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GIS Based Delineation of Groundwater Prospective Zones Using AHP Techniques in Jaldhaka Watershed, Cooch Behar District, West Bengal

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ABSTRACT

Geographic Information Systems (GIS)-based studies have emerged as a rapid and efficient tool for groundwater exploration, providing valuable insights into resource availability for future development. In this study, the groundwater prospective zones (GWPZ) of Jaldhaka River watershed from the north-eastern part of India are delineated, deploying a combined approach, integrating Remote Sensing (RS), GIS and Analytical Hierarchy Process (AHP) techniques. Eight thematic layers of lithology, land use and land cover (LULC), Geomorphology, drainage density, soil, rainfall, lineament density and topographic wetness index (TWI) were generated and analysed. The AHP method was used to assign weightage values to the sub-classes within the thematic layers, considering their specific characteristics and their relative influence over groundwater recharge in the area. The resulting GWPZ (Groundwater Prospect Zone) map was categorized into four classes: high, moderate, low, and very low potential zones. These potential classes cover 11% (103 sq. km), 65% (610 sq. km), 21% (197 sq. km), and 3% (28 sq. km) of the study area, respectively. The precision of the groundwater potential zone map was validated against existing well data available from government and ground truth information. The wells falling in the 'low' to 'very low' prospective classes had lesser yield (10 to 50 lpm) than the others, while those belonging to the 'moderate' to 'high' zones showed higher yield (~100 lpm), conforming to the successful validation.

1.0 Introduction:

Groundwater is a dynamic resource that is being continuously misused and with the steady, steep demand from every rowing sector of energy and agriculture, available freshwater will be reduced by as much as two-thirds by the year 2050 (World Bank, 2005). We are individually accounted for 1000 cubic meters per year to grow the produce we consume. International norms dictate that countries with less than 1700 cubic meters per year per-capita water availability are considered water-stressed (MoWR, 2020). Several international studies featuring suitable groundwater potential have put Asian countries

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like China (Shao et al., 2020), Malaysia (Manap et al., 2013) and Taiwan (Yeh et al., 2016) at critical stages.

India is not too far along. Current estimates show India's total groundwater recharge is 449.08 billion cubic meters (MoJS, 2024), of which 241.34 billion cubic meters is the annual groundwater extraction (MoJS, 2024). Around 87% of this water is utilized for agricultural activities.

In West Bengal, gross annual groundwater availability is 23.90 billion cubic meters and groundwater draft for all uses is 10.71 billion cubic meters. The district of Cooch Behar witnessed a rapid growth in population particularly during the last one and half decades. DPDWB (2005) *Districts statistical handbook (*Retrieved June 3, 2010) revealed that the population jumped from 24, 79, 155 (census, 2001) to 28, 22, 780 (census, 2011) with a growth of 13.86% with a density of 833 person /km^2, putting a considerable dent in the groundwater reserve of the area.

Being one of the major exploited natural resources, groundwater estimation and productivity are becoming a cornerstone to building a sustainable and thriving environment for future generations. In recent years, the rapid emergence of geospatial tools has proven to be the most efficient and cost-effective way to process and analyze geoscientific data. Traditional methods of groundwater potential mapping have been overshadowed by these technological advancements, which streamline the mapping process that previously relied on various hydrogeological tools and ground-truth surveys. Systematic planning for groundwater extraction using modern techniques has always been essential for the proper utilization and management of this valuable but increasingly limited natural resource. The current study strives to implement an integration of the Analytical Hierarchy Process (AHP) with Remote Sensing (RS) and Geographic Information System (GIS) techniques to identify and delineate suitable groundwater prospective zones in the alluvium-rich agriculture-dominant Jaldhaka watershed falling in the Cooch Behar district of West Bengal. The AHP, developed by Thomas Saaty (Saaty, 1980), is an effective Multi-Criteria Decision Analysis tool and can be applied to complex groundwater-related issues. The tool effectively simplifies complex decisions by breaking them down into an array of pairwise comparisons matrix, followed by a systematic synthesis to produce outcomes. The AHP tool effectively assesses result consistency, reducing predisposition in decision-making.

Condappa et al. (2019) while preparing a groundwater model for impact assessment of agricultural water management interventions in the Jaldhaka watershed, noted that groundwater is the primary source of irrigation in Cooch Behar. Cropping intensity has increased recently to 215% with up to three crop cycles per year (three cropped areas: 80,000 Ha), placing tremendous pressure on groundwater. Recent industrial growth, including cold drawing steel plant, casting units, modern jute mills and major cold storage facilities has further strained groundwater resources. Agro-based industries are exacerbating this issue.

Shamsudduha et al. (2009) referencing with Central Groundwater Board (2009) report, noted that apart from anthropogenic activities, natural causes too share a considerable reason for groundwater depletion in the alluvial rich Cooch Behar district. A number of streams, both perennial and seasonal drain the flood plains. Despite a good measure of precipitation, droughts-like conditions are often reported owing to larger intervals between successive monsoon events, particularly in areas frequented by clusters of ephemeral rivulets.

Chatterjee and Purohit (2009) emphasised categorising assessment units in groundwater management along with their regulatory plans. They proposed a GIS-based approach to evaluate groundwater availability by superimposing resource indices into a composite map. Pre- and post-monsoon data, satellite imagery, SOI topographical maps (1:50,000), and fieldwork were integrated to map lithology, geomorphology, and hydrology.

Several studies have been carried out in recent years where a number of multi-criteria decision analyses (MCDA) approaches have been integrated with remote sensing and GIS to solve various geoscientific problems, especially prospecting for groundwater potential zones. Razandi et al. (2015) have applied probabilistic models such as frequency ratio and certainty factors to lay down groundwater potential zones, while, Pourghasemi and Beheshtirad (2015), Pourtaghi and Pourghasemi (2014) used logistic regression and evidential belief function for groundwater spring potential mapping. Evidential belief function aided with GIS was also implemented in similar studies by Nampak et al. (2014) and

Mogaji et al. (2015). Multi-criteria decision analysis aided GIS studies by Pradhan (2009) and Rahmati et al. (2015) are of significant importance. Lee et al. (2018) and Corsini et al. (2009) used the weight-of-evidence method coupled with artificial neural network for groundwater potential delineation studies. Besides all these, several studies were made using Shannon's entropy by Naghibi et al. (2015), decision tree by Chenini and Mammou (2010), machine learning techniques such as random forest (RF), maximum entropy (ME) by Rahmati et al. (2015).

Using AHP-based RS-GIS techniques under the broad spectrum of MCDA approaches, considerable work has been done for groundwater prospect zone studies in hard rock geological terrains, namely, the works of Singh et al. (2013), Shekhar and Pandey (2015), Pande et al. (2019), Maity and Mandal (2019), Bhattacharya et al. (2020), Saikia et al. (2023), and many others, in contrast to similar works in alluvial terrains where agro-industries put a heavy toll on the groundwater reserve. Some of the notable works are by Patra et al. (2018), Biswas et al. (2020), Senapati and Das (2022), and others who have persistently emphasised sustainable groundwater management and planning in rural agricultural alluvial areas in India.

The principal purpose of the present study is to delineate prospective zones for groundwater exploration in the Jaldhaka watershed pertaining to the alluvium rich district of Cooch Behar in West Bengal, with the aid of GIS based AHP techniques, which will help in sustainable development of groundwater reserves in the study area.

