AHP and GIS-based Delineation of Groundwater Potential of Papumpare District of Arunachal Pradesh (India)

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AHP and GIS-based Delineation of Groundwater Potential of Papumpare District of Arunachal Pradesh (India)

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Abstract

Water is crucial to human survival. Studies on surface water are well documented but precise knowledge of groundwater resources is difficult. Thus, accurate knowledge of groundwater resources could meet the necessities of water at present and in the long run. The application of the Analytic Hierarchy Process (AHP) and Geographical Information System (GIS) together with multi-criteria parameters has emerged as an efficient technique for delineation of groundwater potential in recent decades. However, no efforts to delineate the groundwater potential have been attempted in the study area to date. Hence, in this study, the groundwater potential of Papumpare district of Arunachal Pradesh was delineated by combining AHP, GIS, and ten thematic layers (geomorphology, geology, slope, lineament density, drainage density, rainfall, distance from the major river, topographic wetness index, soil texture, and land use/land cover). The results show about 64% of the area under poor groundwater potential. Moderate and good groundwater potential is found in 31% and 5% of the area, respectively. Map-removal and single-parameter sensitivity analyses revealed that the groundwater potential map is most sensitive to the annual average rainfall with a mean variation index of 1.05% and a weight of 19.07%. The flood/alluvial plains, Siwalik formations with sediments, and level to gentle slopes receiving high rainfall show good potential, and the dissected hills/valleys, metamorphic rock assemblages, steep slopes with low rainfall reveals poor groundwater potential. The overall accuracy of 81.25% with a Kappa coefficient of 0.72 explains good agreement between the reference data and the map. The estimated area under good groundwater potential appears too little concerning the increasing population and urbanization. Therefore, the state government in general and the water resources and planning department in particular need to formulate suitable strategies to combat the water scarcity scenario waiting ahead. The study suggests raising the use of surface water from nearby rivers to lessen the pressure on groundwater resources.

Keywords: AHP; GIS; Groundwater; Overlay analysis; Papumpare district.

Introduction

Groundwater is a dynamic and replenishable natural resource of the earth's surface (Jose et al. 2012). Around 34% of the total freshwater resources available worldwide constitute groundwater resources (Shekhar and

Pandey 2015). The dependency on groundwater for various uses is rapidly increasing worldwide, specifically in and around the urban centers. Globally, the groundwater resources are under pressure due to over-exploitation coupled with marked changes in climate over the years.

In India, more than 90% of rural people and almost 30% of urban people depend on groundwater for drinking and domestic needs leading to overexploitation in some parts of the country (Parthasarathy and Deka 2019). The estimated withdrawal rate of groundwater in India is 251 km^3 per year (Gun 2012). About 85% of rural drinking water needs, 65% of irrigation needs, and 50% of urban drinking water and industrial needs of the country are fulfilled with groundwater (India Water Portal 2019). The growing population, urbanization, and agricultural activities demand the creation of more groundwater resources (Bhunia et al. 2012). The northern and eastern states such as Assam, Punjab, Haryana, Uttar Pradesh, Bihar, and West Bengal experienced a rapid decline in usable groundwater between 2005 and 2013, raising the risk of severe droughts, food crisis, and drinking water for millions of people (Mukherjee and Bhanja 2019). About 0.6 billion people in the country face high to too high water stress due to the scarcity of freshwater, while about three-fourths of the households cannot access potable water (NITI Aayog 2018). In the absence of strict measures, by 2025, India will become a water stress zone and, subsequently, a water-scarce zone by the year 2050 (World Bank 2005).

Arunachal Pradesh has 2.56 billion cubic meters (BCM) of annual replenishable groundwater resources and 2.30 BCM of net annual groundwater availability. The annual replenishable groundwater resources of Papumpare district was 132.58 million cubic meters (MCM) with net groundwater availability of 119.32 MCM (TERI School of Advanced Studies 2018). The demand for utilization of groundwater for domestic water consumption in the district is likely to increase manifold in the future due to the growing population and urbanization.

Delineation of groundwater potential is useful for conservation, implementation, and management strategies (Jose et al. 2012). The evaluation of groundwater potential and productivity of aquifers is essential to address the increasing potable water demand for human consumption, agriculture, and industrial uses across the world (Arulbalaji et al. 2019). Hence, precise quantitative assessment based on modern scientific tools is a pre-requisite for the sustainable management of groundwater resources (Agarwal et al. 2013). The integrative technique of Remote Sensing (RS) and Geographical Information Systems (GIS) are useful in the delineation of the groundwater potential of an area (Murthy et al. 2003). Conventionally, geological, hydrogeological, geophysical, and photogeological techniques were employed to delineate the groundwater potential zones (Pinto et al. 2017). Later, RS and GIS techniques have been used along with geomorphology and other associated parameters (Sree Devi et al. 2001; Rao et al. 2004) and hydrologic parameters with encouraging results (Madrucci et al. 2008; Chowdhury et al. 2009). Multi-criteria decision-making using Analytic Hierarchy Process (AHP) is the most common and well-known method for delineating groundwater potential. Recently, many researchers have applied RS, GIS, and Analytic Hierarchy Process (AHP) to delineate groundwater potential based on multi-parameters (Arulbalaji et al. 2019; Rajasekhar et al. 2019; Singha et al. 2019; Ghosh et al. 2020; Halder et al. 2020). Therefore, an attempt has been made to delineate the groundwater potential of Papumpare district of Arunachal Pradesh (India) by integrating RS, GIS, and AHP based on the influencing parameters.

Materials and Methods

Study area

The study area is the Papumpare district of Arunachal Pradesh, India. It covers an area of 3529.9 km^2, approximately. It is located between 26° 56’ 17” to 27° 38’ 32” N and 93° 12’ 43” to 94° 12’ 36” E (Fig. 1). The elevation ranges between 88 to 3,743 m above Mean Sea Level (MSL). The area receives heavy rainfall from the South-West Monsoon. The natural vegetation is mainly tropical semi-evergreen and sub-tropical evergreen forests.

Database

The databases used to generate the ten thematic layers in this study are shown in Table 1.

Table 1: Details of the database used in the study

Database	Data used for	Source	Access date
ASTER GDEM (30 meter resolution)	Slope, Drainage density, Distance from the major river, and TWI	https://search.earthdata.nasa.gov	2nd September 2020
Geomorphology	Geomorphology	http://bhukosh.gsi.gov.in	1st September 2020
Geology	Geology	http://bhukosh.gsi.gov.in	1st September 2020
Soil Characteristics	Soil texture	National Bureau of Soil Survey and Land Use Planning (NBSS & LUP)	Hard copy
Landsat 8-OLI (30 m Spatial resolution)	LULC and Lineament density	https://earthexplorer.usgs.gov	3rd September 2020
Average annual rainfall (Bio12)	Rainfall map	https://www.worldclim.org	7th September 2020

Creation of thematic maps

The study considered ten multi-thematic layers viz. geomorphology, geology, slope, lineament density, drainage density, rainfall, distance from the major river, Topographic wetness index (TWI), soil texture, and Land use/land cover (LULC).

The geomorphic landforms are of paramount importance in the evaluation of the groundwater potential (Roy et al. 2019) due to diverse lithology and undulating structures created by long periods of surface processing (Rejith et al. 2019). On the other hand, the geological characteristics reflect the aquifer status and thereby the groundwater storage (Çelik 2019). The geomorphology and geology maps in shapefile format were downloaded from the website of the Geological Survey of India. Slope plays an essential role in groundwater recharge. Steep slopes lead to rapid runoff formation and low infiltration rates (Rajaveni et al. 2017). The ASTER GDEM data was used to generate the slope map using the spatial analyst tool of ArcGIS 10.3. Lineaments are produced by tectonic activities, reflecting a general surface manifestation of underground fractures with inherent characteristics of porosity and permeability of the underlying materials (Rao 2006). The automatic extraction of lineaments using Geomatica software is a useful way to delineate lineaments for different purposes (Sedrette and Rebai 2016). So, the Landsat 8-OLI (Band-8) was used to extract the lineament density in Geomatica 2012 software. Drainage density is a significant parameter for evaluating the groundwater potential zones (Shekhar and Pandey 2015). The drainage density was generated from ASTER GDEM using ArcGIS 10.3. The annual average rainfall map was derived using the Worldclim database. The distance from the major river was derived from the drainage map by creating a buffer in ArcGIS 10.3. TWI, originally proposed by Beven and Kirby (1979) determines the spatial distribution of wetness conditions in a regional topography and ascertains the tendency of water accumulation and the gravitational attraction to move water down the slope (Bera et al. 2020). The TWI map was calculated by using Equation (1):

$$\text{TWI} = ln\left(\frac{As}{tan\beta}\right) \quad \textbf{Eq. 1}$$

Where, As denotes the upslope contributing area and β denotes the topographic gradient (Slope).

Soil is a significant parameter in identifying groundwater potential zones (Magesh et al. 2012). The soil texture map was prepared using the NBSS & LUP data. The ancillary data was converted into a raster format and reclassified for further processing. The LULC provides important information about the utilization, requirements, and extent of groundwater occurrences (Nithya et al. 2019). The LULC was classified using Landsat 8 – OLI image through supervised classification (Maximum Likelihood Algorithm) in ERDAS Imagine 2014 version.

Finally, all the layers were clipped to the Area of Interest (AOI) with equal geographic dimensions using ArcGIS 10.3. The Analytic Hierarchy Process (AHP) was used to assign weights to each layer. And the groundwater potential map was generated using Weighted Overlay Analysis (WOA) from the reclassified parameters (Fig. 2).

Analytic hierarchy process

Based on the literature review and expert's opinions, the weights were assigned to each thematic layer as per their importance of influence in groundwater potential (Saaty 1980). The expert's opinions were collected from the geomorphologists, geologists, hydrogeologists, and local officials associated with groundwater resources through a questionnaire-based survey. The weights for the selected thematic layers and their sub-categories were assigned on Saaty's nine points scale based on the expert opinions, past studies, and field experiences. After that, the pair-wise comparison matrices of the assigned weights for thematic layers (Table 2) and subcategories have been constructed. Then, the relative importance values were determined, where a score of 1 represents equal influence between the two thematic criteria while a score of 9 indicates the extreme influence of one thematic layer over the other. The assigned weights were then normalized to reduce the dimensionality associated with the assigned weights of the thematic layers (Mallick et al. 2015). The uncertainties in judgments have been examined through the principal eigenvalue and consistency index (Saaty 2004).

To measure the consistency of pair-wise comparison, the Consistency Index (CI), which is a measure of deviation or degree of consistency, was calculated by Equation (2):

$$\text{Consistency Index} = \frac{\lambda_{\max} - n}{n-1} \quad \textbf{Eq. 2}$$

Where $\lambda_{\max}$ shows the largest eigenvalue of the pair-wise comparison matrix,

n is the total number of parameters

Table 2: Pair-wise comparison matrix of the thematic layers

Thematic layers	GM	GL	SL	LD	DD	RN	DR	TWI	ST	LULC
GM	1.00	2.00	2.00	3.00	3.00	2.00	4.00	5.00	5.00	2.00
GL	0.50	1.00	2.00	3.00	2.00	2.00	3.00	3.00	4.00	2.00
SL	0.50	0.50	1.00	4.00	2.00	0.50	4.00	4.00	2.00	3.00
LD	0.33	0.33	0.25	1.00	0.33	0.33	4.00	3.00	0.33	2.00
DD	0.33	0.50	0.50	3.00	1.00	0.33	2.00	2.00	0.50	2.00
RN	0.50	0.50	2.00	3.00	3.00	1.00	4.00	2.00	2.00	3.00
DR	0.25	0.33	0.25	0.25	0.50	0.25	1.00	0.50	0.33	0.50
TWI	0.20	0.33	0.25	0.33	0.50	0.50	2.00	1.00	0.33	0.50
ST	0.20	0.25	0.50	3.00	2.00	0.50	3.00	3.00	1.00	2.00
LULC	0.50	0.50	0.33	0.50	0.50	0.33	2.00	2.00	0.50	1.00

GM: Geomorphology, GL: Geology, SL: Slope, LD: Lineament density, DD: Drainage density, RN: Rainfall, DR: Distance from the major river, TWI: Topographic wetness index, ST: Soil texture, LULC: Land use/land cover.

