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GIS-based identification of potential watershed recharge zones using analytic hierarchy process in Sikkim Himalayan region

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Abstract

Identification of groundwater recharge zone is an important factor for water resource management in any area. The present study investigates the potential water recharge zones in the Sikkim state, a mountain region of the Eastern Himalayas. To identify potential watershed recharge zone in the region, a combination of geographic information system (GIS)-based weighted overlay index (WOI) tools and analytic hierarchy process (AHP) pairwise matrix techniques was applied. The delineated watershed recharge sites were classified into five different potential zones. The results show that the majority of the study area (54.22%) was under moderate recharge potential zone. Some of the suitable recharge potential sites are forest-covered regions; therefore, the construction of surface check dams could be a suitable recharge method; it will escalate the discharge in springs and also help to make them perineal. This study provides first-hand information on the groundwater recharge potential of East Sikkim, where the populace depends largely on spring water discharge. Also, it is useful in selecting areas for digging staggered contour trenches, pits, and other structures to recharge the spring water and improve the watershed management system.

Keywords GIS · AHP · Sikkim Himalaya · Groundwater recharge potential · Watershed management

Introduction

The Himalayan cryosphere is the source of major river systems in Asia, which is the lifeline of more than 1 billion people living in the downstream valley (Immerzeel et al. 2010; Kumar et al. 2017; Wester et al. 2019; Pritchard 2019). Precipitation in the form of rainfall also contributes significantly to the total discharge of the major rivers, especially in the eastern Himalayas (Armstrong et al. 2019). Sikkim, which is in the eastern Himalayan region, has two major rivers, namely Teesta and Rangit. The rivers originate from the high-altitude mountains of Sikkim. Snow and glaciers meltwater as well as the high-altitude mountain lakes are the main water sources of these rivers. At the same time, Sikkim receives high-intensity of precipitation and the southwest monsoon season is responsible for more than 80% of the total annual precipitation in the Teesta Basin of Sikkim (CISMHE 2007). The geographical total area of Sikkim is around 7096 sq. km and is characterized by steep slopes and escarpments having terraces, gorges, and U- and V-shaped valleys at various altitudes. Although river water resources are available in Sikkim throughout the year, this river flows at the bottom of the narrow valleys which makes them inaccessible for the majority of the inhabitants of Sikkim. Therefore, for daily requirements, the region is heavily dependent on perennial springs and small streams (Tambe et al. 2012). However, groundwater development is limited due to the presence of hard rocks having steep slopes and so far no such information is available on the underground water resources of Sikkim. With the increase in population and land-use/cover (LULC) change, water demands per person for daily use have increased around various regions. Similarly issues on water quality and quantity have arisen (Kumar et al. 2017, 2021; Khan et al. 2020). On the other hand, climate change

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adds a new level of uncertainty concerning the availability of spring water across the Himalayas (Scott et al. 2019). In Sikkim, the drying up of springs has been observed during the pre-monsoon season (Tambe et al. 2012). A recent study by Ranjan and Pandey 2019 relates the drying up of many water sources with various factors such as ecological degradation, changing land-use/cover patterns, erratic rainfall patterns, socioeconomic and demographic changes. Rapid urbanization and tourism are other factors that affect groundwater quality (Khan et al. 2020; Kumar et al. 2021). Simultaneously, it is reported that there is undergoing depletion and deterioration of water quantity and quality of the springs (NITI Aayog 2017). In Sikkim, several studies have reported that the glaciers have lost ~20% area in recent decades (Basnett et al. 2013; Debnath et al. 2019). A study on extreme analysis of precipitation and drought in Sikkim has observed extreme excess and deficit of rainfall during different seasons (Dubey et al. 2022). Hence, the climate and water resources of Sikkim are undergoing various changes. Therefore, better planning and effective utilization of water resources has become necessary.

Among the four districts in Sikkim, viz. East, West, North, and South District, East Sikkim is selected as the study area because it is the most populated district in the state, and recently few projects for artificial recharge of groundwater are underway. The development of industrial estates at Marchak, the airport at Pakyong, and changing consumption patterns have led to the rising water demand in the region. To address the water-related problems, efforts have been made by the government of Sikkim. Among them, the Repair, Renovation, and Restoration (RRR) scheme is carried out to revive various dried water bodies in Sikkim (WRRDD 2018). Various measures to augment the water supply of springs such as watershed and "springshed" development are also recommended (Mahamuni and Kulkarni 2012). Among these, digging trenches in hilly terrain is one common method that has been implemented in the region (Tambe et al. 2012). Recently, in the Namcheybong area in East Sikkim, more than 1000 trenches are being dug to improve the discharge of springs in the lean season which is initiated by the Eco-tourism and Conservation Society of Sikkim (ECOSS). However, to date, no such scientific study has been conducted related to hydrogeological study in Sikkim. The lack of data and knowledge related to such a study makes it difficult to assess the efficiency and usefulness of trenches and pits that have been constructed. Also, Sikkim is situated in a very high earthquake vulnerable zone (zone IV) and high landslides susceptible zone. It is among India's most vulnerable regions in regard to natural and human-made disasters. Further, the mountainous terrain is a complex, unstable, and a fragile ecosystem threatened by the major driving force of several devastating natural hazards including soil erosion (Chauhan et al. 2016). A study on morphometry-based watershed prioritization of Teesta Basin suggests that most portion of East Sikkim falls in high and very high erosion susceptible regions (Haokip et al. 2021). A study on landslide hazard risk vulnerability assessment in Gangtok indicates that 7.51% and 18.18% of the area fell in the very high-risk zone and high-risk zone respectively (SSDMA 2012). Considering the vulnerability to landslides and other risks in the region, a proper measure has to be taken in selecting the sites for digging trenches. To conduct a detailed hydrogeological, geological, and geophysical study on the identification and quantification of groundwater resources is often expensive and requires skilled human resources (Machiwal et al. 2015). On the other hand, remote sensing data and geographic information system (GIS) techniques are a crucial alternative approach to delineate groundwater recharge sites that will be a guide for further development on water management in the region.