2.0 Materials and Methods:

2.1 Study Area:

The river Jaldhaka traverses across Bhutan, India and Bangladesh as a tributary of the Brahmaputra River and drains almost 6,140 sq.km of area, of which 66% is located in the north-eastern part of India. In the Cooch Behar district of the state of West Bengal, the Jaldhaka river commands a watershed area of 1002.5 sq.km. It extends between $89^{0}03'16"$E & $89^{0}27'57"$E longitudes and $25^{0}59'57"$N & $26^{0}31'45"$N latitudes (Figure 1) covering parts of Mekhligunj, Mathabhanga I & II, Cooch Behar I, Sitalkuchi, Dinhata I and Sitai blocks (Figure 2).

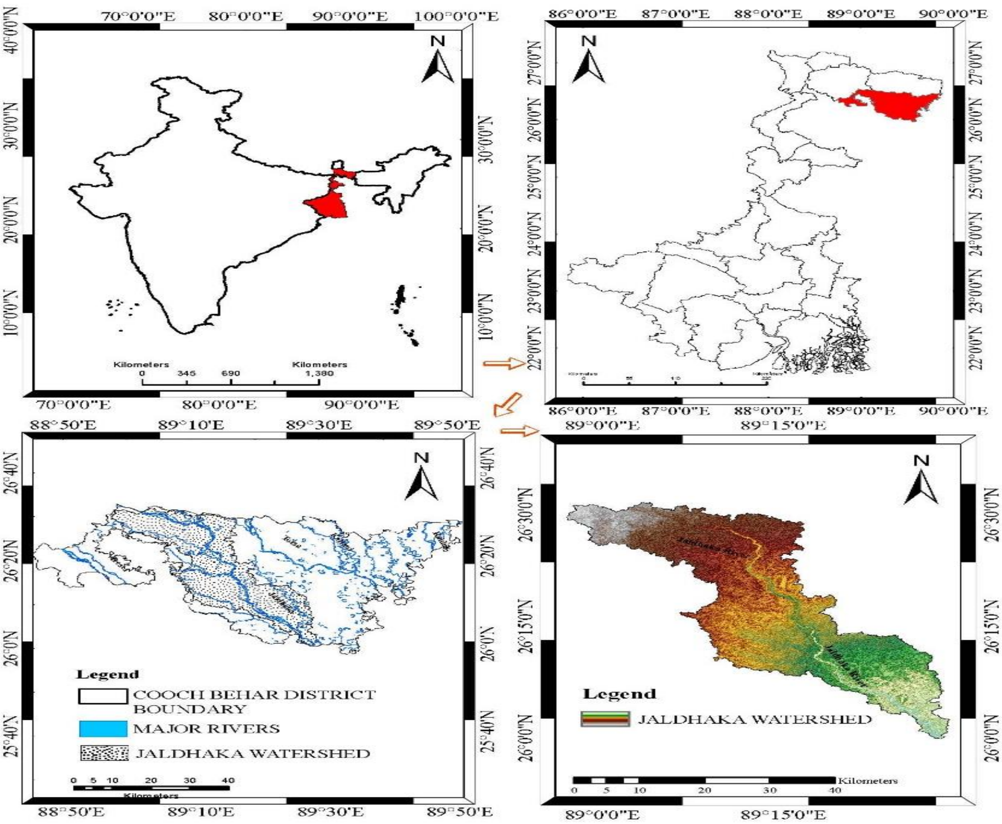

Figure 1. Location Map of Jaldhaka Watershed.

This is an almost level area with a nominal gradient towards the south-eastern direction, along which the major rivers of the district flow. The majority of the highlands belong to the Sitalkuchi and Mekhligunj

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area, while the district troughs around the Dinhata area. Being part of the extensive Ganga-Brahmaputra system, the soil is predominantly alluvial in origin and sand-dominated. The successive fluvial deposits make the surface soil loamy with occasional calcareous concretions and clay loams.

Average annual rainfall in the district is around 2500 mm. About Owing to the Humid Subtropical climate, the district of Cooch Behar experiences gentle winters but heavy monsoon and hot summers. The temperature in winter goes as low as 7 degrees Celsius, while the summer's record highs are 38 degrees Celsius. Monsoon is usually brought about by the south-west monsoon winds, June to September being the rainiest months. The average annual rainfall of the district is around 2500 mm. Although longer gap periods between successive rainfall events are also recorded.

Lithology of Cooch Behar district includes younger and older alluvium whereas major geomorphic features include flood plains, alluvial plains, sand bars, abandoned channels and paleochannels. The floodplains exhibit geomorphic features such as relict fluvial channels, oxbow lakes, and a terrain sculpted by a network of both perennial and ephemeral streams. The combination of intensive agricultural practices and unsustainable land management renders the topsoil susceptible to erosion (Shamsudduha et al., 2009; CGWB, 2009).