To check the consistency analysis and the judgment scale, the Consistency Ratio (CR), which is a measure of the consistency of the pair-wise comparison matrix, was calculated by Equation (3):

$$\text{Consistency Ratio (CR)} = \frac{\text{Consistency Index (CI)}}{\text{Random Consistency Index (RI)}} \qquad \textbf{Eq. 3}$$

Where RI is the Ratio index (Table 3)

The value of CR should be less than 0.1 for consistent weights. If the CR is equal to 0, it means the judgment of the pair-wise comparison matrix is perfectly consistent; otherwise, corresponding weights should be re-evaluated to avoid inconsistency.

Table 3: Random consistency indices (RI) taken from Saaty (1980)

N	1	2	3	4	5	6	7	8	9	10	11	12	13
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.53	1.56

Delineation of groundwater potential map

The groundwater potential was estimated using the formula suggested by Kumar et al. (2014):

$$GWP = (GM_wGM_r) + (GL_wGL_r) + (SL_wSL_r) + (LD_wLD_r) + (DD_wDD_r) + (RN_wRN_r) + (DR_wDR_r) + (TWI_wTWI_r) + (ST_wST_r) + (LULC_wLULC_r)$$

Where, GWP (Groundwater potential), ‘w’ (normalized weight of parameters), and ‘r’ (sub-criteria class ratings).

Sensitivity analysis

Sensitivity analysis provides important information related to the influence of assigned weights to each thematic layer on the output of the GWP map. It can indicate which layer is the most/least significant in determining the output map (Fenta et al. 2015). Hence, both map-removal (Lodwick et al. 1990) and single-parameter (Napolitano and Fabbri 1996) sensitivity analyses were carried out to justify the influence of thematic layers on the

GWP map. The map-removal method recognizes the sensitivity of the GWP map to the removal of each thematic layer from the analysis. It can be determined using Equation (4):

$$S = \frac{\left|\frac{A}{N} - \frac{B}{n}\right|}{A} \times 100 \qquad \textbf{Eq. 4}$$

Where S is the index of sensitivity analysis associated with the removal of one map,

A is the groundwater potential index computed using all the thematic layers,

B is the groundwater potential index computed by excluding one thematic layer at a time,

N and *n* are the numbers of thematic layers used to compute *A* and *B* respectively.

The single-parameter method examines the impact of each thematic layer on the GWP map. This test compares the “effective” or “real” weight for each of the thematic layers with the “empirical” weight assigned to the same layer in the GWP map. The effective weight was calculated using Equation (5):

$$W = \frac{P_r P_w}{A} \times 100 \qquad \textbf{Eq. 5}$$

Where W is the effective weight of each thematic layer,

Pr and *Pw* are the rates and weight values of each thematic layer,

A is the groundwater potential map generated using all the thematic layers.

Validation

The GWP map was validated through an accuracy assessment using the groundwater level (below the surface) data of 14 Central Groundwater Board (CGWB) observation wells (Groundwater Year Book 2019) and supplemented by field visits and interviews with owners of 50 dug wells from November to December 2020. The methods used in the study conform to the relevant guidelines and regulations. The protocol was approved by the Institutional Ethical Committee of Rajiv Gandhi University, Itanagar, India (Ref. No. IEC/RGU/01). Both oral and written informed consent to participate was also obtained from all the respondents.

Results and Discussion

The relative weights obtained from AHP were assigned to each thematic layer and cumulative weights were generated. The highest or lowest weights were assigned as per the real situation on the field (Table 4). In this study, the CR of pair-wise comparison for all the parameters was 0.07, which shows the comparisons of evaluation criteria are reasonably consistent.

Table 4: Consistency ratio, normalized weights, and ratings of the parameters

Thematic layers	Domain of effect	Ratings	Normalized weights (Subcategories)	Consistency ratio	Normalized weights (Thematic layers)
Geomorphology	Rivers	5	0.17	0.011	0.21
	Water bodies	5	0.17		
	Active Flood Plain	4	0.10		
	Older Flood Plain	4	0.10		
	Younger Alluvial Plain	4	0.10		
	Older Alluvial Plain	4	0.10		
	Piedmont Alluvial Plain	4	0.10		

	Mass Wasting Products	1	0.02		
	Piedmont Slope	2	0.03		
	Pediment Pediplain Complex	3	0.05		
	Highly dissected structural hills and valleys	1	0.02		
	Moderately dissected structural hills and valleys	1	0.02		
	Low dissected structural hills and valleys	1	0.02		
Geology	Potin Formation	1	0.05	0.002	0.16
	Garubathan Formation	3	0.13		
	Miri Formation	3	0.13		
	Sela Group	1	0.05		
	Sediments	5	0.23		
	Granite	1	0.05		
	Undifferentiated Potin and Khetabari Formation	1	0.05		
	Middle Siwalik Group	5	0.23		
	Bichom Formation	2	0.08		
Slope	Level to gentle slope (0°-2°)	5	0.47	0.028	0.13
	Gentle slope (2°-5°)	4	0.26		
	Moderate slope (5°-10°)	3	0.16		
	Steep slope (10°-45°)	2	0.08		
	Precipitous to vertical slope (45°-90°)	1	0.03		
Lineament density (km^2)	Very low (0-0.66)	1	0.05	0.050	0.07
	Low (0.66-1.32)	2	0.09		
	Moderate (1.32-1.98)	3	0.15		
	High (1.98-2.64)	4	0.28		
	Very high (2.64-3.30)	5	0.43		
Drainage density (km^2)	Very low (0.02-0.77)	5	0.43	0.040	0.07
	Low (0.77-1.52)	4	0.30		
	Moderate (1.52-2.27)	3	0.16		
	High (2.27-3.02)	2	0.07		
	Very high (3.02-3.77)	1	0.04		
Rainfall (cm)	Very low (67-119)	1	0.06	0.015	0.14
	Low (119-171)	2	0.10		
	Moderate (171-223)	3	0.16		
	High (223-275)	4	0.26		
	Very high (275-327)	5	0.42		
Distance from the major river (m)	Upto 200	5	0.43	0.056	0.03
	200-500	4	0.28		
	500-1000	3	0.15		
	1000-2000	2	0.09		
	Above 2000	1	0.05		
Topographic Wetness Index	1.69-5.14	1	0.06	0.021	0.04
	5.14-8.59	2	0.09		
	8.59-12.04	3	0.15		
	12.04-15.49	4	0.29		
	15.49-18.94	5	0.41		
Soil texture	Loam: Moderately hill side-slope	3	0.08	0.007	0.09
	Clay Loam: Moderately hill side-slope	2	0.04		
	Fine Clay Loam: Well-drained moderately hill side-slope	1	0.03		
	Fine Loam: Moderately hill side-slope	4	0.13		
	Fine Loam: Well-drained moderately hill side-slope	4	0.13		
	Fine Clay: Moderately hill side-slope	1	0.03		
	Fine Loamy-skeletal: Very steep slope	2	0.04		

	summit				
	Fine Loam: Moderately steep slope summit	2	0.04		
	Loamy-skeletal: Steep slope summit	3	0.08		
	Loamy-skeletal: Moderately steep hill side-slope	3	0.08		
	Fine Loam: Steep hill side-slope	3	0.08		
	Fine Loamy-skeletal: Moderately hill side-slope	3	0.08		
	Coarse Loamy: Piedmont	5	0.16		
Landuse/ Landcover	Forest cover	5	0.25	0.021	0.06
	Cropland	4	0.15		
	Water bodies	5	0.25		
	Built-up areas	2	0.07		
	Sandbank	5	0.24		
	Wasteland	1	0.04		

Geomorphology

The highest weight was assigned to geomorphology as it plays important role in the movement and storage of groundwater (Thomas et al. 2009). The study area has been divided rivers, other water bodies, active flood plain, older flood plain, younger alluvial plain, older alluvial plain, piedmont alluvial plain, mass wasting products, piedmont slope, pediment pediplain complex, highly dissected structural hills and valleys, moderately dissected structural hills and valleys and low dissected structural hills and valleys (Fig. 3). Out of the total area, 52.37 km^2 (1.49%) was under rivers and other water bodies, which plays a vital role in groundwater recharge. The floodplains and alluvial plains cover 94.63 km^2 (2.67%) which shows high groundwater potential due to the high infiltration rate of weathered material deposits (Thapa et al. 2017). A significantly less area of 0.13 km^2 is under denudational origin, which is considered suitable for groundwater recharge (Murmu et al. 2019). Structural hills are controlled with complex folding, faulting with numerous joints and fractures that mostly act as a runoff zone and facilitate a limited infiltration (Deepika et al. 2013). An area of 3359 km^2 (95.16%) is under the structural origin of dissected hills and valleys. The piedmont slope covers 21.35 km^2 (0.60%) and mass wasting products 2.38 km^2 (0.07%), which have medium to low potential of groundwater (Raju et al. 2019).

Geology

The geological formations of the study area include Potin, Garubathan, Miri, Sela group, Sediments, Granite, Undifferentiated Potin and Khetabari, Middle Siwalik group, and Bichom (Fig. 4). The occurrence and movement of groundwater depend on the porosity and permeability of rocks that are different for each rock type (Balaji et al. 2019). Hence, the formations were grouped into three lithological categories: Granite-Gneiss-Schist-Amphibolite, Quartzite-Phyllite-Metagraywacke-Chert, and Conglomerate-Sandstone-Shale. The first group is found in Potin, Sela, Granite, and Undifferentiated Potin and Khetabari formations while Quartzite- Phyllite-Metagraywacke-Chert is found in Garubathan, Miri, and Bichom formations. The Middle Siwalik group and Sediments mostly consists of Conglomerate-Sandstone-Shale. A high weight was given to Conglomerate-Sandstone-Shale, moderate weight to Quartzite-Phyllite-Metagraywacke-Chert, and lower weight for Granite-Gneiss-Schist-

Amphibolite. The Conglomerate-Sandstone-Shale which covers 34% of the total area is considered good aquifers due to highly weathered and fractured characteristics (Abijith et al. 2020) whereas the Granite-Gneiss-Schist-Amphibolite has less groundwater potential due to hardness and low fractures.