In recent years, geospatial technology has been increasingly used for the identification of potential groundwater zones (Shaban et al. 2006; Gupta and Srivastava 2010; Gumma and Pavelic 2013; Nampak et al. 2014; Khan et al. 2020; Pradhan et al. 2021). The advantage of remote sensing and GIS-based analytic hierarchy process (AHP) is that it allows evaluation by considering various factors and utilizes them in decision-making. It has the application of scientific knowledge and proven field evidence, as well as an evaluation of the matrix for consistency (Yeh et al. 2016a, b). AHP is proven significant in the field of decision analysis across various disciplines such as waste management, land-use allocation group dynamics in psychology, real estate for picking preferred locations during house hunting, resource mapping in mineral exploration, etc. (Saaty 1980; Şener et al. 2006; Wang et al. 2009; Mohd et al. 2011; Felice et al. 2016). AHP ranks the influence of different factors on groundwater recharge, and thus, along with GIS, it becomes a compatible tool (Lentswe and Molwalefhe 2020). The influencing parameters, e.g., geology, soil, slope, geomorphology, LULC, drainage density, lineament density, and rainfall, are selected based on their contribution toward water yield to underground water. For the first time, the application of remote sensing, GIS, and AHP techniques is used to study groundwater recharge potential in Sikkim. This study will help to select the appropriate sites for digging trenches and pits for underground water recharge. The objective is to delineate the spatial distribution of groundwater recharge potential in the mountainous region of East Sikkim by (i) preparing thematic layers for eight parameters controlling groundwater recharge in the region, (ii) reclassifying and ranking the parameters based on their influence on groundwater recharge, and, (iii) producing groundwater recharge potential map. This study will benefit in identifying the potential recharge zone for various springs and wetlands in the study area.

Study area

Sikkim is located in the North-Eastern part of India, bordered by West Bengal in the south. It shares international boundaries with China in the north and northeast, Bhutan in the east, and Nepal in the west (Fig. 1). According to the 2011 census, it is the least populous and the second smallest state in India. It extends between 27°04′ 46″ and 28°07′ 48″ N latitudes and 88°00′58″ and 88°55′25″ E longitudes with elevations having a wide range from 280 to 8586 m above mean sea level.

The southern part of the state exhibits softer sedimentary rocks, and the northern and eastern parts are dominated by high-grade gneisses (GSI 2012). The degree of deformation of rock is quite variable, with the southern parts more deformed than the rocks found in the northern regions of the State. In East Sikkim, the dominant rock types include granite gneiss, phyllite, schist, quartzite, and migmatite (GSI
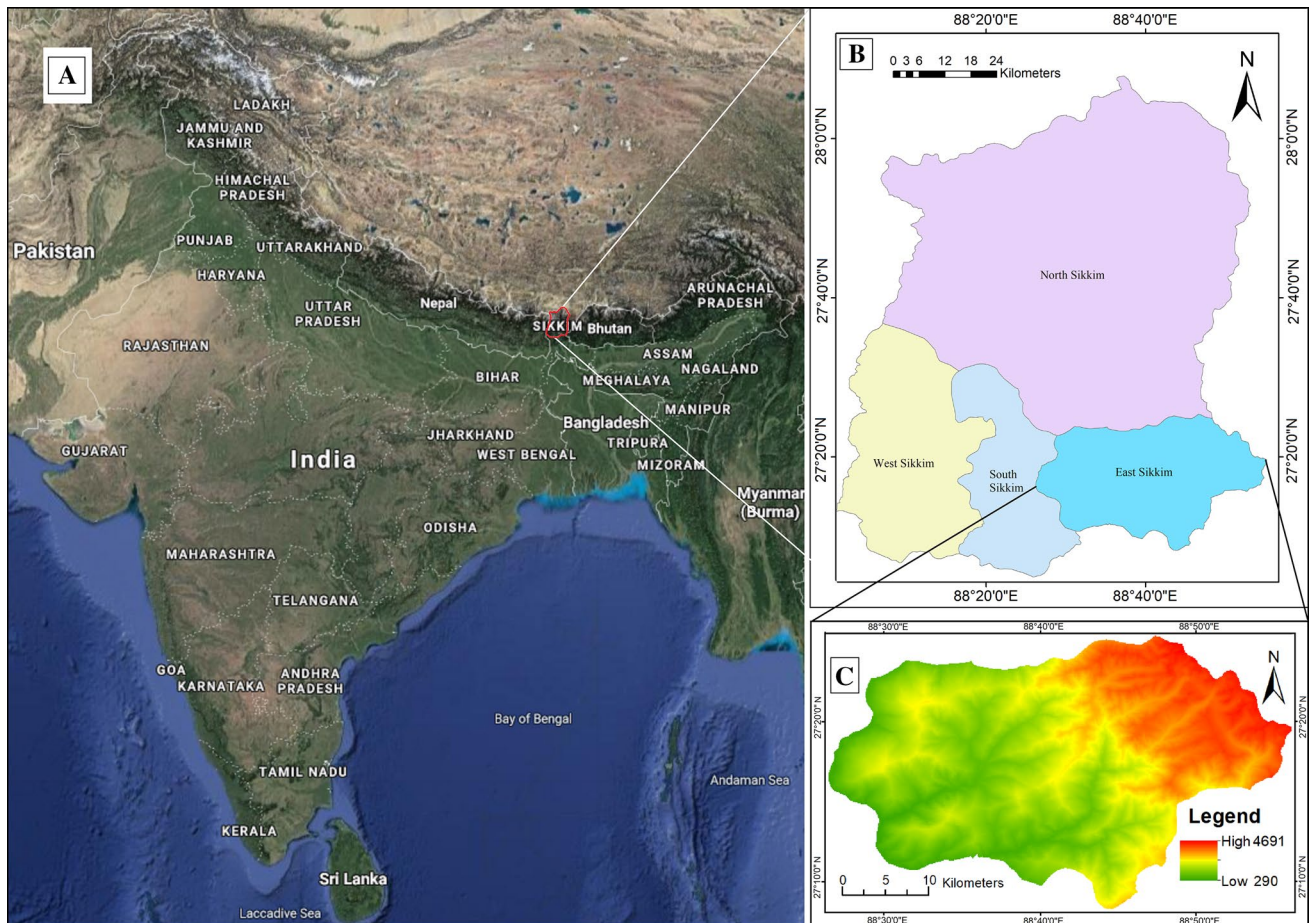
Fig. 1 Maps: **A** Location of Sikkim and the neighboring states in India which is bordered by China, Bhutan, and Nepal, **B** Four districts of Sikkim: East, West, North, and South Sikkim, and **C** Digital elevation map of the study area. Elevation given in m