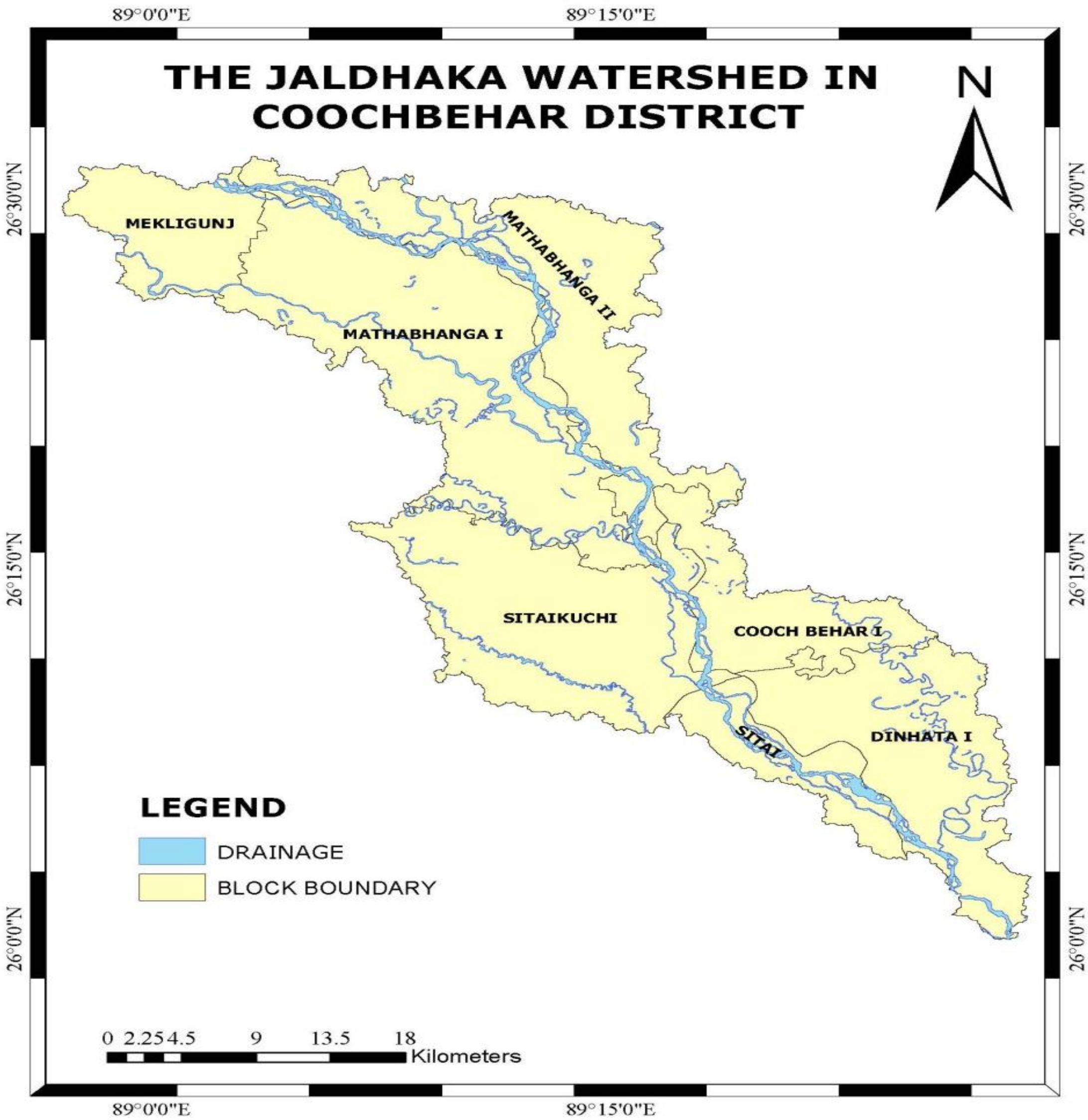
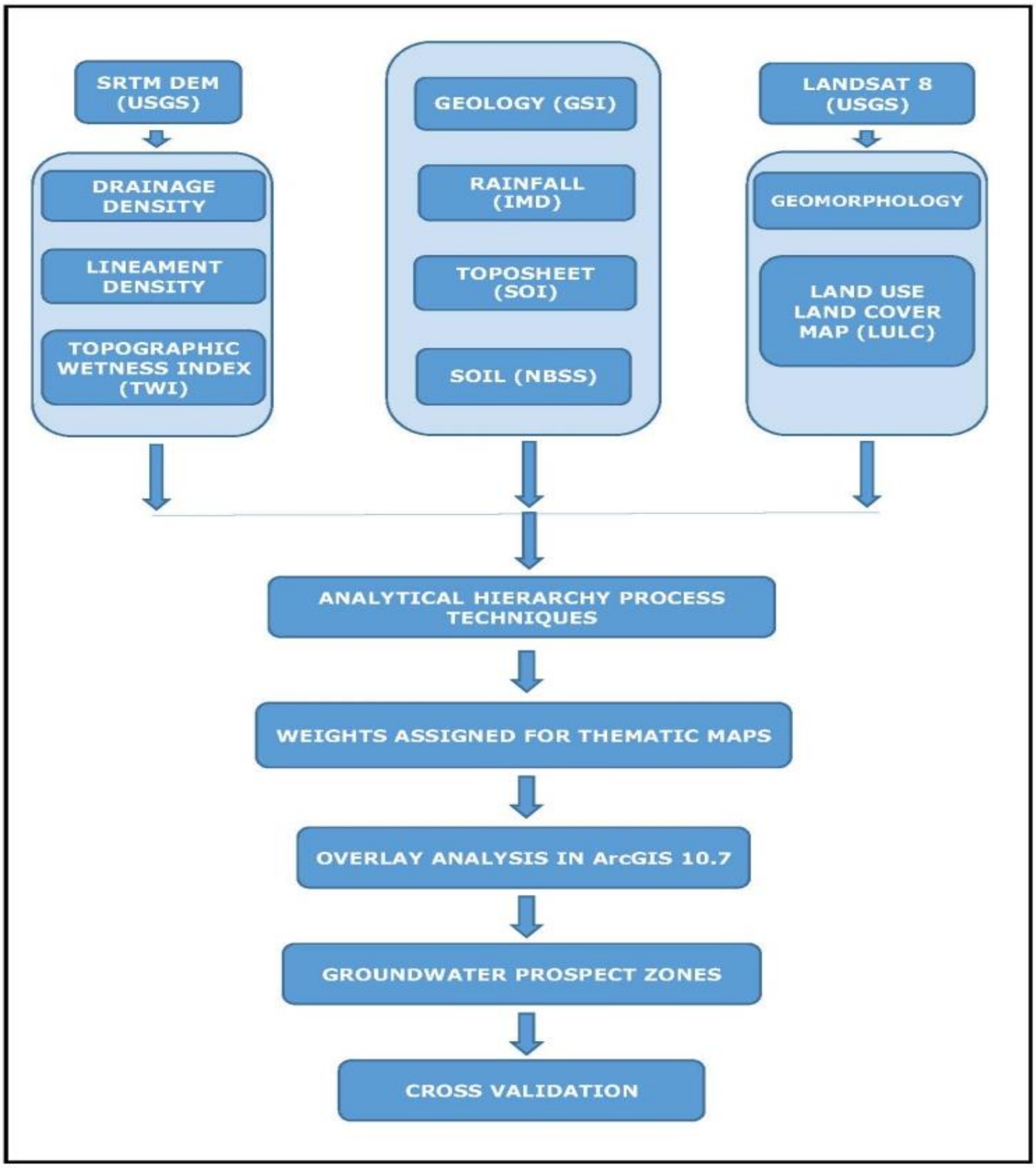


Figure 2. Administrative Block Boundaries with the Jaldhaka Watershed.

2.2 Data Collection and Preparation:

The major thematic layers prepared for this study involved the lithology layer which was procured from the Bhukosh portal of the GSI (Geological Survey of India). The rainfall data was collected from IMD (India Meteorological Department) and WRIS (Water Resource Information System). They were then processed in GIS with IDW to create the rainfall intensity raster. The soil map is created from the soil data procured from the NBSS & LUP (National Bureau of Soil Survey and Land Use Planning). Relevant toposheets were procured from the Survey of India website. Landsat 8 OLI (Operational Land Imager) satellite image obtained from USGS (United States Geological Survey) Earth Explorer website for land use and land cover (LULC) as well as geomorphological maps in ArcGIS. The same website provided the SRTM DEM (Shuttle Radar Topography Mission Digital Elevation Model) for generating various surface maps like drainage density, lineament density and topographic wetness index (TWI). All the maps had a 30m spatial resolution and were projected in the WGS (World Geodetic System) 84 datum and UTM (Universal Transverse Mercator) zone 45N projection system. The following flow-chart shows the workflow in a schematic (Figure 3).



Flow chart of the methodology used for Groundwater Potential Zones Mapping.

Figure 3. Flow-chart for groundwater potential zone mapping.

2.3 The Analytical Hierarchy Process (AHP):

Individual thematic layers on geology, geomorphology, and hydrology (drainage), along with drainage density, lineament density, rainfall, soil type, land use/land cover, and topographic wetness index, were prepared by visual interpretation of satellite data in conjunction with limited field/existing data in the GIS platform of ArcGIS. The spatial analyst, hydrological analysis, data management, raster processing and several other necessary tools were used to prepare the required thematic maps. The cumulative process involved digitizing scanned maps, assigning attributes, editing errors and buffering, etc., which helped build the spatial database. The applied AHP (Analytical Hierarchical Process) (Saaty, 1980) is a multi-criteria decision analysis (MCDA) technique that involves preparing a comparison matrix between the several factors influencing the groundwater potential of the area under study. Each individual thematic layer is pitted against another, and a weighted value following Saaty's scale of 1 to 9 (Table 1) is assigned to each one of them, where 9 is the dominant importance over all, while 1 is of equal importance. Several intermediate values are also assigned. The geometric mean of the assigned values in each row is then further normalized to get the priority vector (Table 3). The priority vector and the comparison matrix product would provide the weighted sum vector. These values when normalized would show the general directional tendency of the matrix which is the principal Eigenvalue λmax. This is required to check the consistency of the weights assigned by calculating the consistency ratio, which should always be equal to or less than 10% according to Saaty. Otherwise, the whole weight assignment is to be repeated and carefully calibrated. Consistency ratio is defined as-

CR = CI/RCI,

Where, CI is Consistency Index and RCI is Random Consistency Index standardised by Saaty (Saaty, 1990) (Table 2). To generate the value of CI, we use the following relation,

CI = = (λmax – n) / (n-1),

Where λmax is the principal Eigenvalue and n is the number of factors.