Slope

The areas having low-slope are favorable for groundwater occurrence due to a longer duration of travel time to downstream or provide adequate time for infiltration to increase groundwater recharge (Rajaveni et al. 2017). Thus, the highest ratings were assigned to the low slope degree areas. The study area has been classified into five slope categories viz. level to gentle (0 - 2°), gentle (2 - 5°), moderate (5 - 10°), steep (10 - 45°), and precipitous to vertical slope (45° and above). The level to gentle slope cover 12.87 km^2 (0.36%) and gentle slope 40.92 km^2 (1.16%) of the total area, which forms the suitable locations of groundwater potential. About 94.87 km^2 (2.69%) of the area was under the moderate slope, and the majority of the area was under steep and precipitous slope covering an area of 1516.76 km^2 (42.97%) and 1864.44 km^2 (52.82%), respectively that are unsuitable for groundwater recharge (Fig. 5).

Lineament density

The lineament density of an area can indirectly expose the groundwater potential since the lineaments usually denote a porous zone. The areas with high lineament density are considered excellent for potential groundwater zones (Haridas et al. 1998). Therefore, high weight is assigned for high density and low weight for low density classes. The lineament density map (Fig. 6) was classified into five categories: very low (0-0.66 km/km^2), low (0.66-1.32 km/km^2), moderate (1.32-1.98 km/km^2), high (1.98-2.64 km/km^2) and very high (2.64-3.30 km/km^2) covering an area of 241.13 km^2 (6.83%), 1133.76 km^2 (32.12%), 1355.22 km^2 (38.39%), 713.51 km^2 (20.22%) and 86.24 km^2 (2.44%) respectively. The results show a declining intensity of groundwater potential with increasing distance from the lineaments in conformity with an earlier study (Arulbalaji et al. 2019).

Drainage density

Drainage density is a significant parameter for evaluating the groundwater potential zones (Shekhar and Pandey 2015). The areas having high drainage density have less potential for groundwater recharge, and the areas with low drainage density have a high potential for groundwater recharge (Halder et al. 2020). Hence, the areas having low drainage density are favorable for high groundwater potentiality (Mandal et al. 2016). So, higher weights were assigned to the areas having low drainage density. The drainage density was classified into five categories viz. very low (0.02-0.77 km/km^2), low (0.77-1.52 km/km^2), moderate (1.52-2.27 km/km^2), high (2.27-3.02 km/km^2) and very high (3.02-3.77 km/km^2). The highest area was under low density with 39.29 km^2, followed by very low with 27.52 km^2, moderate 21.58 km^2, high 10.48 km^2, and very high 1.13 km^2 (Fig. 7).

Rainfall

The infiltration rate and possibility of groundwater potential zones are directly affected by the rainfall distribution and slope gradient (Kumar et al. 2014). Hence, high ratings were given to the areas receiving the highest rainfall and low ratings for lesser rainfall areas. The annual average rainfall was classified into equal intervals as very low (67-119 cm), low (119-171cm), moderate (171-223 cm), high (223-275cm), and very high (275-327cm). An area of 563.28 km^2 (15.95%) and 1216.33 km^2 (34.46%) receives high and very high rainfall, respectively. The area under moderate, low, and very low rainfall were 986.47 km^2 (27.95%), 527.66 km^2 (14.95 %), and 236.12 km^2 (6.69%) respectively (Fig. 8).

Distance from the major river

The two main sources of groundwater within a river basin aquifer are precipitation and river water (Vrzel et al. 2018). There is a close relationship between rivers and groundwater. Thus, the areas close to surface water have a good probability of groundwater potential (Halder et al. 2020). The distance from the major river was derived by creating buffers of up to 200 m, 500 m, 1000 m, 2000 m, and above 2000 m. High weights are assigned to the areas nearby the major river and low weights to distant locations. The results show an area of 494.66 km^2 (14.01%) up to 200 m, 534.04 km^2 (15.13%) at 500 m, 694.59 km^2 (19.68%) at 1000 m, 926.88 km^2 (26.26) at 2000 m, and 879.69 km^2 (24.92%) at above 2000 m distance from the major River (Fig. 9).

Topographic wetness index

TWI is widely applied to explain the impact of topography on the location and size of saturated zones of runoff generation (Saha 2017). There is a positive relationship between TWI and groundwater occurrence where higher TWI values indicate a higher probability of groundwater potential (Nampak et al. 2014). Therefore, higher weights for high values and lower weights for low classes were assigned. The TWI in this study is classified into 1.69-5.14, 5.14-8.59, 8.59-12.04, 12.04-15.49, and 15.49-18.9 (Fig. 10).

Soil texture

The permeability of soil is highly dependent on the texture, structure, and continuity of the pore spaces in soil (Ghosh et al. 2020). The grain size of the soil determines the infiltration rate. The fine-grained soils have limited infiltration while coarse-grained soils have a high degree of infiltration rate (Fashae et al. 2014). The loamy soils have a high probability of infiltration (Rajasekhar et al. 2019) whereas clayey soils have the least infiltration rate (Kumar et al. 2014). So, based on the infiltration rate, the highest weight has been assigned to coarse loamy skeletal and the lowest weight to the fine clay/loam soil. The soil texture of the study area mostly consists of clay and loam, which was further distinguished by fine, coarse, and skeletal characteristics as well as location attributes in moderate, steep, and very steep hillside slope, summit, and piedmont (Fig. 11).

Land use/ Land cover

The LULC categories of the study area are forest cover, cropland, water bodies, built-up, sandbanks, and wasteland (Fig. 12). The largest area of 3233.33 km^2 (91.60%) was covered by forests, followed by croplands with 129.89 km^2 (3.68%), sandbanks 62.75 km^2 (1.78%), built-up 51.15 km^2 (1.45%), wasteland 47.60 km^2 (1.35%) and water bodies 5.14 km^2 (0.14%). The high weights were assigned to water bodies, sandbanks (Rejith et al. 2019), forest cover, and cropland, while low weights to the built-up areas and wasteland (Arulbalaji et al. 2019).

Groundwater potential map

The final GWP map was classified into five potential zones: very poor, poor, moderate, good, and very good. The highest area of 1331.14 km^2 (37.71%) has poor groundwater potential, followed by 1087.96 km^2 (30.82%) under moderate and 942.45 km^2 (26.70%) under very poor groundwater prospects. The area under good and very good groundwater potential zones were 143.54 km^2 (4.07%) and 24.77 km^2 (0.70%), respectively (Table 5 & Fig. 13). Based on the sensitivity analysis, the GWP map is almost reflective of the annual average rainfall, geology, LULC, drainage density, and soil texture. The southern and western margins receiving high rainfall are suitable locations for groundwater whereas a major share of the area with low rainfall towards the northern parts is unsuitable for groundwater recharge. The Middle Siwalik groups of formations with sediment deposits show good groundwater prospects while the northern parts

Table 5: Area under groundwater potential categories

GWP Categories	Area (km^2)	Area (%)	Number of reference wells
Very poor (1.35-2.03)	942.45	26.70	0
Poor (2.03-2.71)	1331.14	37.71	2
Moderate (2.71-3.39)	1087.96	30.82	15
Good (3.39-4.07)	143.54	4.07	28
Very good (4.07-4.75)	24.77	0.70	19
Total	**3529.86**	**100.00**	**64**

with assemblages of metamorphic rocks show poor groundwater potential. The flood plains and alluvial plains with low drainage density and coarse loamy skeletal soil texture show good groundwater potential due to high infiltration rates. The good potential areas are mostly located in the southern foothill plains bordering the state of Assam and the river valleys.

Sensitivity analysis

Map-removal sensitivity analysis

The statistics of the variation index of map-removal sensitivity analysis are shown in Table 6. The highest variation index with a mean of 1.05% was found in the removal of the rainfall layer. The other layers showing high variation index were TWI, geology, and distance to the major river with mean values of 0.80, 0.78, and 0.75%, respectively. The geomorphology, lineament density, soil texture, slope, LULC, and drainage density recorded the lowest variation index with mean value ranges of 0.24 to 0.38%.

Table 6: Statistics of map-removal sensitivity analysis

Layer removed	Variation index (%)			
	Min	Max	Mean	SD
GM	0.00	3.85	0.24	0.35
GL	0.00	2.61	0.78	0.72
SL	0.00	2.48	0.35	0.17
LN	0.00	1.45	0.32	0.23
DD	0.00	1.69	0.38	0.28
RN	0.00	2.94	1.05	0.43

DR	0.01	1.03	0.75	0.18
TWI	0.04	1.01	0.80	0.13
ST	0.00	1.31	0.34	0.21
LULC	0.00	1.08	0.37	0.25

Single-parameter sensitivity analysis

The statistics of single-parameter sensitivity analysis are shown in Table 7. There are some deviations in the effective weights when compared to the empirical weights. In conformity with the results of the map-removal analysis, the single-parameter analysis also shows rainfall as the most effective layer in GWP mapping with a mean effective weight of 19.07%. The next higher mean effective weights of 14.41, 12.44, 11.47, and 10.23% were recorded in geology, LULC, drainage density, and soil texture, respectively. The geomorphology, lineament density, and slope exhibit moderate mean effective weights of 9.81, 8.32, and 8.19%, respectively. The geomorphology and slope with higher empirical weights of 21 and 13% appear to be less effective layers compared to the mean effective weights of 9.81 and 8.19%. The empirical and effective weights for the distance from the major river and TWI were found close to each other.

Table 7: Statistics of single-parameter sensitivity analysis

Thematic layers	Empirical weight (%)	Effective weight (%)			
		Min	Max	Mean	SD
GM	21	5.31	44.68	9.81	3.81
GL	16	4.17	33.47	14.41	8.48
SL	13	3.05	32.34	8.19	3.01
LN	7	1.50	23.03	8.32	3.12
DD	7	1.54	25.18	11.47	4.02
RN	14	4.00	36.46	19.07	4.63
DR	3	0.69	10.20	3.28	1.66
TWI	4	0.93	9.61	2.78	1.14
ST	9	2.62	21.82	10.23	3.62
LULC	6	1.50	19.74	12.44	3.19

Validation of results

The groundwater potential map is not useful if it is not validated by groundwater level data (Ghosh et al. 2020). Hence, an accuracy assessment was performed using the groundwater level (below the surface) data of 14 observation wells taken from the CGWB (Groundwater Year Book 2019) and 50 dug wells collected from various parts of the study area. Hence, a total of 64 wells were used as reference data for the classification accuracy of the groundwater potential map. As there were no existing wells in the very poor zone, the groundwater level data was divided into four categories i.e. very good (0-3 m), good (3-6 m), moderate (6-9 m), and poor (9-12 m). The wells with low depth to water levels are considered good while high depth to water levels was considered poor groundwater potential areas (Table 8). The analysis shows an overall accuracy of 81.25% and a Kappa coefficient of 0.72. The Kappa coefficient values usually range between 0 and 1 where 0 represents low agreement while 1 shows perfect agreement (Viera and Garrett 2005). The coincidence of the low water level wells in the good groundwater potential areas validates the results of the study. However, the lack of spatially representative location of wells constraints the validation of the results to a certain extent.