Table 1 Geological succession of East Sikkim (GSI 2012)

Formation	Group/Supergroup	Age
Lingtse Granite Gneiss		Meso Proterozoic
Reyong Formation	Daling Group	Proterozoic Undifferentiated
Gorubathan Formation		
Kanchenjunga Gneiss/Darjeeling Gneiss (Undifferentiated)	Central Crystalline Gneissic Complex (CCGC)	
Chungthang Formation		

2012). The geological succession of East Sikkim is given in Table 1. The Himalayan fold-thrust belt (FTB) is dominant in the study area, which is characterized by a series of south-verging, folded thrust faults (Medlicott 1864; Gansser 1964; Srivastava and Mitra 1994; Pearson and DeCelles 2005). The belt accommodated a significant portion of the total Indo-Eurasian convergence in the Himalayan arc. The other significant faults in the belt are the Main Central thrust (MCT), the Main Boundary Thrust (MBT), and the Main Frontal Thrust (MFT). The MCT and the MBT mark the boundaries between the Greater and Lesser Himalayan, and the Lesser and Sub-Himalayan sequences (Bhattacharyya et al. 2015). The MCT is in contact with the Paro gneiss and lies above the Pelling Thrust (PT). There is the occurrence of a large number of perennial springs with varying discharge, which is an indication of the occurrence of groundwater in various rock formations and weathered zones in the host rocks such as phyllite, schist, gneisses, and quartzite. Direct infiltrations of rainwater through weathered zones of the rock, soil covers, joints, and fractures are the principal mode of recharge of the springs which is used by the populace for consumption and other domestic uses. Sikkim region has a relatively high slope; thus, the recharge of rainwater is minimized and flows off as surface runoff through streams and intermittent springs. The average maximum temperature is 27.2 °C, and the average minimum temperature is 1.6 °C. The annual rainfall varies spatially and temporally in Sikkim, and the study area receives an annual average rainfall of 3894 mm (CGWB 2013). A study on rainfall variability in Sikkim from 1951 to 2018 using daily gridded rainfall data revealed significantly widespread changing rainfall patterns (Dubey et al. 2022). The study indicates a decline in annual precipitation in the study area during the monsoon season. In July and September, negative changes in precipitation are observed, whereas positive changes are observed in February, March, April, May, November and December showing shifting of the rainfall patterns. Further, both negative and positive changes are observed in other months. The yearly precipitation changes show negative precipitation changes in 85% and positive changes in 15% of the area (Dubey et al. 2022). The soils in East Sikkim between 15 and 30% slopes are deep, excessively drained, coarse loamy to the fine loamy surface with moderate erosion, predominantly under forest and cultivation. The soils between 30 and 50% slopes are moderately shallow to deep, well-drained, silty to fine loamy with moderate erosion, and largely under temperate forest. The soils with more than 50% slope are moderately deep, excessively drained, coarse loamy to fine loamy with moderate erosion, and under temperate forest covers (Haokip et al. 2021).

Data and methods

Data acquisition and development of thematic layers

In this study, the maps for geology, geomorphology, and soil were prepared from the existing maps. The terra Advanced Spaceborne Thermal Emission and Reflection Radiometer Digital Elevation Model (ASTER DEM) data were used to generate drainage density and slope maps. The rainfall map was prepared from the IMD gridded data. Lineament map and LULC maps were generated from Landsat 8 image. The details of the data collected, sources, and their purposes are given in Table 2.

Analytic hierarchy process

There are several assessment techniques for delineating groundwater recharge potential such as single-factor analysis, multifactor analysis, fuzzy-analytical hierarchy process (F-AHP), fuzzy clustering, geographic information fusion systems, fuzzy-analytical hierarchy process indices, the multi-criteria decision-making method, and the multi-influencing approach (Xin-feng et al. 2012; Pinto

Table 2 Details of data collected, sources, and its purpose

Sl No	Data	Source	Purpose
1	Annual rainfall of 2020 (0.25 × 0.25 degree)	https://www.imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html	Rainfall map
2	ASTER DEM (30 m resolution)	https://asterweb.jpl.nasa.gov/data.asp	Drainage Density, and Slope map
3	Landsat 8 (30 m resolution)	https://earthexplorer.usgs.gov/	LULC and Lineament map
4	Geology map of Sikkim	Geological Survey of India: Miscellaneous Publication No. 30, Part XIX – Sikkim	Geology map
5	Natural resources atlas of Sikkim	ENVIS Hub: Sikkim Status of Environment and Related Issues. http://sikenvis.nic.in/Database/NaturalResources_790.aspx	Soil map
6	Geomorphology map of Sikkim	https://bhuvan-app1.nrsc.gov.in/thematic/thematic/index.php#	Geomorphology map