Putting the respective values (Table 4), we get λmax = 8.

Thus, CI = (8 – 8) / (8 – 1) = 0, and CR = 0/1.41 = 0.

The present study follows Saaty's principle of less than or equal to 0.1, which ensures the matrix is consistent.

The groundwater potential zone map was then prepared in ArcGIS platform using the weighted overlay analysis integrating all the thematic layers using the following equation,

$$GWPZ = \sum_i^n (X_A * Y_B)$$

Where, GWPZ = Groundwater Potential Zone, X = weight of the thematic layers, and Y = rank of the thematic layers' subclass (Table 5). The A term represents the thematic map and the B term represents the thematic map classes. The final output map of groundwater potential zone showed four individual classes from very low, low, moderate and high potential zones.

Table 1. Scale for Pair wise Comparison (Saaty, 1980).

Sl. No.	Amount of Significance	Characterization	Description
1.	1	Equal importance	Both factors have similar effect over the event.
2.	3	Moderate importance	One factor has slightly more effect over another on the event.
3.	5	Strong importance	One factor has a stronger effect over another on the event.
4.	7	Very strong importance	One factor has a very strong effect on another in the event.
5.	9	Extreme importance	One factor has almost all control over another in the event.
6.	2, 4, 6, 8	Intermediate values	When negotiation is in order to assign weightage to one over another.

Table 2. Saaty's ratio index for different values of N (Saaty, 1989).

Random Consistency Index Values												
N	1	2	3	4	5	6	7	8	9	10	11	12
RCI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.53

Table 3. Pair-wise comparison matrix table of eight thematic layers.

Factors	Assigned weights	Geology	LULC	Geomorphology	Drainage Density	Soil	Lineament Density	Rainfall	TWI	Geometric Mean	Normalised Weight
Geology	8	1	1.14	1.33	1.33	1.33	1.6	1.6	2	1.389	0.167
LULC	7	0.875	1	1.17	1.17	1.17	1.4	1.4	3.5	1.325	0.16
Geomorp	6	0.75	0.86	1	1	1	1.2	1.2	1.5	1.041	0.125
Drainage	6	0.75	0.86	1	1	1	1.2	1.2	1.5	1.041	0.125
Soil	6	0.75	0.86	1	1	1	1.2	1.2	1.5	1.041	0.125
Lineamen	5	0.625	0.71	0.83	0.83	0.83	1	1	1.25	0.868	0.104
Rainfall	5	0.625	0.71	0.83	0.83	0.83	1	1	1.25	0.868	0.104
TWI	4	0.5	0.57	0.67	0.67	0.67	0.8	0.8	1	0.694	0.083

Table 4. Consistency Ratio outcome.

Factors	Geology	LULC	Geomorphology	Drainage Density	Soil	Lineament Density	Rainfall	TWI	Weighted Sum	Row Avg.	λ
Geology	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.337	2.31	8
LULC	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.34	1.314	2.27	8
Geomorphology	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.002	1.73	8
Drainage Density	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.002	1.73	8
Soil	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.002	1.73	8
Lineament Density	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.835	1.44	8
Rainfall	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.835	1.44	8
TWI	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.668	1.15	8

Table 5. Categorization of factors influencing Groundwater Potential Zones for AHP weightage overlay analysis in ArcGIS.

Factor	Assigned weight	Domain of effect	Rank
Geology	8	Present Day Deposit	8
		Shaugaon Formation	7
		Jalpaiguri Formation	7
		Baikunthapur Formation	5
LULC	7	Agriculture	8
		Built-up Area	3
		Fallow Land	6
		Flooded Vegetation	5
		Forest	7
		Rangeland	6
Geomorphology	6	Meander Scar	9
		Paleo Channel	8
		Back Swamp	8
		Flood Plain	7
		Younger plain Alluvium	7
		Older Plain Alluvium	6
		Piedmont Alluvium	4
Drainage Density (Km/Sq.Km)	6	0 - 0.31	8
		0.31 -0.77	7
		0.77 - 1.28	6
		1.28 - 1.90	4
		1.90 - 3.20	3
Soil	6	Fine Loamy	6
		Coarse Loamy	8
		Fine Silty	5
Lineament Density (Km/Sq.Km)	5	Upto 0.046	3
		0.047 – 0.30	5
		0.31 – 0.64	6
		0.65 – 0.92	6
		0.93 -1.21	7
Rainfall (mm)	4	2032 - 2141	7
		2142 – 2211	7
		2212 – 2271	7
		2272 – 2330	8
		2331 - 2415	8
TWI	4	-7.4 - -3.3	8
		-3.2 - -1	7
		-0.9 - 1.3	5
		1.4 - 4.5	5
		4.6 - 13	3

3.0 Results and Discussions:

The eight thematic layers are thus prepared (Figure 4 & 5). The individual reclassified thematic layers are assigned weightage values to each comprising class, the consistency ratio is verified and sustained. The weighted values of each thematic class are further discussed.

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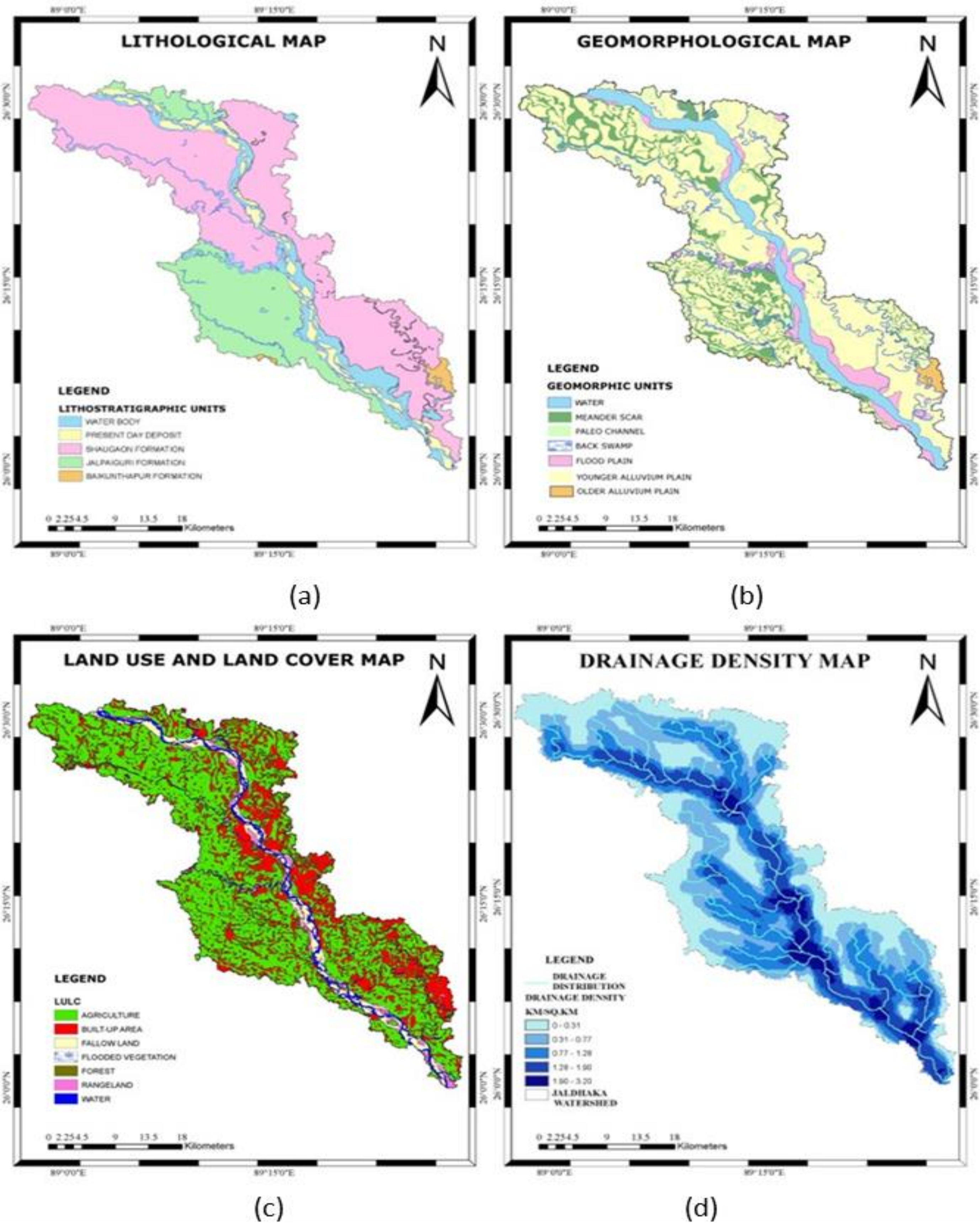