Table 8: Location, groundwater level and agreement with groundwater potential map

Sl. No.	Location Name	Longitude	Latitude	Depth to water level (mbgl) CGWB observation wells & existing dug wells	Reference class	Map class	Agreement
1.	Banderdewa I	93.826	27.105	11.29	P	M	Partially agree
2.	Chimpu	93.600	27.070	2.69	VG	M	Disagree
3.	Naharlagun	93.711	27.113	6.68	M	G	Partially agree
4.	Itanagar I	93.642	27.104	2.65	VG	VG	Agree
5.	Itanagar II	93.625	27.093	0.37	VG	M	Disagree
6.	NirjuliVill IIA	93.733	27.131	0.70	VG	VG	Agree
7.	Naharlagun I	93.695	27.103	5.78	G	G	Agree
8.	Naharlagun II	93.700	27.100	1.17	VG	G	Partially agree
9.	Sonajuli	93.740	27.030	2.08	VG	VG	Agree
10.	Itanagar III	93.600	27.080	4.20	G	G	Agree
11.	Banderdewa II	93.830	27.100	5.82	G	G	Agree
12.	Sonajuli	93.688	27.046	2.88	VG	G	Partially agree
13.	Kimin	93.969	27.308	1.37	VG	VG	Agree
14.	Doimukh	93.756	27.142	0.90	VG	VG	Agree
15.	Kakoi I	94.027	27.354	1.23	VG	G	Partially agree
16.	Kakoi II	94.048	27.363	1.45	VG	VG	Agree
17.	Kakoi III	94.052	27.358	3.20	G	G	Agree
18.	Kakoi IV	94.051	27.358	3.35	G	G	Agree
19.	Kakoi V	94.053	27.358	1.90	VG	VG	Agree
20.	Kakoi VI	94.065	27.339	3.13	G	G	Agree
21.	Kimin I	93.966	27.305	2.72	VG	VG	Agree
22.	Kimin II	93.969	27.304	1.70	VG	VG	Agree
23.	Kimin III	93.967	27.307	2.04	VG	VG	Agree
24.	Nirjuli I	93.738	27.122	5.27	G	G	Agree
25.	Nirjuli II	93.746	27.128	2.02	VG	G	Partially agree
26.	Karsingsa I	93.775	27.125	7.90	M	M	Agree
27.	Karsingsa II	93.788	27.120	4.84	G	G	Agree
28.	Banderdewa I	93.805	27.116	4.10	G	G	Agree
29.	Yupia I	93.728	27.145	3.37	G	G	Agree
30.	Yupia II	93.726	27.147	1.73	VG	VG	Agree
31.	Yupia III	93.714	27.142	5.95	G	G	Agree
32.	Sagalee I	93.498	27.246	9.08	P	P	Agree
33.	Chimpu I	93.606	27.065	10.35	P	P	Agree
34.	Chimpu II	93.606	27.064	6.58	M	M	Agree
35.	Itanagar I	93.608	27.088	3.85	G	M	Partially agree
36.	Itanagar II	93.611	27.111	3.23	G	M	Partially agree
37.	Itanagar III	93.632	27.095	6.31	M	M	Agree
38.	Itanagar IV	93.600	27.084	6.02	M	M	Agree
39.	Itanagar V	93.601	27.079	4.20	G	M	Partially agree
40.	Itanagar VI	93.620	27.093	6.11	M	M	Agree

41.	Itanagar VII	93.606	27.083	6.53	M	M	Agree
42.	Itanagar VIII	93.599	27.077	4.17	G	G	Agree
43.	Itanagar IX	93.623	27.100	6.42	M	M	Agree
44.	Naharlagun I	93.678	27.100	4.08	G	G	Agree
45.	Naharlagun II	93.702	27.106	0.75	VG	VG	Agree
46.	Naharlagun III	93.698	27.101	3.37	G	G	Agree
47.	Naharlagun IV	93.687	27.105	3.67	G	VG	Partially agree
48.	Naharlagun V	93.696	27.110	3.29	G	G	Agree
49.	Lekhi village I	93.713	27.113	4.38	G	G	Agree
50.	BagheTinali I	93.732	27.130	1.19	VG	VG	Agree
51.	BagheTinali II	93.740	27.133	3.23	G	G	Agree
52.	Emchi village I	93.773	27.140	4.42	G	G	Agree
53.	Gumto village I	93.805	27.137	3.11	G	G	Agree
54.	Gumto village II	93.776	27.142	5.41	G	G	Agree
55.	Doimukh I	93.756	27.140	1.88	VG	VG	Agree
56.	Doimukh II	93.755	27.143	3.03	G	G	Agree
57.	Doimukh III	93.752	27.143	1.30	VG	VG	Agree
58.	Amba village I	93.753	27.141	1.53	VG	VG	Agree
59.	Balijan I	93.498	26.950	1.96	VG	VG	Agree
60.	Balijan II	93.500	26.858	2.20	VG	VG	Agree
61.	Balijan III	93.495	26.953	3.41	G	G	Agree
62.	Taraso I	93.389	26.935	6.23	M	M	Agree
63.	Taraso II	93.389	26.934	5.25	G	G	Agree
64.	Taraso III	93.379	26.938	6.11	M	M	Agree

[VP – Very Poor; P – Poor; M – Moderate; G – Good; VG – Very Good]

Concluding Remarks

The study delineates the groundwater potential of the Papumpare district of Arunachal Pradesh integrating GIS and AHP techniques. The results show 64% of the area under poor to very poor groundwater potential. However, about 31% of the area has moderate potential, while only 5% of the area has good and very good potential. Since a major part of the study area in the northern region is comprised of hills and mountains with a large number of perennial rivers and streams, the dependence on groundwater resources is negligible at present in these areas. However, the southern foothill and plain areas that comprise important urban centers and irrigational areas are mostly dependent on groundwater resources. Thus, the coincidence of good groundwater potential with urban centers and irrigational areas may lead to over-exploitation of groundwater resources in the future. There has been a decrease in the utilization of surface water and a continuous increase in groundwater for irrigation over the years in India (Ministry of Agriculture 2015). Therefore, the estimated 5% area of good and very good groundwater potential appears to be significantly less to meet the demands of increasing population and urbanization. The state government in general and the water resources and planning department in particular need to develop appropriate strategies considering the results of the study to address the issues of water scarcity scenario waiting ahead. Furthermore, suitable efforts to augment the sustainability of aquifer management in the 31% moderate groundwater potential area may be fruitful to meet the requirements of water for domestic and agricultural purposes.

Alternatively, the possibilities of increasing surface water utilization from nearby perennial rivers like Dikrong, Pachin, Ranganadi, etc. may reduce pressure on the groundwater resources.

Conflicts of interest

The author(s) declare no competing interests.

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Figure captions

Fig. 1. Location map of the study area.

Fig. 2. Methodology followed in the study.

Fig. 3. Geomorphology map.

Fig. 4. Geology map.

Fig. 5. Slope map.

Fig . 6. Lineament density map.

Fig. 7. Drainage density map.

Fig. 8. Rainfall map.

Fig. 9. Distance from the major river map.

Fig. 10. Topographic wetness index map.

Fig. 11. Soil texture map.

Fig. 12. Land use / Land cover map.

Fig. 13. Groundwater potential map.

Figures

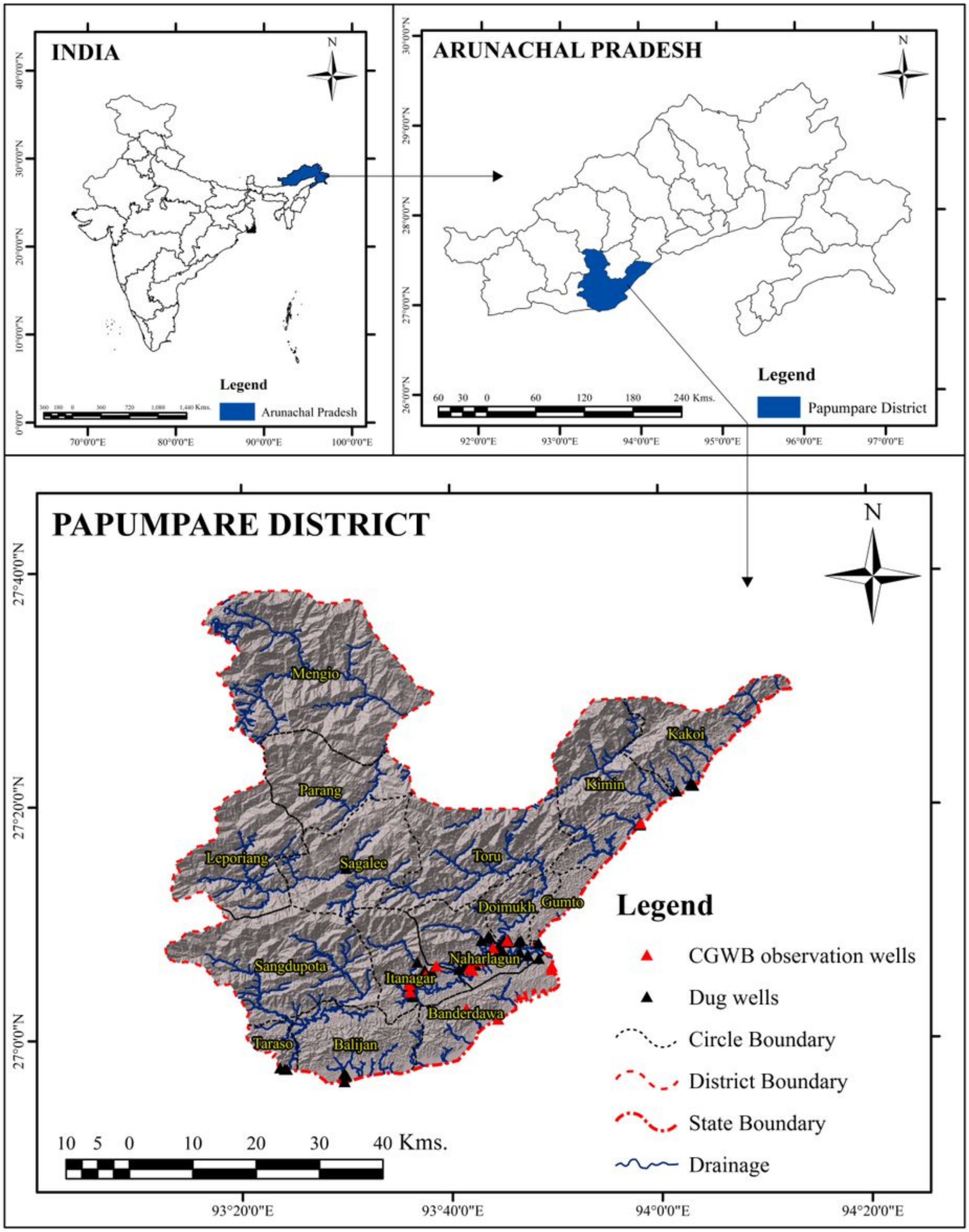

Figure 1

Location map of the study area.