et al. 2017; Nag and Kundu 2018; Nasir et al. 2018; Celik 2019; Thapa et al. 2017; Ahmad et al. 2020; Lentswe and Molwalefhe 2020; Shao et al. 2020). Among these, the multi-criteria decision-making method using AHP is one of the most significant because it involves decision-making based on various parameters (Lentswe and Molwalefhe 2020; Fauzia et al. 2021a, b). The various parameters which influence groundwater recharge potential include geology, topography (slope), lineament, rainfall, land-use/cover, geomorphology, drainage density, primary porosity, elevation, secondary porosity, soil type, soil texture, fractures, and weather in a region (Rahmati et al. 2015; Jasrotia et al. 2013; Adiat et al. 2012). Based on the availability of data and the factor of influence for groundwater recharge in the region, a total of eight sets of criteria/factors are considered in this study. The factors include drainage, lineament, LULC, rainfall, slope, geomorphology, soil, and geology. The various thematic layers were transformed into raster data. It is then followed by the weighted overlay method (rank and weightage-wise thematic maps). Based on Saaty's 9-point scale, the parameters were assigned an appropriate weight and through AHP, the weights were normalized. AHP was applied to rank the importance of each parameter relative to one another concerning groundwater recharge. The weighted layers were statistically computed in the overlay analysis to generate the groundwater recharge potential. The general methodology is summarized in Fig. 2, which includes the preparation of thematic layers, reclassifying and ranking the parameters, and generation of a groundwater recharge potential map.

Each of the eight thematic layers was georeferenced and projected to Universal Transverse Mercator (UTM) World Geodetic System 84 (WGS-84). Further, the images were reclassified and assigned a weight according to their relative influence on groundwater recharge using the AHP technique (Saaty 1977; Brunelli 2014). The weight is assigned to each map layer to represent the relative importance of each parameter class concerning recharge. AHP is a common technique applied for structuring information alternatives on a hierarchical framework aided by mathematical pairwise comparisons (Chowdhury et al. 2009; Hachem et al. 2014; Yeh et al. 2016a, b; Arulbalaji et al. 2019). The process is significant for compiling multiple layers to get a single layer. The requirement of separating into a series of pairwise comparisons is aided by AHP. The fundamental scale used in AHP is given in Table 3, and the weights of various parameters by multi-criteria evaluation technique and the ranking for individual features are given in Table 4.

Eigenvector and principal eigenvalue

The eigenvector is the ordering of parameters that were computed to show the relative weights of each of the parameters (Saaty 2003; Brunelli 2014). The eigenvectors were calculated first by dividing column values by
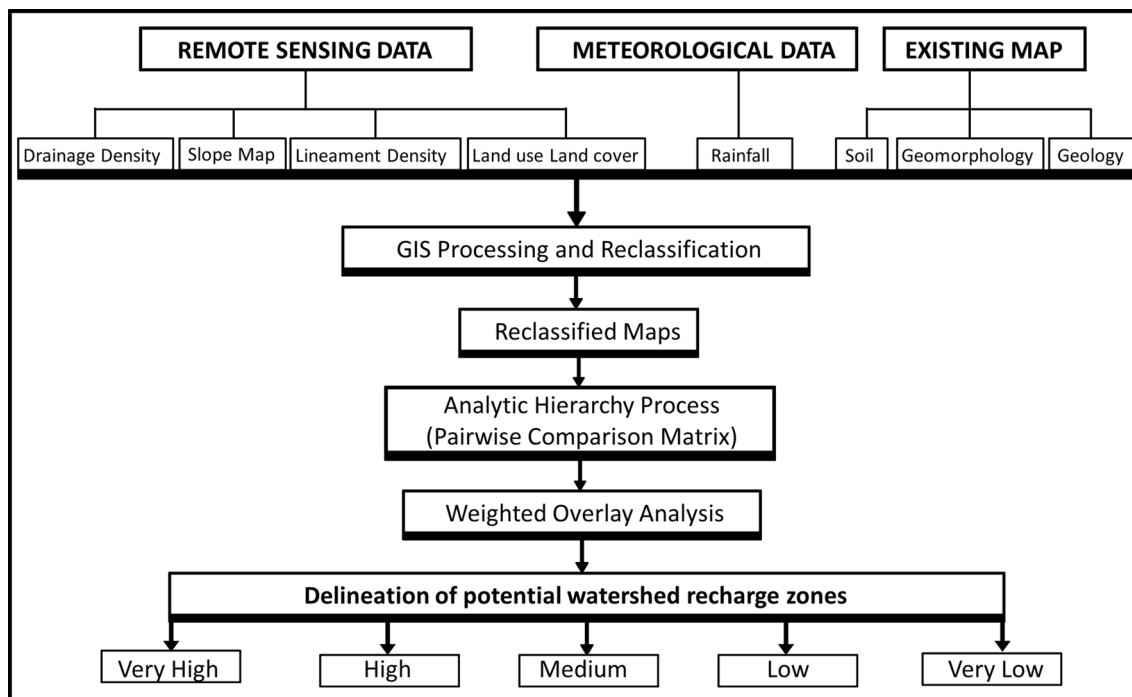

Fig. 2 Workflow diagram for the evaluation of potential groundwater recharge zones

Table 3 The fundamental scale for AHP (Saaty, 1980)

Intensity of importance	Definition	Details
1	Equal importance	The contribution of the two activities is equal
3	Moderate importance of one over another	The contribution of one activity favors the other
5	Strong importance	The contribution of one activity strongly favors the other
7	Very strong importance	The contribution of one activity very strongly favors the other
9	Extreme importance	The highest possible order of affirmation of one factor over the other
2, 4, 6, 8	Intermediate values between the absolute scale	When compromise is needed
Reciprocal	For any activity i and j, the value of one will be reciprocal of the other	
Rational	Ratios arising from the scale	

the column sum and then averaging row values (Saaty 1980). The eigenvalue is used to rank the importance of the parameters. The sum of eigenvalues called principal eigenvalue (λ_{max}) is a measure of matrix deviation from consistency (Brunelli 2014). A pairwise comparison matrix is considered to be consistent only if the principal eigenvalue (λ_{max}) is greater than or equal to the number of the parameters considered (n); otherwise, a new matrix is required (Saaty 1980). The principal eigenvalue was obtained from the summation of the products column in the pairwise matrix and eigenvector. The principal eigenvalue was achieved for the 8*8 matrix to calculate the consistency index. The standardized pairwise comparison matrix and weight factors influencing recharge for all parameters are given in Table 5.