Figure 4. Lithological, Geomorphological, LULC and Drainage Density map of Jaldhaka Watershed.

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3.1 Lithology and Groundwater Recharge:

Lithological characteristics are a fundamental prerequisite for evaluating groundwater porosity and flow dynamics. The hydrogeological processes of groundwater recharge and development are significantly governed by the intrinsic properties of permeability and porosity (Akinlalu et al., 2017). The oldest geological unit in this area is the Baikunthapur Formation, dating from the Lower Holocene to the Upper Pleistocene epoch. This formation primarily comprises sediments of older alluvium, characterised by unconsolidated sand, silt, and clay with calcareous concretions. Overlying the Baikunthapur Formation is the younger Jalpaiguri Formation, exhibiting mildly oxidised sand, silt, and clay. The Shaugaon Formation is characterized by alternating strata of sand, silt, and clay (Figure 4a). Such cyclical deposition of sediments has the potential to create productive aquifers; furthermore, the unconsolidated nature of these sediments facilitates enhanced infiltration, underscoring the critical role of geology in determining an area's groundwater potential. Coarse to fine sand, silt, and clay are accorded a higher significance compared to silty and clay loams, which exhibit a lower rate of infiltration (Shekar et al., 2015).

3.2 Land use and Land cover (LULC) and Groundwater Recharge:

Preparing LULC maps from Landsat 8 imagery in ArcGIS entails acquiring data and applying radiometric/atmospheric corrections to obtain surface reflectance. Supervised classification is then performed using well-defined training samples and an appropriate algorithm. Finally, post-classification refinement and rigorous accuracy assessment validate the thematic output. Land Use and Land Cover (LULC) constitute significant factors influencing soil moisture retention, infiltration capacity, and surface runoff coefficients, which directly modulate groundwater recharge dynamics (Yeh et al., 2016). Areas characterised by agricultural land, water bodies, and vegetation (Figure 4c) exhibit favourable conditions for groundwater replenishment through water infiltration processes (Thapa et al., 2017). Natural vegetation zones have been assigned a moderately high significance due to the capacity of their vegetative cover to progressively attenuate surface flow and enhance infiltration rates (Bhattacharya et al., 2020). Agricultural landscapes present substantial potential for groundwater recharge (Biswas et al., 2020), whereas settlement areas typically exhibit lower groundwater recharge rates owing to reduced infiltration capacities.

3.3 Geomorphology and Groundwater Recharge:

Geomorphology, encompassing the landform and topographic characteristics of a region, stands as a principal determinant frequently employed in the spatial demarcation of groundwater potential zones (Kumar et al., 2016). The alluvium flood plains (Figure 4b) which are active reside along the rivers. Besides those, abandoned channels, meander scars, back swamps etc. also provide valuable insight into groundwater prospecting. A higher weightage has been assigned to the flood plains and meander scars as infiltration is higher that adds to the recharge volume and relatively lower values were assigned for the older alluvium plains.

3.4 Drainage Density and Groundwater Recharge:

The configuration of the drainage network is contingent upon the underlying lithology and serves as a significant indicator of the infiltration rate (Ganapuram et al., 2009). Drainage density (Figure 4d) exhibits an inverse relationship with permeability. Consequently, it constitutes a crucial parameter in the spatial delineation of groundwater potential zones. High drainage density is indicative of reduced infiltration and exerts a negative influence on the groundwater potential of the area. Conversely, low drainage density signifies high infiltration and thus contributes positively to the groundwater potential.

3.5 Soil and Groundwater Recharge:

Soil typology exerts a pivotal influence on the volume of water that can infiltrate into subsurface geological formations, thereby impacting groundwater recharge dynamics (Patra et al., 2018). The soil's texture (Figure 5a) and hydraulic characteristics are the primary factors taken into account when estimating the rate of infiltration. A sand rich soil will contribute more to the groundwater recharge whereas, a clay loam soil would be intermittent in percolating water under gravity. More clay content will highly affect groundwater recharge and pose a major threat when combined with heavy drawdown. Coarser materials are therefore assigned a higher value over finer sediments.