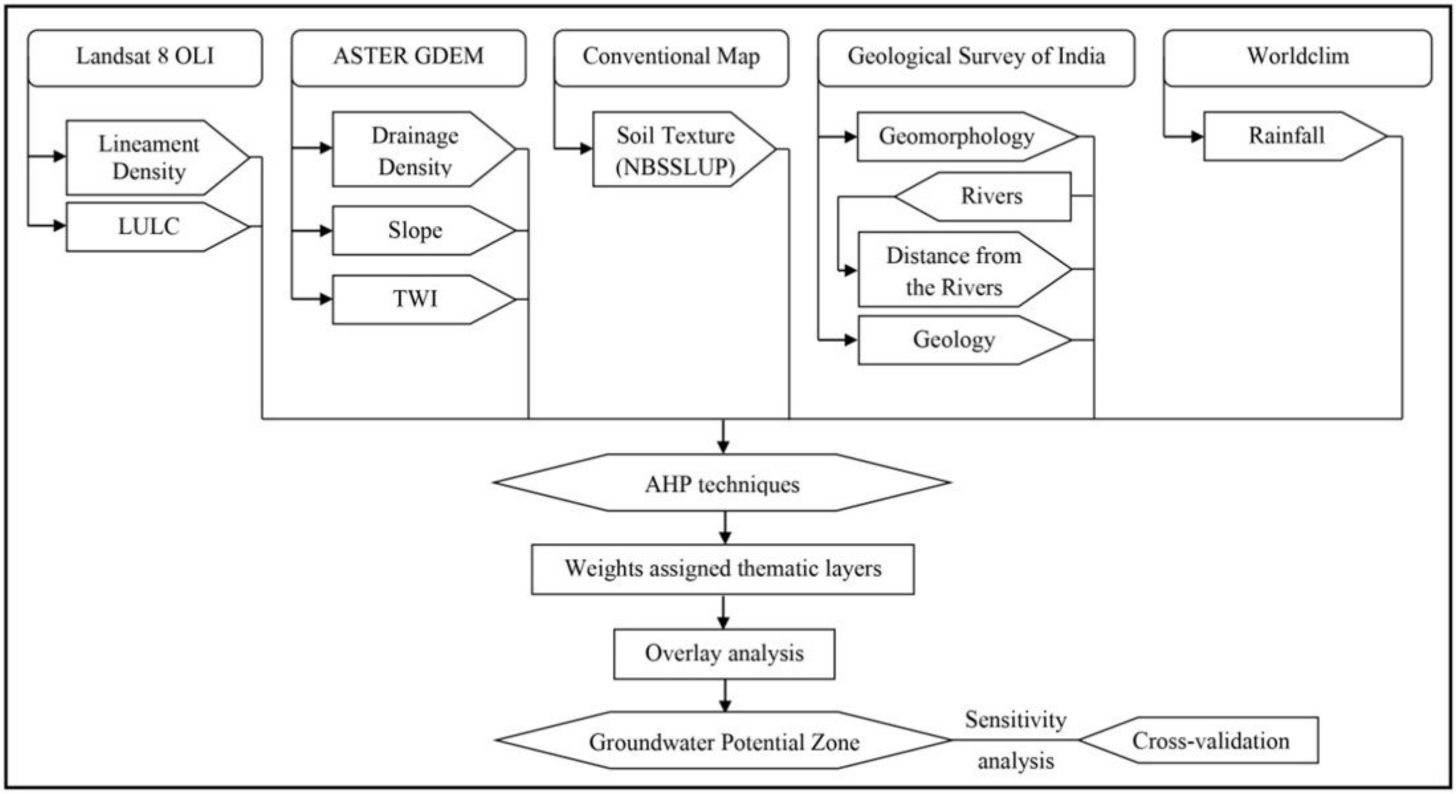

Figure 2

Methodology followed in the study.

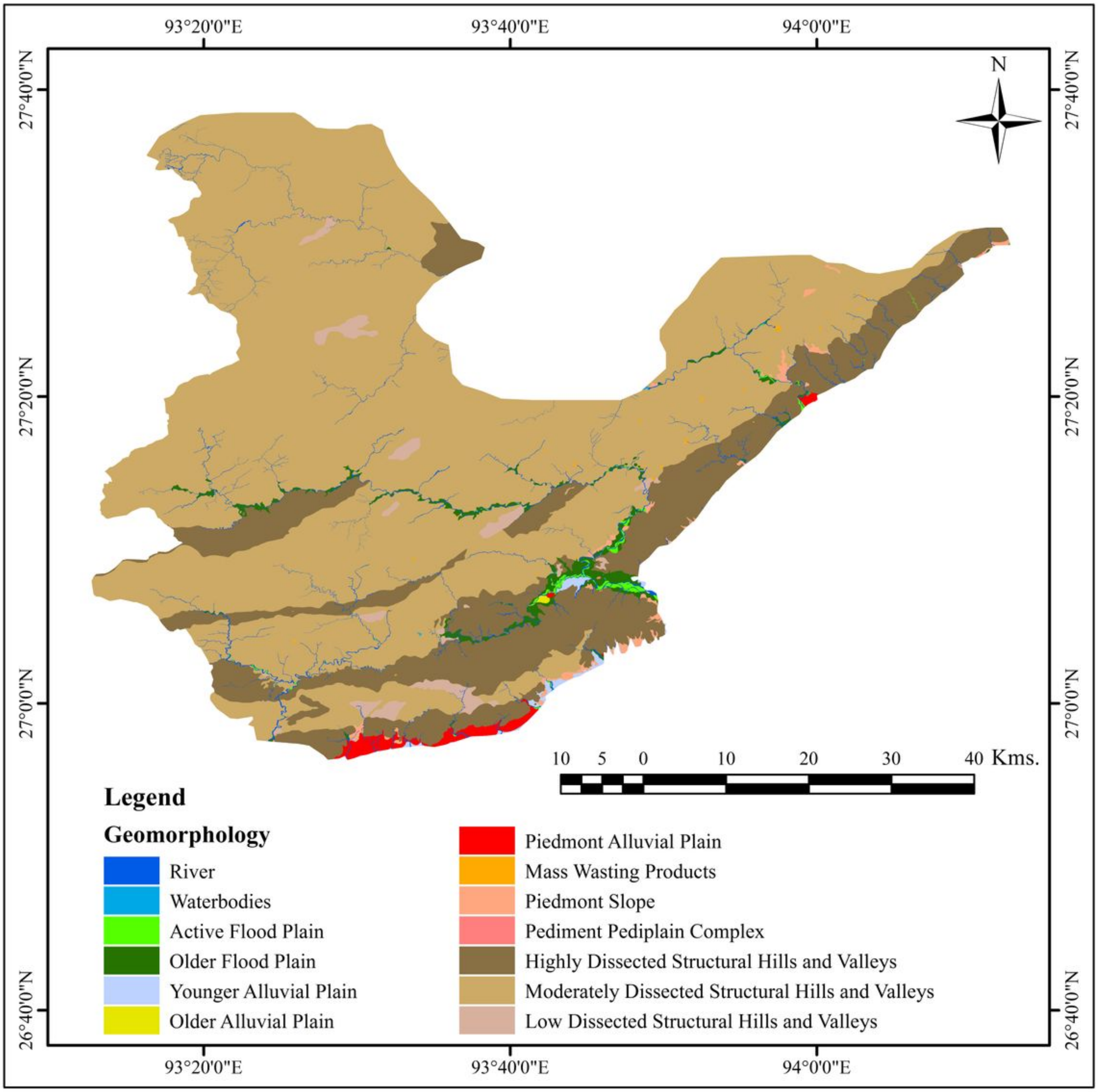

Figure 3

Geomorphology map.

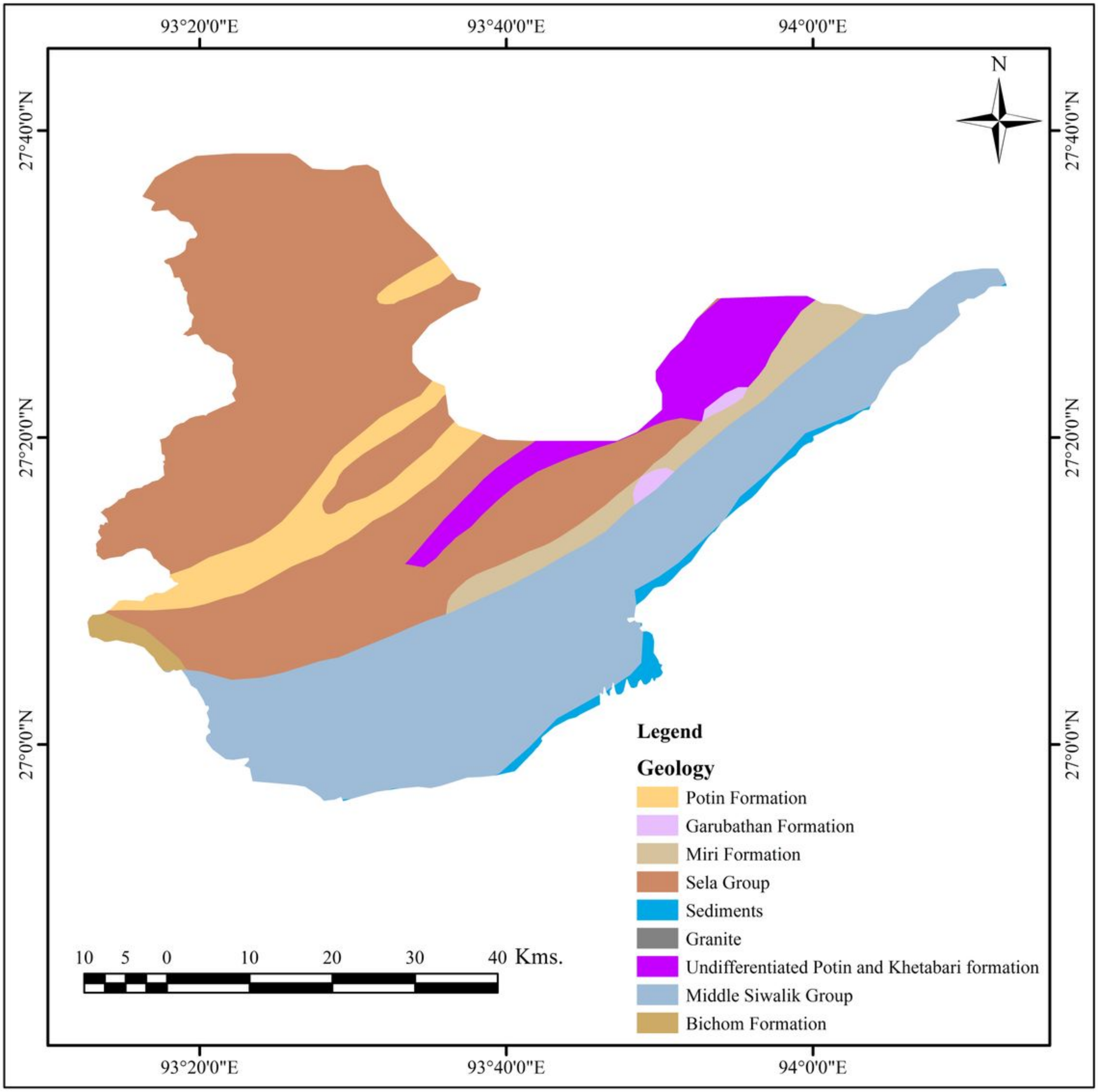

Figure 4

Geology map.