The pairwise matrix is given by the matrix as follows (Saaty 1980):

$$A = \begin{bmatrix} K & Ai & . & . & . & An \\ Ai & 1 & ai & . & . & an \\ . & 1/ai & 1 & . & . & . \\ . & . & . & 1 & . & . \\ . & . & . & . & 1 & . \\ An & 1/an & . & . & . & 1 \end{bmatrix}$$

where A = pairwise comparison matrix of Ai; i = 1, 2…. 8 for criteria K; n = the number of evaluation criteria (Table 6).

The consistency index (CI) may be expressed in Eq. (1) (Saaty 1988):

$$CI = \frac{\lambda \max - n}{n - 1} \tag{1}$$

$$\lambda_{max} = (7.69 + 7.63 + 8.13 + 8.13 + 8.13 + 8.12 + 8.12 + 8.12)/8$$

$$= (64.07)/8$$

$$= 8.009$$

$$CI = \frac{8.009 - 8}{8 - 1} = 0.00129$$

The consistency ratio (CR) is expressed in Eq. (2) as:

$$CR = \frac{CI}{RCI}$$
$$= \frac{0.00048}{1.41} = 0.0009 \tag{2}$$

where RCI is the random index for n number of evaluation criteria. The RI value for $n = 8$ is given in Table 7 (Saaty 1980).

For consistent decisions, the value of CI is 0, but inconsistency may be tolerated for (CR) < 0.1 (Saaty 1990). The value of acceptable CR values differs based on the matrix size. The acceptable CR values are as follows: for a 3×3 matrix, CR < 0.05; for a 4×4 matrix CR < 0.09; and for larger matrices CR < 0.1 (Saaty 1980). In this study, since the CI and CR values are 0.00129 and 0.0009, respectively, the judgments matrix is very consistent.

Delineation of potential recharge zones

To delineate potential recharge zones in the study area, the AHP technique was implemented in four phases: (1) selection of factors influencing groundwater recharge (2) pairwise comparison matrix, (3) estimating relative weights, and (4) assessing matrix consistency. The first phase in the AHP technique includes the selection of factors influencing groundwater recharge and their attributes. It enables the identification of the problem into a pyramid structure comprising objectives and eventually, the influencing factors are selected (Saaty 1980; Boroushaki and Malczewski 2008; Brunelli 2014). To delineate potential recharge zones in East Sikkim, the various factor attributes comprise thematic layers of geology, soil, drainage density, lineament density, LULC, geomorphology, rainfall, and slope. The reclassified layers of the influencing factors show potential recharge zones based on each factor. The relative importance of the parameters was graded based

Table 4 Weightage of various parameters by AHP

Thematic layers	Weightage	Individual features	Rank
Geology	19	Granite Gneiss	2
		Gorubathan Formation	4
		Kanchenjunga Gneiss/Darjeeling Gneiss	4
		Chungthang Formation	6
		Reyong Formation	6
Soil		Snow	2
	17	Entisols	7
		Inceptisols	5
		Mollisols	3
LULC	14	Dense forest	6
		Water	9
		Built-up	2
		Barren	1
		Agriculture	7
		Open forest	5
Geomorphology	12	Structural Origin-Highly Dissected Hills and Valleys	2
		Structural Origin-Moderately Dissected Hills and Valleys	3
		Fluvial Origin-Younger Alluvial Plain	7
		Glacial Origin-Glacial Terrain	2
		Glacial Origin-Snow Cover	2
		Waterbodies	9
Slope	12	Very high	1
		High	3
		Medium	5
		Low	7
		Very low	9
Drainage density	10	Very high	1
		High	3
		Medium	5
		Low	7
		Very low	9
Lineament density	8	Very high	9
		High	7
		Medium	5
		Low	3
		Very low	1
Rainfall	8	Very high	9
		High	7
		Medium	5
		Low	3
		Very low	1

on a nine-point scale (Table 3). A score of 1 indicates equal importance between the two factors. Likewise, a score of 9 indicates the extreme importance of the parameter in the row compared to the parameter in the column (Saaty 1980). The second phase is the construction of a pairwise comparison matrix (8*8), based on the number of input factors for the delineation of recharge potential zones (Saaty 1980). Each entry of the matrix represents the influence of the row-factor relative to the column factor. Due to the significance of geology in groundwater recharge, the selection and weighting of factors for delineating recharge zones were based on geology and processes affecting recharge in the study area. Geology was selected as the first parameter and recorded in row 1 and column 1 of the matrix. The soil was selected as the second most important parameter followed by LULC, geomorphology,

Table 5 Weight assigned and pairwise comparison matrix of eight thematic layers influencing recharge in the study area

Parameter	Assn. Wt	GG	SO	LULC	GM	SL	DD	LD	R
Geology (GG)	9	9/9	9/8	9/7	9/6	9/6	9/5	9/4	9/4
Soil (SO)	8	8/9	8/8	8/7	8/6	8/6	8/5	8/4	8/4
Land-use/cover (LULC)	7	7/9	7/8	7/7	7/6	7/6	7/5	7/4	7/4
Geomorphology (GM)	6	6/9	6/8	6/7	6/6	6/6	6/5	6/4	6/4
Slope (SL)	6	6/9	6/8	6/7	6/6	6/6	6/5	6/4	6/4
Drainage Density (DD)	5	5/9	5/8	5/7	5/6	5/6	5/5	5/4	5/4
Lineament Density (LD)	4	4/9	4/8	4/7	4/6	4/6	4/5	4/4	4/4
Rainfall (R)	4	4/9	4/8	4/7	4/6	4/6	4/5	4/4	4/4