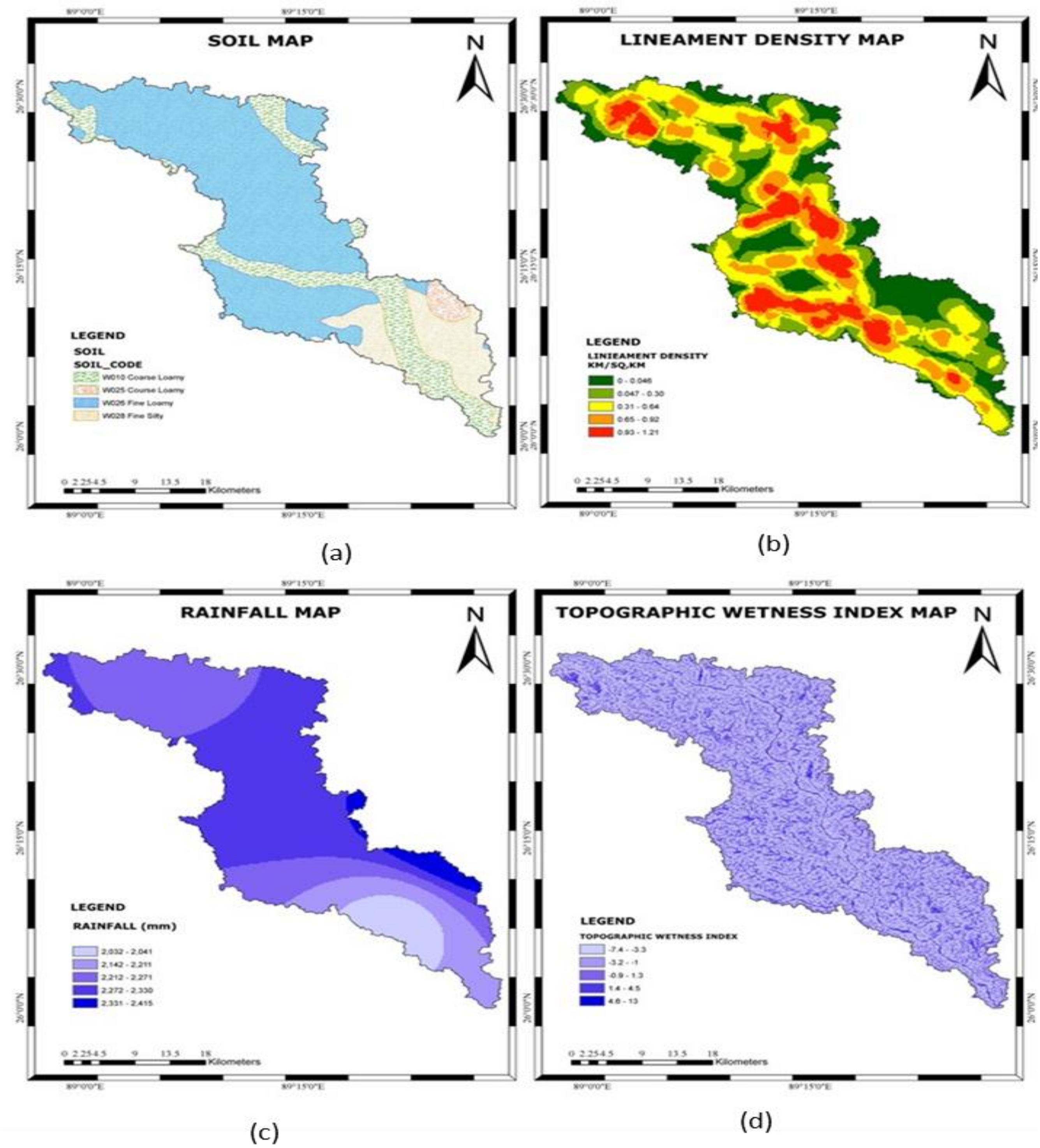

Figure 5. Soil, Lineament density, Rainfall intensity and TWI Map of Jaldhaka Watershed.

3.6 Lineament Density and Groundwater Recharge:

Lineaments, which can manifest as linear or curvilinear features, are geological expressions governed by structural controls. These features are identifiable in satellite imagery due to their predominantly rectilinear alignments (Nag and Kundu, 2016). Lineaments are indicative of zones characterized by faulting and fracturing, which enhance secondary porosity and permeability within the subsurface (Yeh et al., 2016). Lineament density is categorized and ranked based on the spatial proximity of these features (Figure 5b). It is observed that the magnitude of groundwater potential exhibits an inverse relationship with increasing distance from lineaments. Consequently, higher weightings are assigned to high-density lineament classes, and lower weightings to low-density classes.

3.7 Rainfall and Groundwater Recharge:

Precipitation constitutes the primary source of water within the hydrological cycle and represents the most significant influencing variable on the groundwater resources of a region. The spatial distribution of rainfall was delineated (Figure 5c) through the application of the Inverse Distance Weighting (IDW) interpolation technique. Rainfall events characterised by high intensity and short duration tend to result in diminished infiltration and increased surface runoff, conversely, precipitation of lower intensity and longer duration promotes greater infiltration relative to surface runoff (Ibrahim and Ahmed, 2016). Consequently, higher weightings are assigned to areas experiencing high rainfall, with an inverse relationship applied to areas of lower precipitation.

3.8 Topographic Wetness Index (TPI) and Groundwater Recharge:

The TWI map (Figure 5d) provides a quantitative measure of the potential for water accumulation at a given point, directly reflecting topographic influences. It essentially estimates the spatial distribution of soil moisture based on geomorphological controls.

The TWI is determined by the following formula:

$$TWI=\ln[\alpha/\tan(\beta)],$$

where: α represents the area upstream of a cell from which water can drain to that cell; β denotes the local slope angle (Mokarram et al., 2015). The higher TWI values are assigned higher weights and vice versa.

3.9 Groundwater Potential Zone Map:

The delineation of groundwater potential zones within the Jaldhaka watershed in Cooch Behar district was accomplished (Figure 6) through the application of the weighted overlay methodology. The resulting map is divided into 4 different classes as high, moderate, poor and very poor groundwater potential zones, covering 11% (103 sq.km), 65% (610 sq.km), 21% (197 sq.km), and 3% (28 sq.km) respectively. The higher potential areas mostly fall into parts of Mathabhanga II, Mekhligunj and some patches in Mathabhanga I and Sitalkuchi blocks. The very lower potential zone is mostly concentrated in the Dinhata I block. The Jaldhaka river drains the area with its tributaries across the seven blocks where mostly active flood plain prevails. Owing to the fact that the drainage density is very high in these parts of the area, huge volume of water ends up as surface run-offs. Only regions with high lineament density have some potential for higher infiltration, thereby recharging groundwater. Shallow aquifers are easily affected by these factors whereas the deep-seated ones are more depleted by anthropogenic activity owing to multi-cropping and heavy withdrawal for irrigation purposes.

The groundwater potential zones thus prepared are further subjected to cross-validation from existing 42 well data (Figure 7) from Central Ground Water Board (CGWB) and field collected data (Table 6). Around 10% or 4 wells are found to be of very low yield mostly concentrated in the Dinhata I block. 9 of the wells comprising 21% are found to be below average potential. Maximum well data comprising 57% or 24 wells are moderately affecting the groundwater potential and only 5 wells or 12% scattered around the blocks of Mekhligunj, Mathabhanga I & II and parts of Sitalkuchi are of high potential. These data correspond to the GWPZ map zones delineated. Higher potential wells yield in the range of 100 – 200 LPM whereas the lower potential values are 10 – 50 LPM, with intermediate values therein (Table 6).

Table 6. GWPZ validation results.

GWPZ class	Percentage of Wells	Approximate Yield
Very low	10% (04)	10 LPM
Low	21% (09)	10 – 50 LPM
Moderate	57% (24)	~100 LPM
High	12% (05)	100 – 200 LPM