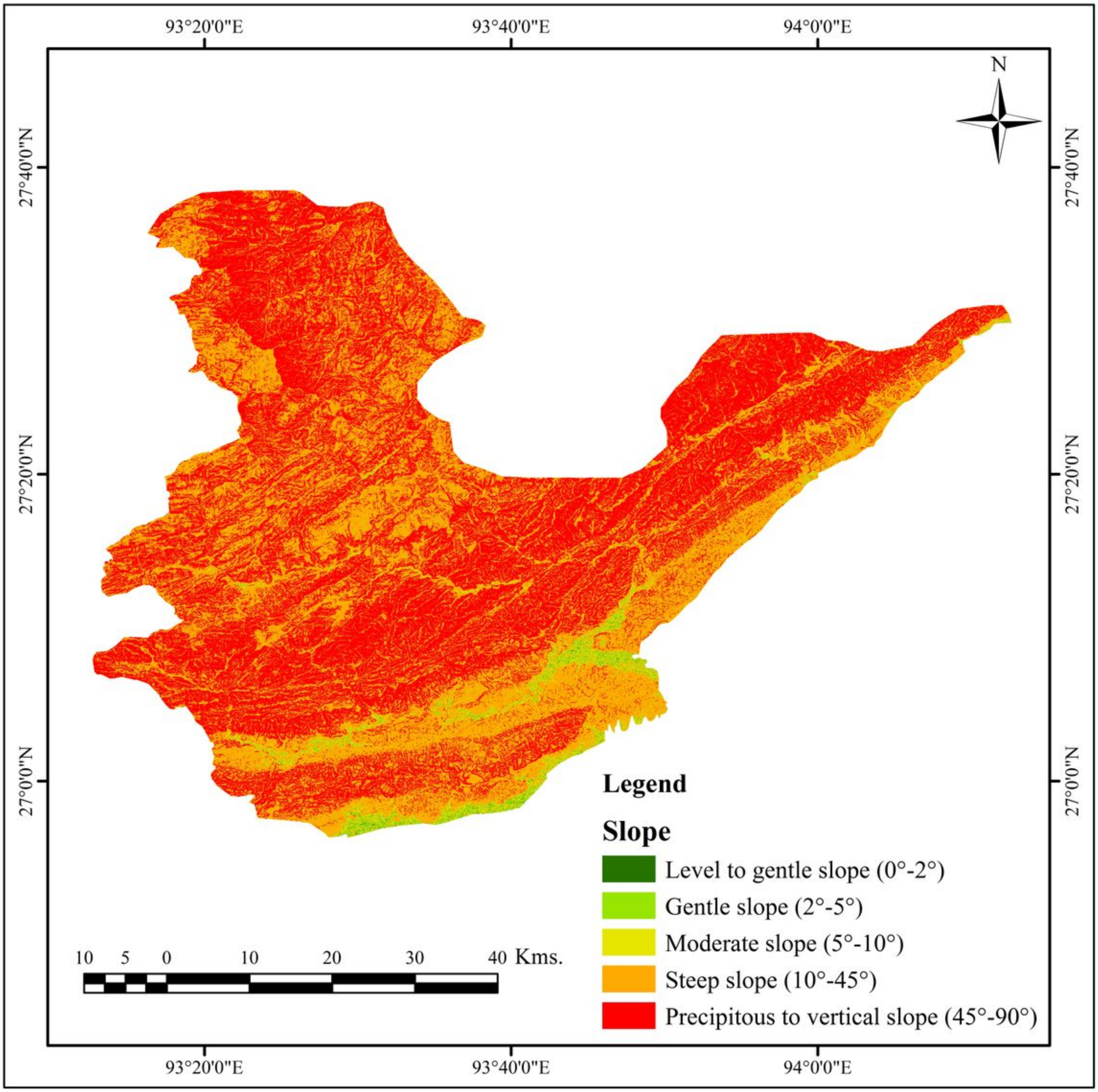

Figure 5

Slope map.

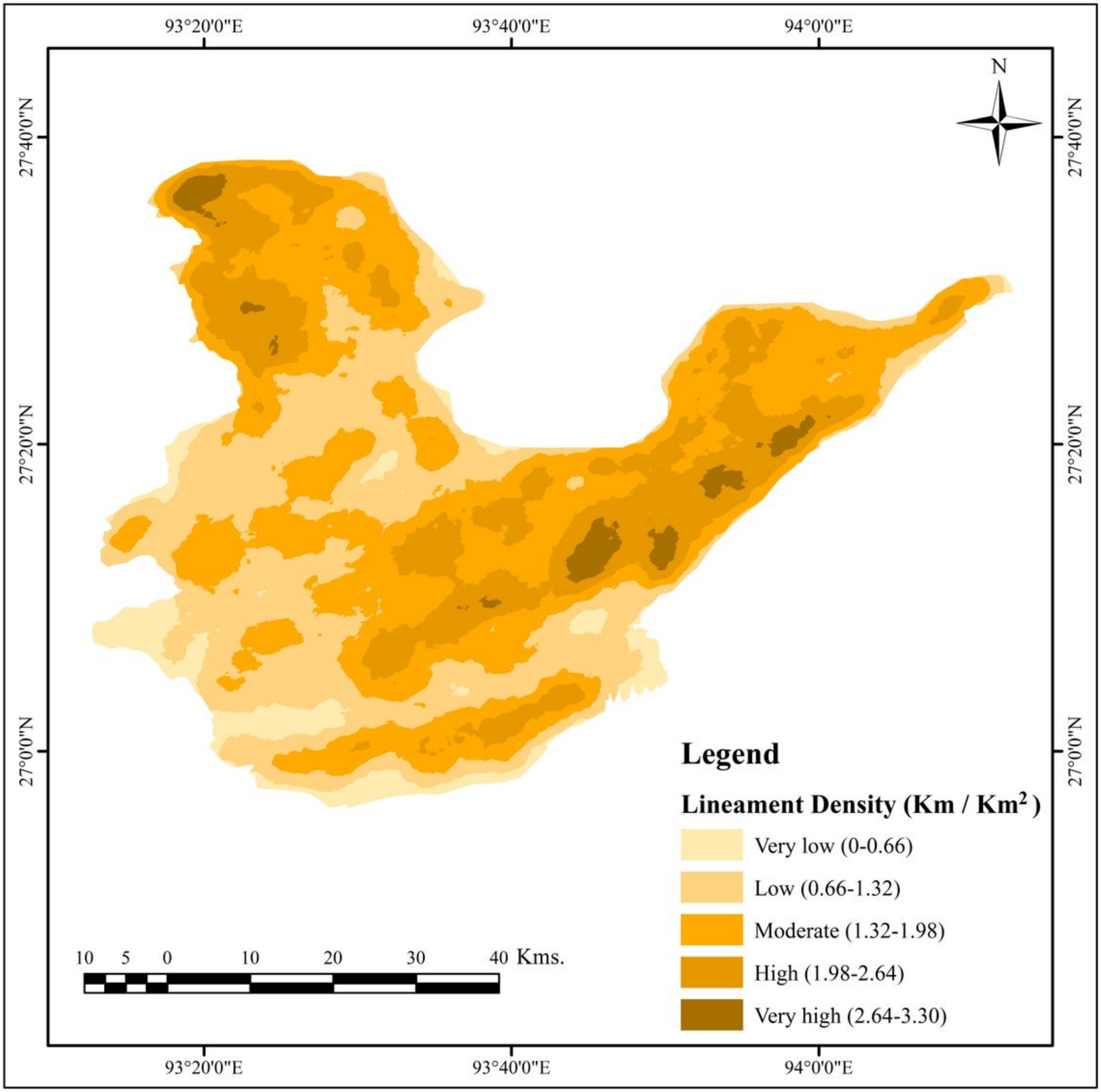

Figure 6

Lineament density map.

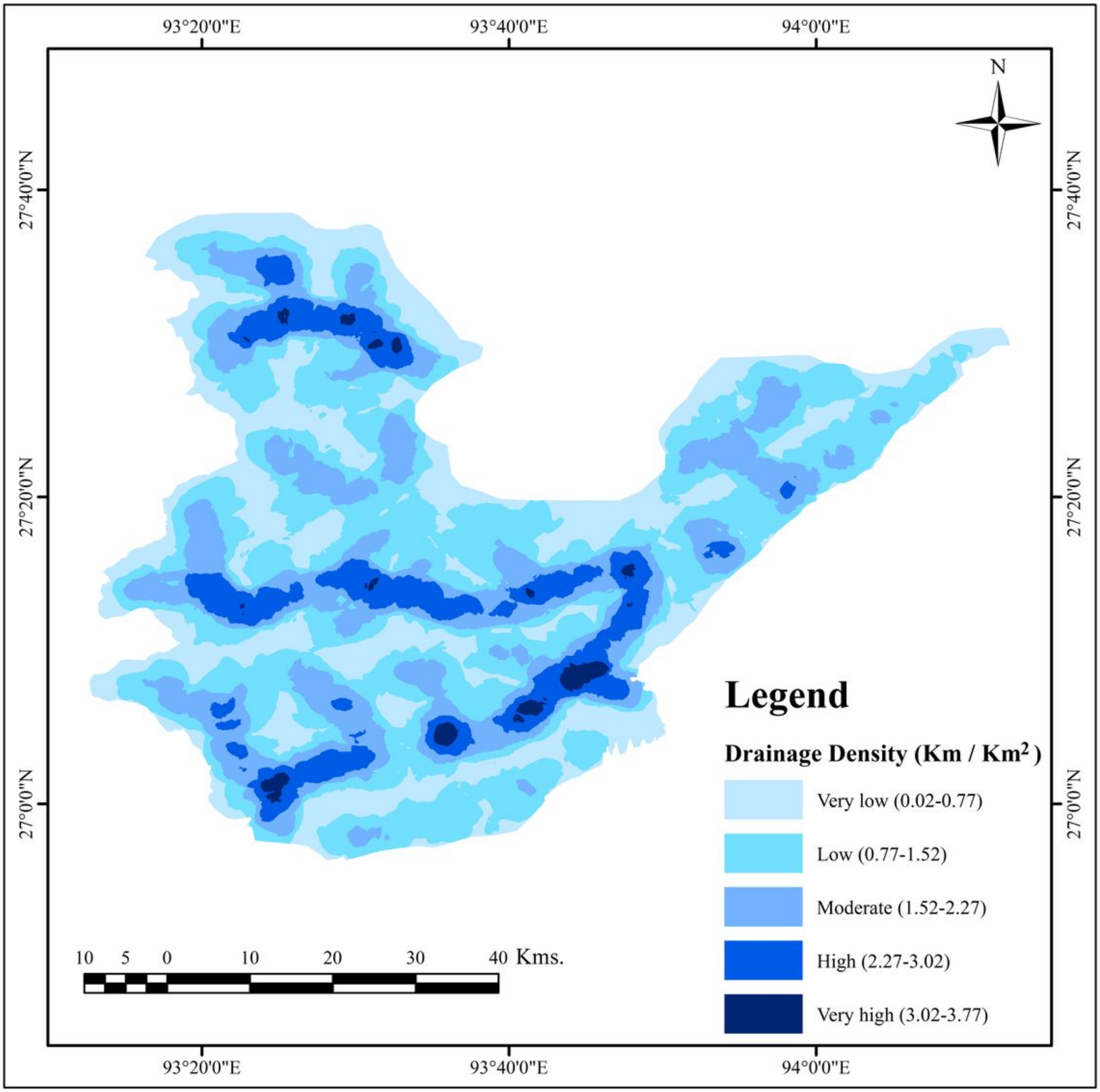

Figure 7

Drainage density map.

