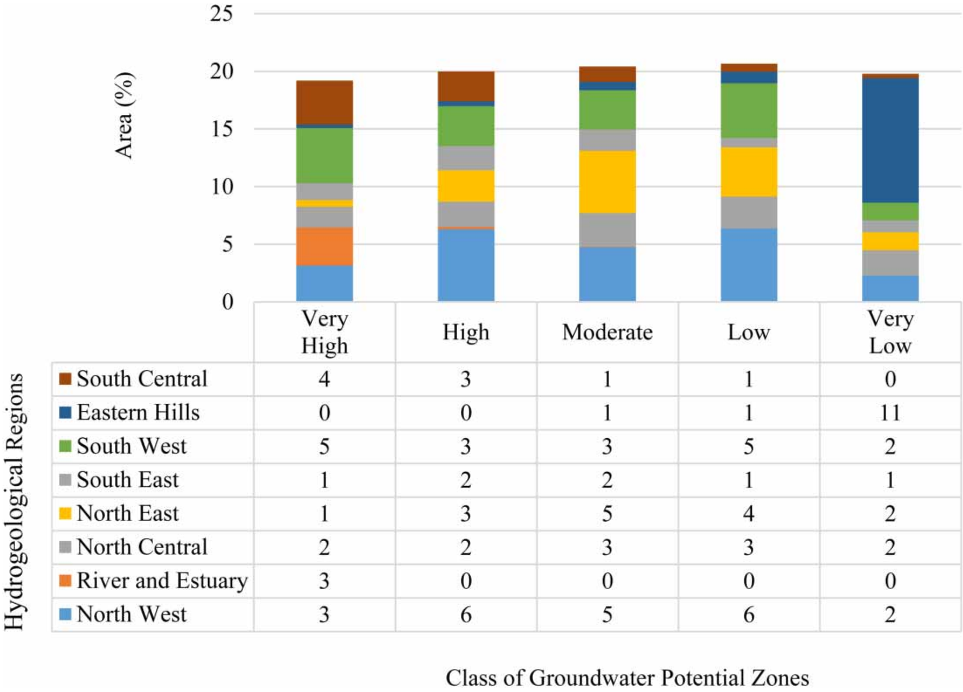


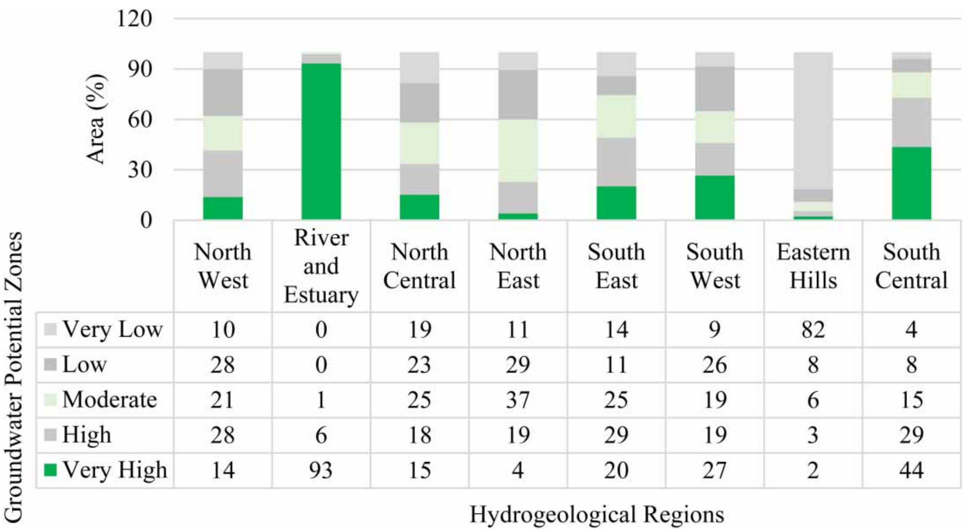
Figure 4 | Groundwater potential zones.

include more groundwater observation wells. Groundwater data was used to ascertain the relationship of the water table depth (i.e., averge of pre monsoon and post monsoon depth) to groundwater potential index found through the weighted overlay approach mentioned earlier. The downward slope of the fitted line of groundwater potential index on the depth of



	Very High	High	Moderate	Low	Very Low
South Central	4	3	1	1	0
Eastern Hills	0	0	1	1	11
South West	5	3	3	5	2
South East	1	2	2	1	1
North East	1	3	5	4	2
North Central	2	2	3	3	2
River and Estuary	3	0	0	0	0
North West	3	6	5	6	2

Figure 5 | Status of Groundwater Potential Zones in different hydrogeological zones of Bangladesh.



	North West	River and Estuary	North Central	North East	South East	South West	Eastern Hills	South Central
Very Low	10	0	19	11	14	9	82	4
Low	28	0	23	29	11	26	8	8
Moderate	21	1	25	37	25	19	6	15
High	28	6	18	19	29	19	3	29
Very High	14	93	15	4	20	27	2	44

Figure 6 | Groundwater Potential Zones in each hydrogeological region of Bangladesh.

groundwater table shows a negative relationship between them (Figure 7). The value of the R^2 is 0.6932, which means that the variation in groundwater table depth alone can explain 69.32% of the variation in groundwater potential index.

The areas with a smaller depth to groundwater table from the land surface have greater groundwater potential index, which means that the groundwater table of these locations is higher because they have a high potential for groundwater and vice versa. So, it is clear that the findings from the observed data coincide to a great extent with the results found for the study area. Finally, the study concludes that GIS-based approaches are a superior method for groundwater potential zones delineation for effective planning and development with varying geo-environmental settings.

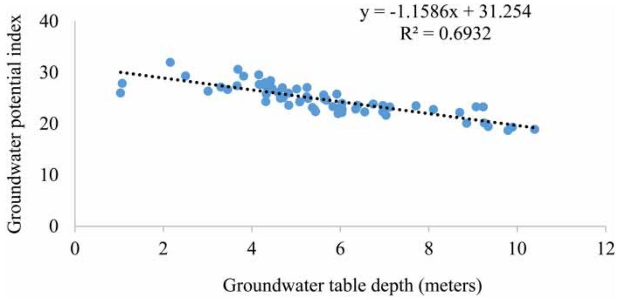


Figure 7 | Scattered plot of groundwater table depth and groundwater potential index.

4. CONCLUSION

For developing GIS-based groundwater zoning, the research applied 14 influential factors associated with topography, geology and meteorological issues. The CR for factors and sub-factors was less than 0.10, as determined by the pairwise comparison matrix. The most significant factors for groundwater potential zoning were general soil type (eigenvalue 0.17), geology (eigenvalue 0.16) and geomorphology (eigenvalue 0.15). The maximum and minimum values for groundwater potential index were 45.99 and 10.34, respectively. Finally, the groundwater potential map was divided into five categories (i.e., very low, low, moderate, high and very high) based on percentile. The findings show that higher groundwater potential zones were largely located in the study region's southern sections, along the Bay of Bengal, and places next to important rivers. The findings of the study will aid government authorities in making evidence-based decisions about national water policy and planning.

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CONFLICTS OF INTEREST/COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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