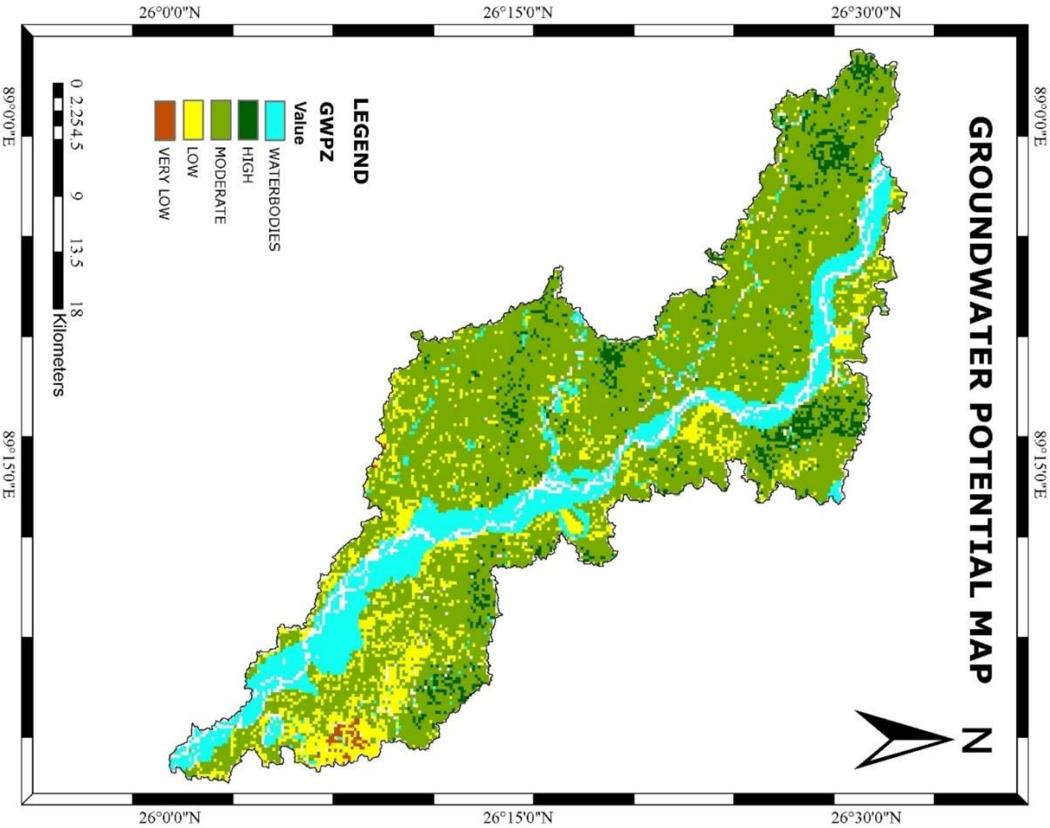

Figure 6. GWPZ Map of Jaldhaka Watershed.

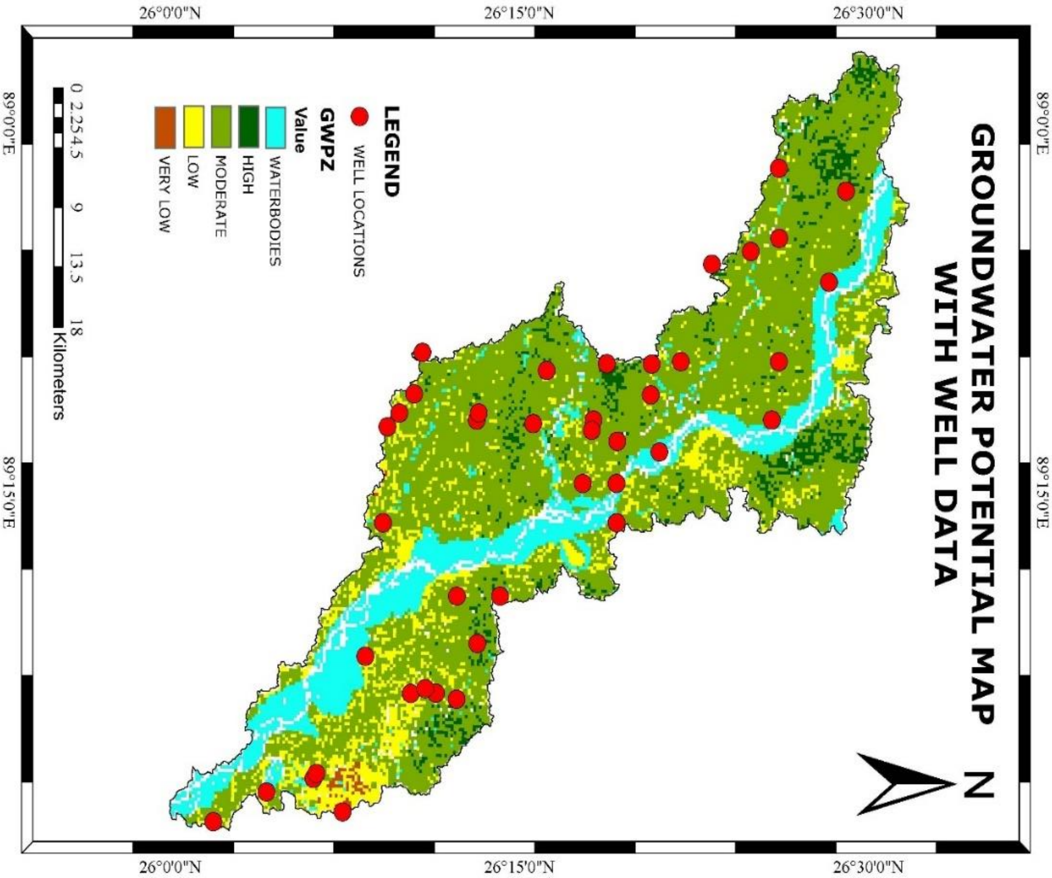

Figure 7. The GWPZ Map validated against well data values.

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Table 7. Detailed Ground Water Exploration (Govt. & Pvt.) in Jaldhaka Watershed, Cooch Behar district, West Bengal.

Sl. No.	Latitude	Longitude	Block	Location	Depth To Water Table (mbgl)	well	type	Use	Total Depth of Well (mbgl)	Yield LPM	Lithology
1	26.0686	89.4525	Dinhata I	Panchatory	1.83	OHP	DW	Irrigation	15	80 - 150	Recent Alluvium
2	26.1022	89.4433	Dinhata I	Sinhabari	1.65	OHP	DW	Multipurpose	14	Oct-50	Older Alluvium
3	26.1522	89.2703	Sitalkuchi	Chara	3.1	M-II	TW	Multipurpose	88	50 - 80	Younger Alluvium
4	26.0333	89.1203	Sitalkuchi	Chapta	3.76	M-II	TW	Multipurpose	85	50- 80	Younger Alluvium
5	26.1719	89.3858	Dinhatai	Kapibii	1.63	M-II	TW	Multipurpose	86	50- 80	Younger Alluvium
6	26.19	89.3856	Dinhatai	Charkapara	1.82	M-II	TW	Multipurpose	80	80 - 150	Younger Alluvium
7	26.205	89.32	Coochbeh ari	Chadarima	1.73	M-II	TW	Multipurpose	86	80 - 150	Younger Alluvium
8	26.2192	89.2006	Sitalkuchi	Babra pali	3.12	M-II	TW	Multipurpose	85	80 - 150	Younger Alluvium
9	26.2197	89.3519	Coochbeh ari	Kirahi	2.45	M-II	TW	Multipurpose	85	100 - 200	Recent Alluvium
10	26.2361	89.32	Coochbeh ari	Marapa	1.92	M-II	TW	Multipurpose	90	80 - 150	Younger Alluvium
11	26.2694	89.1672	Sitalkuchi	Sonarchalu	2.64	M-II	TW	Multipurpose	80	100 - 200	Recent Alluvium
12	26.295	89.2436	Mathabha ngai	Naidapara	3.21	M-II	TW	Multipurpose	88.5	50- 80	Recent Alluvium
13	26.3028	89.2006	Mathabha ngai	Kunamadi	2.12	M-II	TW	Multipurpose	85	80 - 150	Younger Alluvium
14	26.3122	89.1625	Mathabha ngai	Dhabdaguri	1.93	M-II	TW	Multipurpose	86	100 - 200	Recent Alluvium
15	26.3192	89.2436	Mathabha ngai	Laspa	2.52	M-II	TW	Multipurpose	85	80 - 150	Younger Alluvium