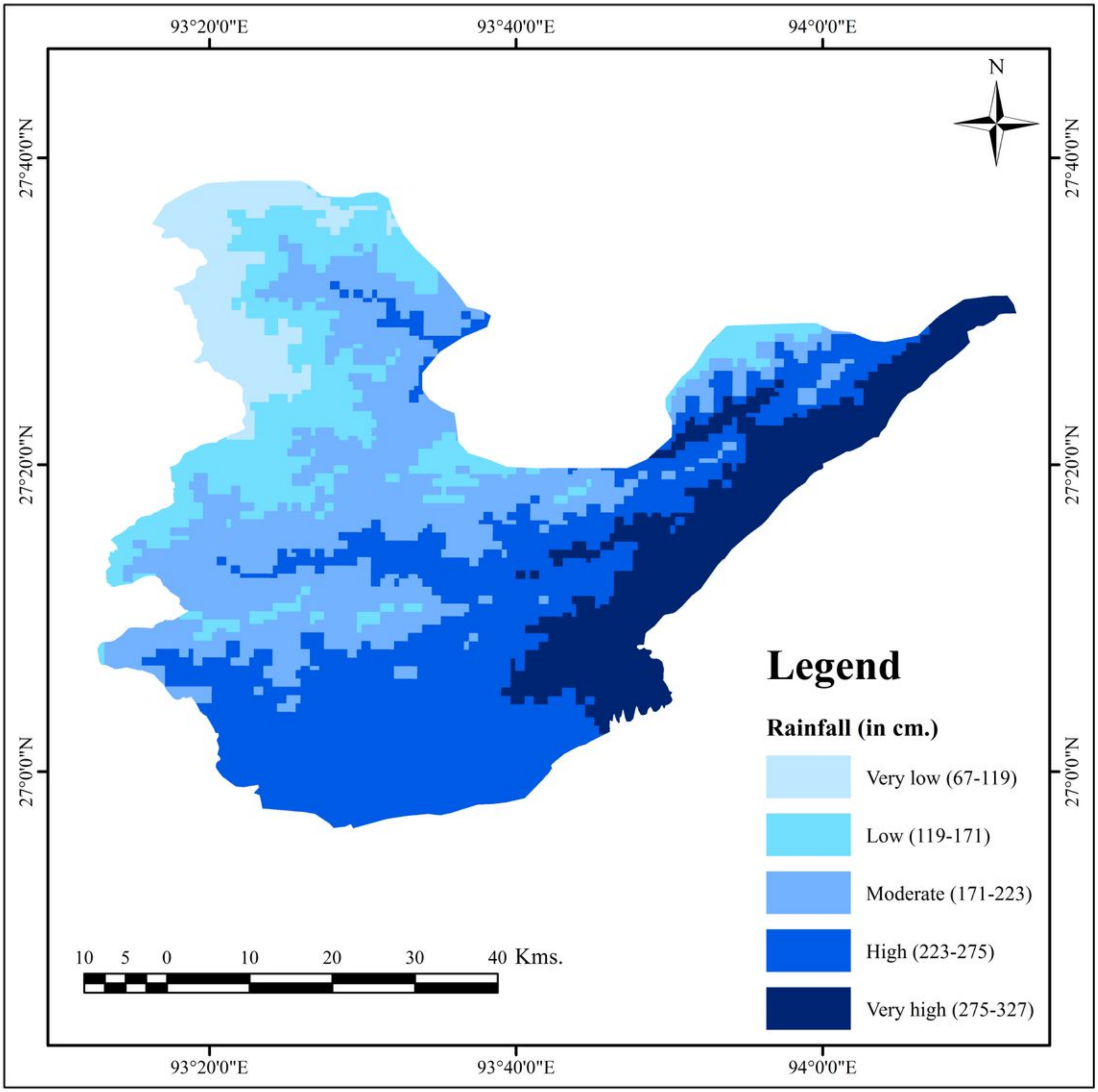

Figure 8

Rainfall map.

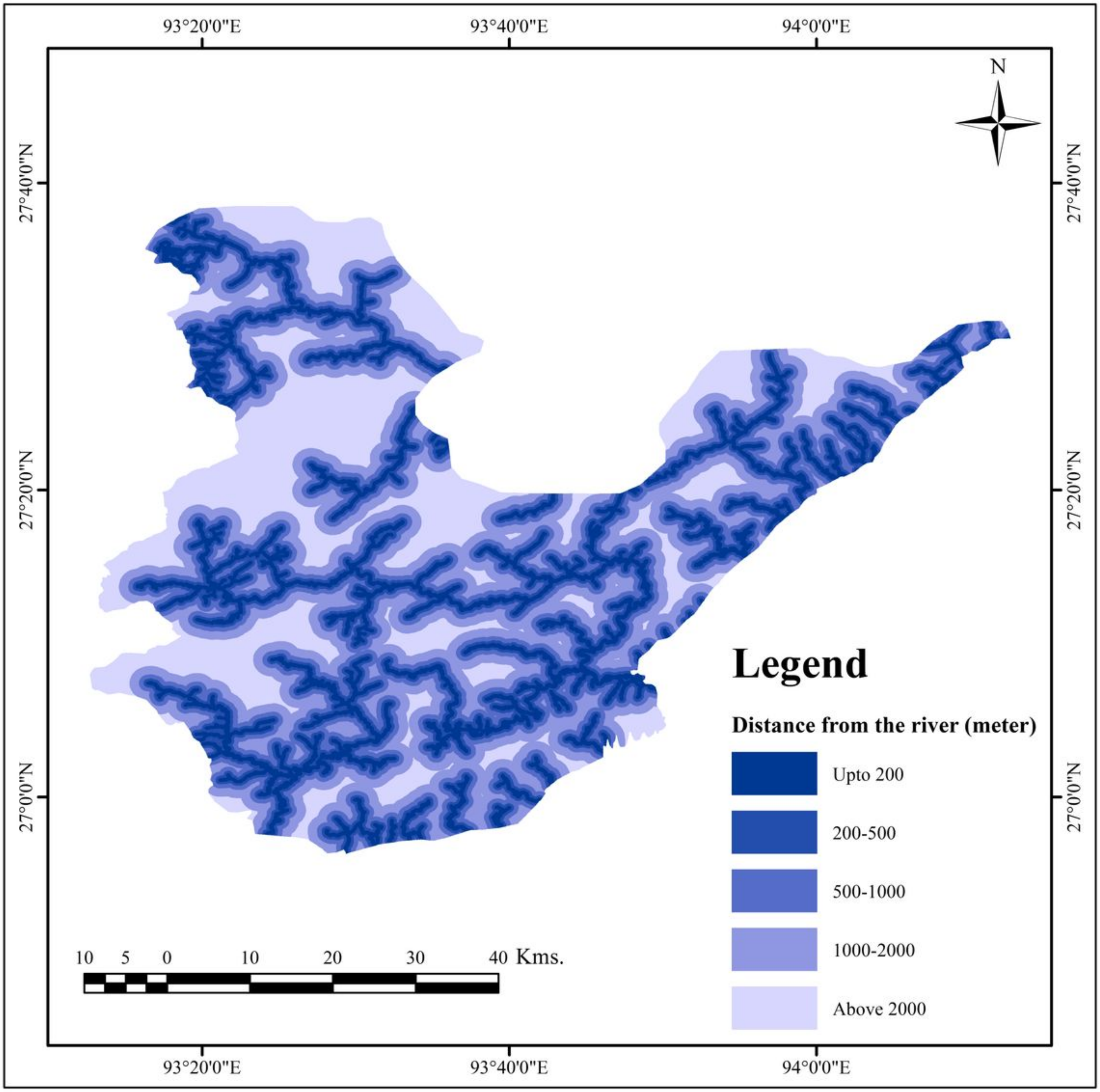

Figure 9

Distance from the major river map.

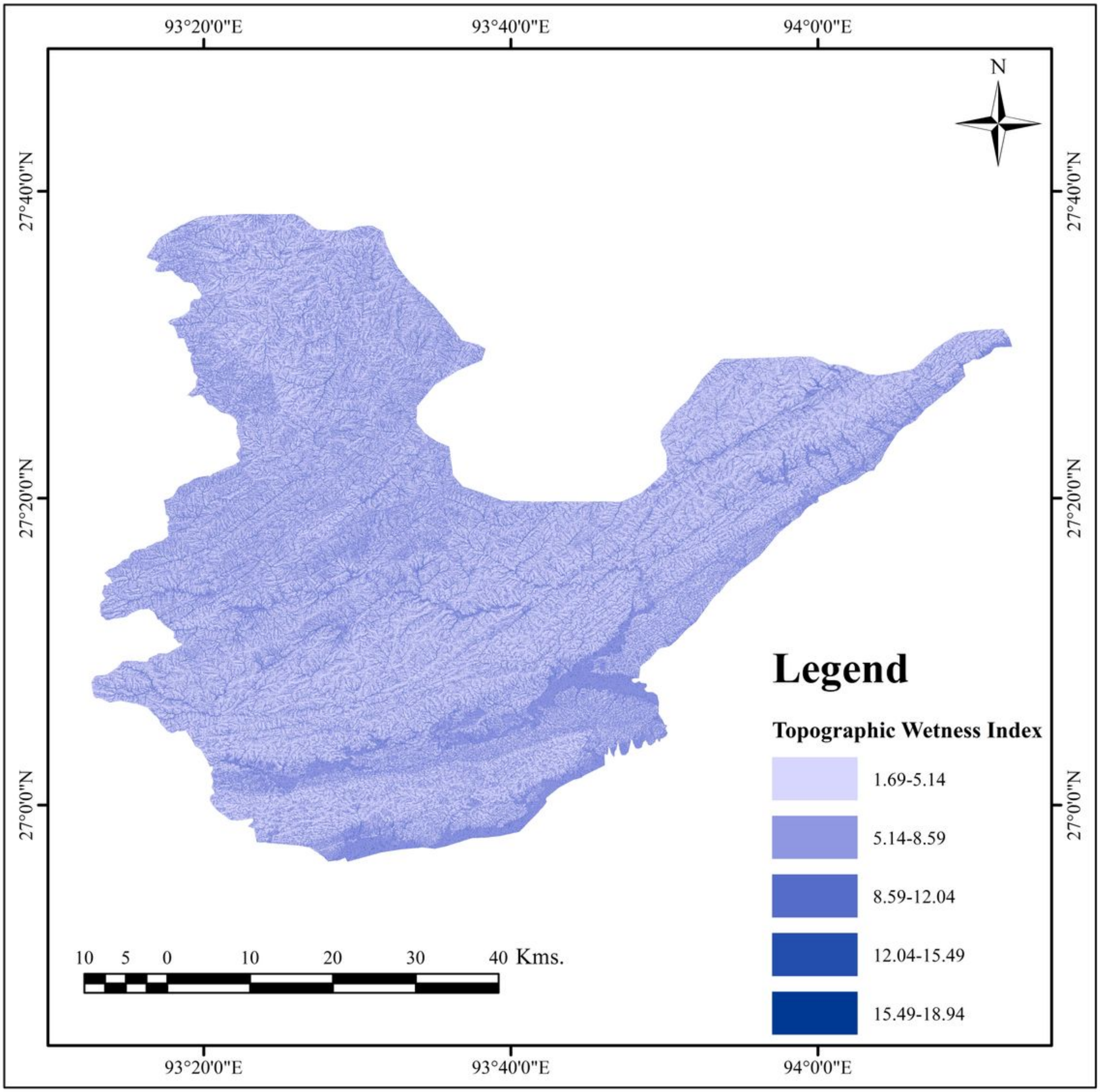

Figure 10

Topographic wetness index map.