Table 6 Standardized pairwise comparison matrix showing values of normal weight and λ

Parameter	GG	SO	LULC	GM	SL	DD	LD	R	Nor.Wt.	λ
Geology (GG)	1	1.13	1.29	1.5	1.5	1.8	2.25	2.25	0.19	7.69
Soil (SO)	0.89	1	1.14	1.33	1.33	1.6	2	2	0.17	7.63
Land-use/cover (LULC)	0.78	0.88	1	1.17	1.17	1.4	1.75	1.75	0.14	8.13
Geomorphology (GM)	0.67	0.75	0.86	1	1	1.2	1.5	1.5	0.12	8.13
Slope (SL)	0.67	0.75	0.86	1	1	1.2	1.5	1.5	0.12	8.13
Drainage Density (DD)	0.56	0.63	0.71	0.83	0.83	1	1.25	1.25	0.10	8.12
Lineament Density (LD)	0.44	0.5	0.57	0.67	0.67	0.8	1	1	0.08	8.12
Rainfall (R)	0.44	0.5	0.57	0.67	0.67	0.8	1	1	0.08	8.12

Table 7 Average random consistency (RI) for various matrix size

Size of matrix	1	2	3	4	5	6	7	8	9	10
Random consistency	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

slope, drainage density, lineament density, and rainfall. Drainage density and lineament density largely depends on other parameters under investigation, so it was allocated in the lower order. Rainfall is an important factor in recharge, but since the difference in average annual rainfall in the study area is not significant, it is considered in the lowest order. The selection parameter pair, as well as the assignment of pair weight, was based on the interrelationship between geology and other factors affecting recharge. The eigenvector and eigenvalue are used to reduce noise in the data by eliminating features that have a strong correlation and help in reducing over-fitting (Lentswe and Molwalefhe 2020). Expert opinion and eigenvector are used to assign factor weight, while principal eigenvalue is used to rank the factors (Saaty 1980; Carver 1991; Malczewski 2006; Hajkowicz and Higgins 2008). All the inputs were integrated through the weighted overlay method after assigning weights and ranks to the parameters and their subclasses using Eq. (3):

where *GWRP* denotes groundwater recharge potential, 'x' denotes factor class, and 'y' denotes factor subclass, respectively.

Results and discussion

Geology

Geology controls recharge through the nature of rocks at the outcrops and topography, slope, and nature of soils (Simmers 1990; Freeze and Cherry 1979). The different structural entities in the basement rocks control the occurrence and movement of groundwater to a great extent (Pradhan and Biswal 2019). Based on the porosity and hydraulic conductivity of the rock types, the ranks are given for the various geological features (Earle 2015). In the study area, the rocks are highly foliated and deformed, so they have significant secondary porosity and permeability which plays

$$GWRP = GGxGGy + GMxGMy + SOxSOy + LULCxLULCy + DxDy + SLxSLy + LxLy + RxRy \tag{3}$$

an important role in the ranking of the geology. Chungthang Formation is the oldest formation in the geological succession consisting of rock types such as Quartzite, Garnet kyanite sillimanite biotite schist/Garnetiferous mica schist, Calc-silicate, and carbonaceous schist (GSI 2012). Kanchenjunga Gneiss/Darjeeling Gneiss consists of rock types such as Banded/streaky migmatite, Augen bearing (garnet) biotite gneiss with/ without kyanite, sillimanite with palaeosols of staurolite, kyanite, mica schist, and sillimanite granite gneiss GSI 2012). It is the highest-grade metamorphic rock of the Greater Himalayan Sequence (GHS) in the Darjeeling–Sikkim Himalaya. The rock types prevalent in Chungthang Formation and Kanchenjunga Gneiss have coarser grain size and penetrative foliation, so it is assigned the highest rank (6). Gorubathan Formation consists of rock types such as interbanded chlorite-sericite schist/phyllite and quartzite, meta-greywacke (quartzo-feldspathic greywacke), pyritiferous black slate, biotite phyllite/mica schist, biotite quartzite, mica schist with garnet, with/without staurolite, chlorite quartzite (GSI 2012). Reyong Formation consists of variegated cherty phyllite. The rock types in the Daling Group (Gorubathan and Reyong) have relatively finer grain sizes and are dominated by cleavage plains, so it is assigned a medium rank (4). Lingtse Granite Gneiss is a coarse-grained orthogneiss with less permeability and relatively less foliation, and so it is assigned the lowest rank (2). The geological map of the study area is classified in six groups which is shown in Fig. 3.

Soil type

Soil covers the outermost layer of the earth's crust, and hence, the initial infiltration capacity of a region is highly dependent on the prevalent soil type. The soil types of the region were grouped according to grain size. There are 14 types of soils within the study area which are grouped into three, namely entisols, inceptisols, and mollisols (Fig. 4). Entisols are assigned the highest rank (7) because it consists mostly of coarser grains. Coarse-grained soils have higher infiltration capabilities than fine-grained soils. Hence they are assigned higher recharge potential values (FitzPatrick 1986; Brady and Weil 2014). Further, inceptisols and mollisols are assigned lower ranks of 5 and 3 because it consists mostly of medium and fine grains.

Land-use/cover

For land-use/cover classification, a satellite image retrieved on January 2, 2018, from Landsat 8 was used. The various classifications are water bodies, built-up, barren, agriculture, dense forest, and sparse forest. For each classification, the various features considered are given in Table 8. The land-use/cover classification is done by knowledge-based supervised classification technique and maximum likelihood classifier in ArcGIS 10.4.1. The barren land is mostly covered by snow in winter, and thus, the weightage of barren land is given considering the snow cover aspect also. The LULC classification map of the study area is shown in Fig. 5. Further, the land-use/cover map generated was compared with the ground truth data and Google Earth image. The photographs taken in the field and the Google earth image are shown in Supplementary Sections, with the reference in the land-use/cover map shown in subset parallelogram A to J.