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Sl. No.	Latitude	Longitude	Block	Location	Depth To Water Table (mbgl)	well	type	Use	Total Depth of Well (mbgl)	Yield LPM	Lithology
17	26.35	89.2222	Mathabhanga I	Nidi II	1.75	M-II	TW	Multipurpose	98	80 - 150	Younger Alluvium
18	26.3653	89.1611	Mathabhanga I	Nidi II	1.54	OHP	TW	Irrigation	88.5	80 - 150	Younger Alluvium
19	26.3853	89.0858	Mathabhanga I	Rampakuri	0.65	OHP	DW	Irrigation	9.53	80 - 150	Younger Alluvium
20	26.4306	89.2006	Mathabhanga I	Hairahas	2.84	M-II	TW	Multipurpose	75	80 - 150	Younger Alluvium
21	26.4356	89.1611	Mathabhanga I	Bamudin	2.76	M-II	TW	Multipurpose	85	80 - 150	Younger Alluvium
22	26.4358	89.0778	Mathabhanga I	Dhandhian	2.65	M-II	TW	Multipurpose	85	80 - 150	Younger Alluvium
23	26.4714	89.1075	Mathabhanga I	Koihira	0.92	M-II	TW	Multipurpose	98	80 - 150	Younger Alluvium
24	26.4836	89.0458	Mekhligunj	Gopapio	1.98	M-II	TW	Multipurpose	88.5	100 - 200	Recent Alluvium
25	26.0305	89.4727	Dinhata I	Jot srinarayan	3.12	OHP	TW	Irrigation	85	50- 80	Younger Alluvium
26	26.1044	89.44	Dinhata I	Bara solmari I	2.45	OHP	TW	Irrigation	85	Oct-50	Older Alluvium
27	26.1044	89.44	Dinhata I	Bara solmari II	1.92	M-II	TW	Multipurpose	90	Oct-50	Older Alluvium
28	26.1232	89.4659	Dinhata I	Dinhata	2.64	M-II	TW	Multipurpose	80	Oct-50	Older Alluvium
29	26.1394	89.3606	Dinhata I	Gosaimari bandor	3.21	M-II	DW	Multipurpose	12	50- 80	Younger Alluvium
30	26.1553	89.2053	Sitalkuchi	Goila nauhati	2.12	M-II	TW	Multipurpose	86	50- 80	Younger Alluvium
31	26.1743	89.183	Sitalkuchi	Sathkuthi	1.93	M-II	TW	Drinking	28	80 - 150	Younger Alluvium
32	26.1805	89.1548	Sitalkuchi	Rajabari	2.52	M-II	TW	Drinking	21	80 - 150	Younger Alluvium

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Sl. No.	Latitude	Longitude	Block	Location	Depth To Water Table (mbgl)	well	type	Use	Total Depth of Well (mbgl)	Yield LPM	Lithology
33	26.1805	89.1548	Sitalkuchi	Rajabari	1.43	M-II	DW	Drinking	11	80 - 150	Younger Alluvium
34	26.1824	89.3825	Dinhata I	Chakyapara	1.75	M-II	TW	Multipurpose	95	50- 80	Younger Alluvium
35	26.2048	89.3896	Coochbehar I	Nalangibari	1.54	M-II	TW	Multipurpose	82	80 - 150	Younger Alluvium
36	26.2598	89.2032	Sitalkuchi	Kaimari	0.65	OHP	TW	Irrigation	88	80 - 150	Younger Alluvium
37	26.3016	89.2077	Mathabhnaga I	Nendrapar	2.84	M-II	TW	Multipurpose	94	80 - 150	Younger Alluvium
38	26.3197	89.2151	Mathabhnaga I	Kursamari	2.76	OHP	TW	Irrigation	90	100 - 200	Recent Alluvium
39	26.3437	89.1838	Mathabhnaga I	Mathabhnaga	2.65	OHP	TW	Irrigation	82	80 - 150	Younger Alluvium
40	26.3443	89.1629	Mathabhanga I	Shikarpur	0.92	M-II	TW	Multipurpose	87	80 - 150	Younger Alluvium
41	26.4153	89.0865	Mathabhanga I	Gopalpur	1.98	M-II	DW	Drinking	15	50- 80	Younger Alluvium
42	26.4356	89.0303	Mekhligunj	Lanaldaha	3.12	OHP	TW	Irrigation	85	80 - 150	Younger Alluvium

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4.0 Conclusion:

Remote sensing satellite imagery, DEMs and conventional data have been used to prepare eight thematic layers namely, Lithology, LULC, Geomorphology, Drainage Density, Lineament Density, Soil and Topographic Wetness Index maps and these are integrated through the application of GIS. Input raster maps are reclassified to a common measurement scale. Each raster map is assigned a percentage influence. The discrete reclassification of raster is essential in the overlay analysis. The integrated approach using the Remote Sensing technique and Geographic Information System along with the aid of Analytical Hierarchy Process (AHP) is the perfect platform to find out the groundwater prospect map for its judicious development and management. The output GWPZ map provides a clear picture that almost 65% of the area is moderate to high range in groundwater potential. While there are pockets of low potentials ranging around 3% to 21%, they can be remedied by suitable measures like artificial recharge, rain water harvesting and strict management enforcement on unrestricted groundwater exploitation. As zones for groundwater potential have been identified, concerned decision-makers/planners would be able to enforce a groundwater management plan in the study area to safeguard the sustainability of this vital resource.

Recommendations for Future Groundwater Sustainability:

#Prioritising High Potential Zones for Sustainable Extraction: Future groundwater development should initially focus on the identified as "very high" potential zones. Extraction rates in these areas should be carefully monitored to ensure they remain within sustainable limits and do not lead to depletion or land subsidence.

#Implementing Integrated Water Resource Management: Adopt an integrated approach that considers surface water and groundwater as interconnected resources. Management strategies should account for the interaction between rainfall, surface runoff, infiltration, and groundwater recharge across different LULC and geomorphic units.

#Promoting Water-Efficient Agricultural Practices: Given the agricultural nature of the district, promoting and incentivising water-efficient irrigation techniques (e.g., drip irrigation, sprinkler systems) can significantly reduce groundwater demand. Education and subsidies can encourage farmer adoption of these practices.

#Enhancing Groundwater Recharge in Suitable Zones: Implement measures to enhance natural groundwater recharge, particularly in areas identified as having high infiltration rates (e.g., flood plains, meander scars, areas with sandy soils and natural vegetation). This could involve rainwater harvesting structures, permeable pavements in settlements, and the preservation/restoration of natural infiltration zones.

#Regulating Groundwater Extraction and Monitoring Water Levels: Establish and enforce regulations on groundwater extraction for domestic, agricultural, and industrial purposes. Implement a comprehensive monitoring network to track groundwater levels across different potential zones to detect early signs of depletion and inform adaptive management strategies.

#Protecting and Enhancing Natural Vegetation: Recognize the role of natural vegetation in promoting infiltration and reducing surface runoff. Efforts should be made to protect existing natural vegetation and promote afforestation/reforestation initiatives, particularly in moderately high-weighted areas identified in the LULC analysis.

#Implementing Soil and Land Management Practices: Promote soil health management practices that enhance soil structure and infiltration capacity, especially in agricultural areas. Sustainable land management practices can improve water retention and reduce runoff, thereby contributing to groundwater recharge.

#Integrating Climate Change Projections: Future water resource planning should incorporate climate change projections, which may impact rainfall patterns and groundwater recharge rates. Adaptive management strategies should be developed to address potential future vulnerabilities.

#Community Engagement and Awareness: Engage local communities and stakeholders in groundwater management efforts. Raising awareness about the importance of sustainable groundwater use and the findings of this study is crucial for fostering responsible water stewardship.

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By implementing these recommendations, the Jaldhaka watershed area in Cooch Behar district can work towards ensuring the long-term sustainability of its vital groundwater resources, supporting agricultural activities, domestic needs, and overall environmental health.

5.0. Conflict of interest:

The authors do not claim any conflict of interest based on the presented work.

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