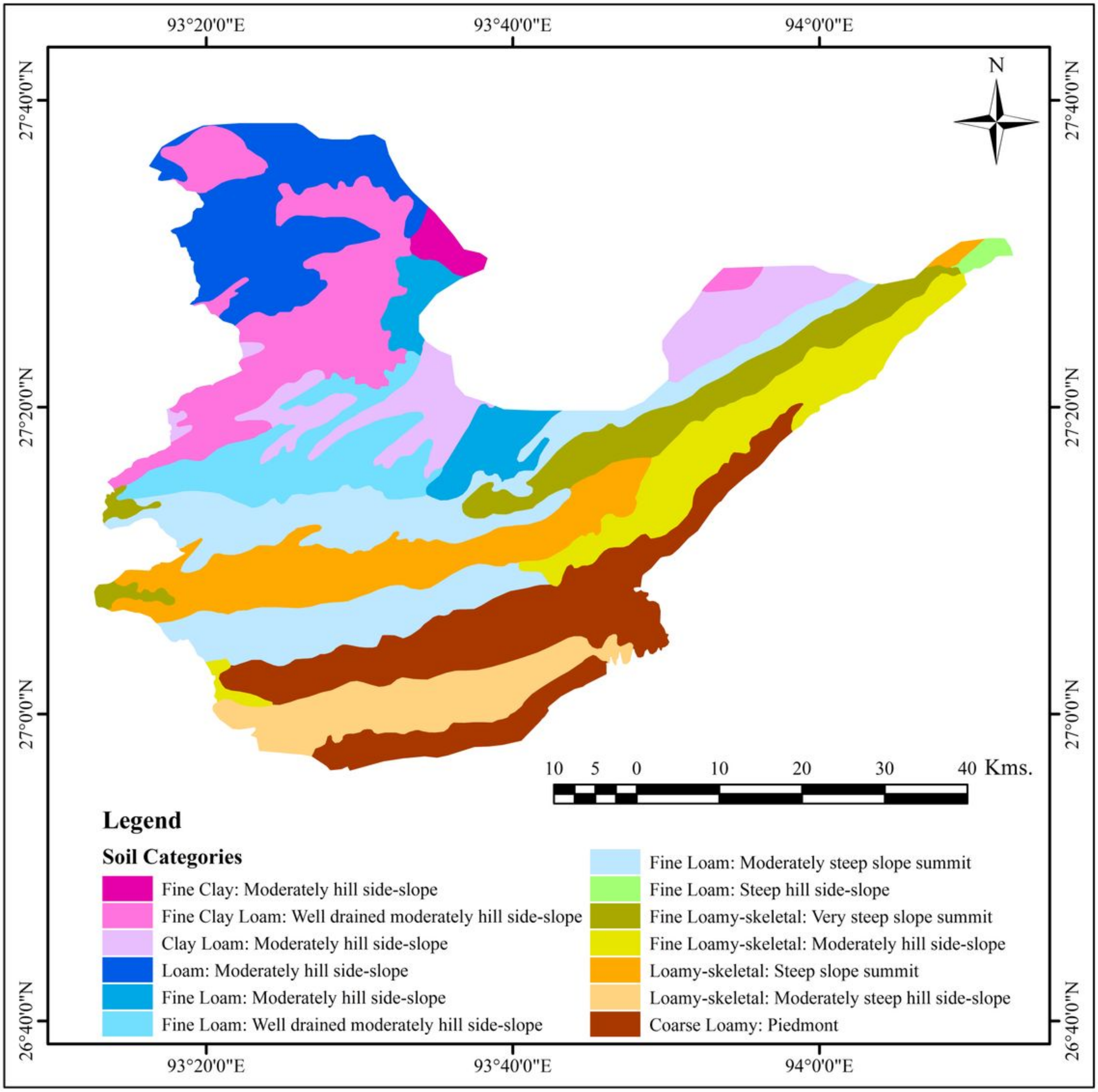

Figure 11

Soil texture map.

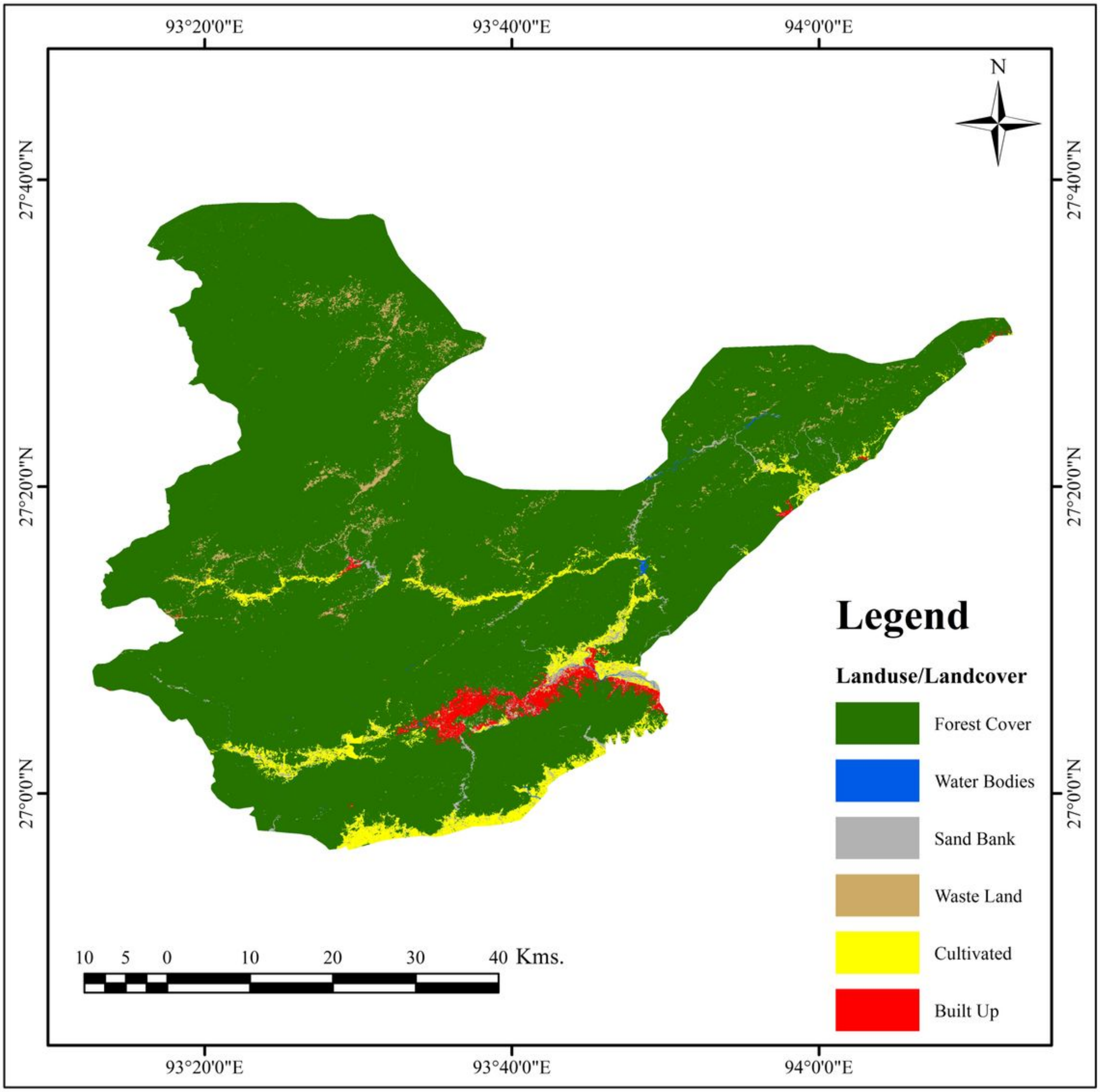

Figure 12

Land use / Land cover map.

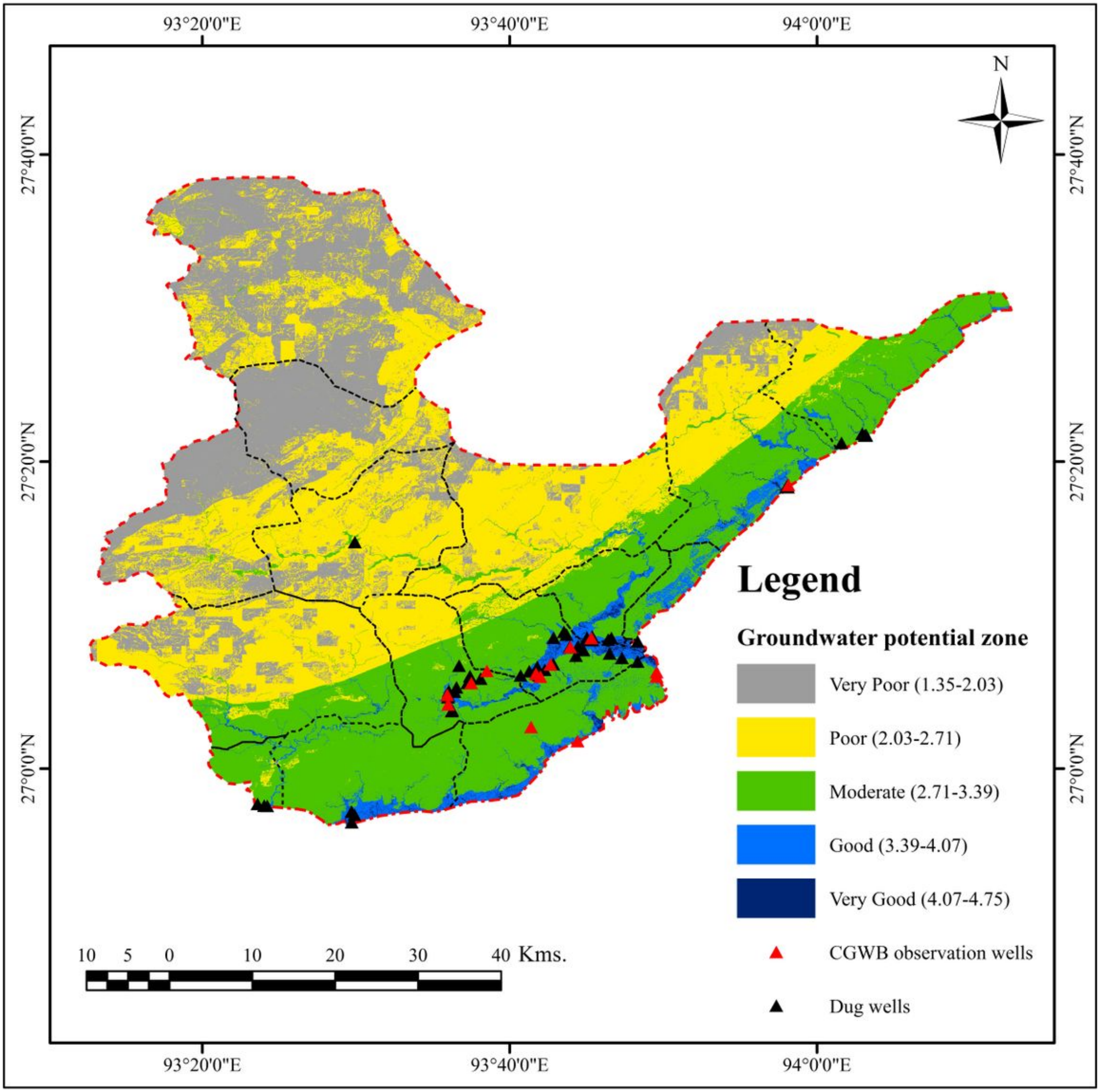

Figure 13

Groundwater potential map.

Supplementary Files

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- Supplementary1.docx