Fig. 3 Geological map of East Sikkim
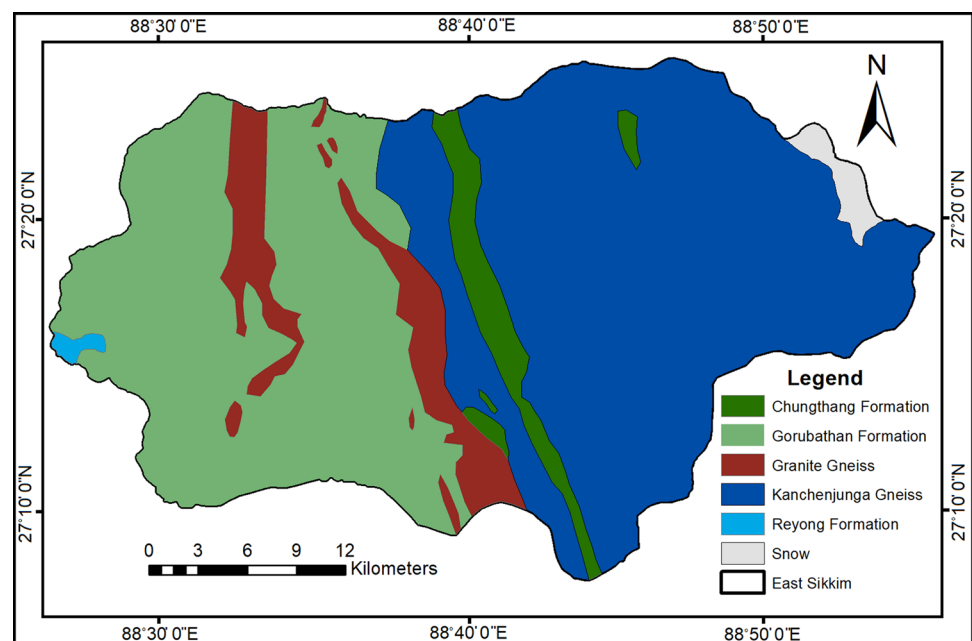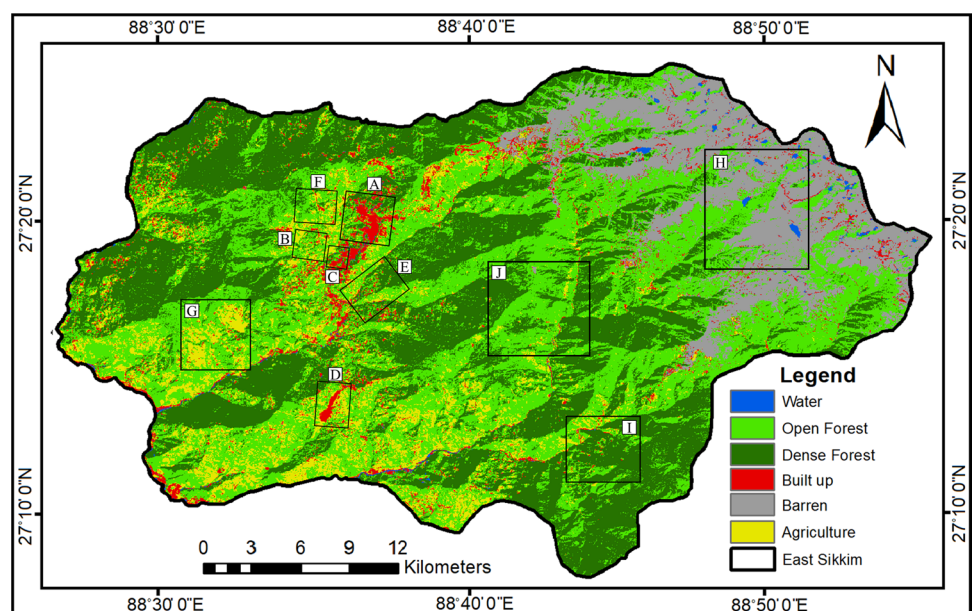
Fig. 4 Soil map of East Sikkim

Geomorphology
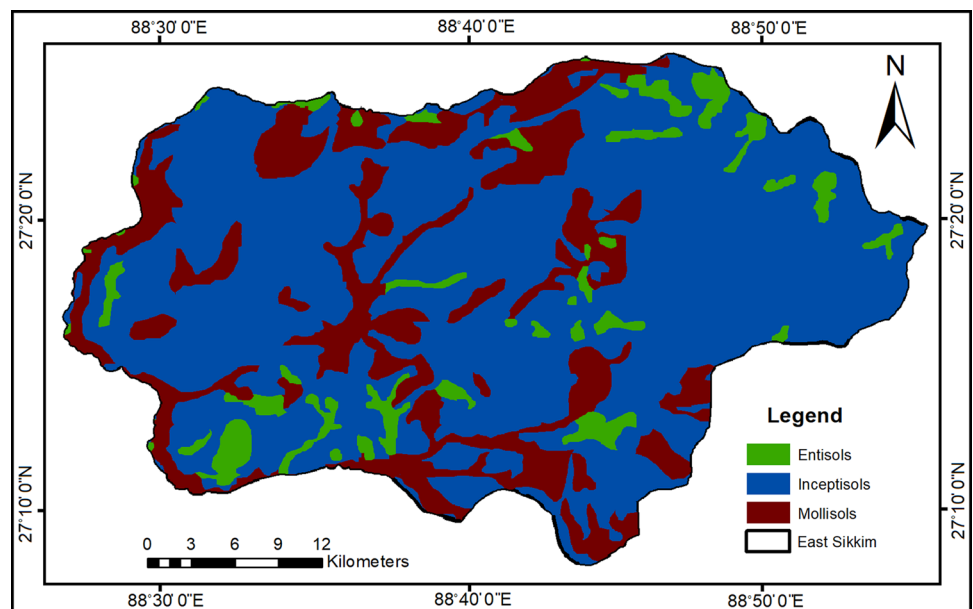
Table 8 The LULC types and their respective classes

Classes	Features
Built-up land (BL)	Residential, industrial, and roads
Agricultural land (AL)	Cropland and pasture
Dense forest (DF)	Thick tree canopy density
Open forest (OF)	Sparse tree canopy density
Water (W)	Rivers, streams and canals, lakes, reservoirs, bays, and estuaries
Barren land (BL)	Bare exposed rock and mixed barren land

Geomorphology represents the landform and topography of a region, and hence, it is an important parameter widely used for the delineation of water recharge zones (Arulbalaji et al. 2019). The groundwater in the study area is mostly confined within the fracture zones in various lithological units and weathered residuum in gneisses, phyllite, schist, and quartzite. Based on the geomorphology, the study area is classified into six different types as (i) structural origin-highly dissected hills and valleys, (ii) structural origin-moderately dissected hills and valleys, (iii) fluvial origin-younger alluvial plain, (iv) glacial origin-glacial terrain, (v) glacial origin-snow cover, and (vi) waterbodies accumulation (https://

Fig. 5 Land-use/cover classification of the study area with various sections A to J. Field photographs and google imagery of sections A to J are included in Supplementary sections (Annexures 1 and 2)

Fig. 6 Geomorphology map of East Sikkim
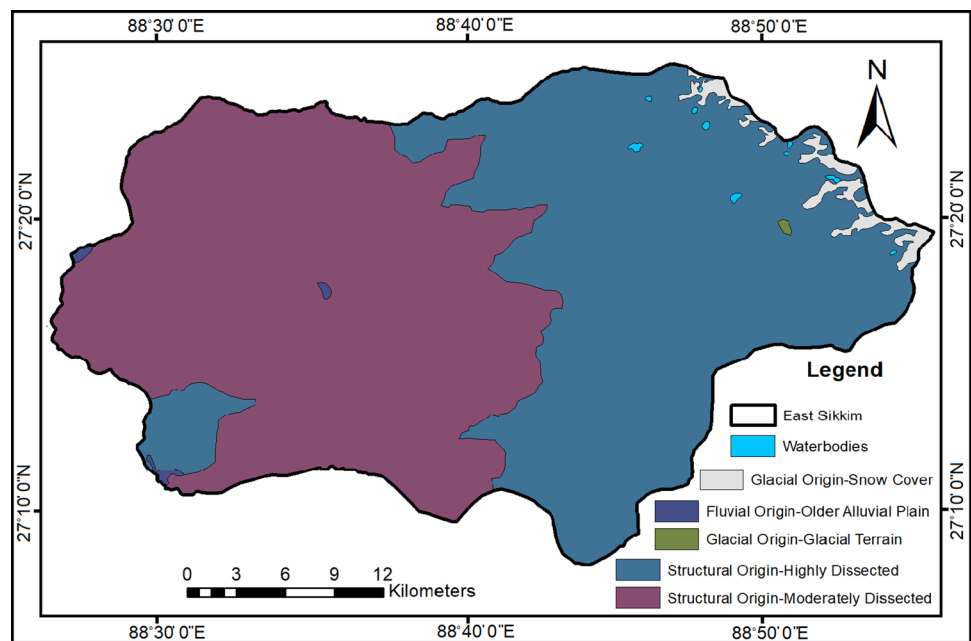
bhuvan-app1.nrsc.gov.in/thematic/thematic/index.php#). The study area is dominant of structural origin with high and moderately dissected hills and valleys (Fig. 6). Hills and valleys of structural origin are dissected by the drainage lines, and accordingly, it has been classified as highly and moderately dissected depending on the density of lineaments, joints, and drainage. Thus, moderately dissected hills and valleys are assigned a slightly higher rank (3) than highly dissected hills and valleys (2). Fluvial-originated alluvial plains are those landforms that are formed by rivers and streams. Among the classifications, waterbodies are assigned the highest rank (9) followed by fluvial-originated alluvial plain (7). The lowest rank of 2 each is assigned to the glacier-originated landforms and highly dissected hills and valleys of structural origin.

Slope

The slope of a region is defined as the angle between the tangent plane and the horizontal plane which is given in degree (Maidment 1993). Slope influences the amount of infiltration and runoff to a great extent (Simmers 1990). Gently sloping areas allows maximum infiltration, whereas areas with steeper slope lead to minimum recharge to the underlying aquifers (Rashid et al. 2012). It is observed that the slope parameter is ignored in some studies related to groundwater flow and storage conducted in less mountainous terrain (Al Saud 2010). However, in this study, the region being a hilly terrain, the slope of the region plays an important role in the water recharge. The slope map of the study area is given in Fig. 7 which was created from ASTER DEM using the slope tool in ArcGIS 10.4.1. The slope values were reclassified

and categorized into five classes, namely very low (0–7.36), low (7.36–14.6), medium (14.6–24.4), high (24.4–41.2), and very high (> 41.2). The highest rank (9) is assigned for a very low slope, and likewise, the lowest rank (1) is assigned for a very high slope.

Drainage Density

A drainage network of a region can be expressed as drainage density. Drainage density is calculated as the total length of streams to the surface area (Schillaci et al. 2015). The drainage order map (Fig. 8) and drainage density map (Fig. 9) were extracted from ASTER DEM using the line hydrology tool of the Spatial Analyst tool in ArcGIS 10.4.1. The drainage density is calculated by dividing the length of the drainage line by the total area using the line density tool (ESRI 2015). Areas with high drainage density are characterized by excessive runoff and are assigned a lower rank concerning recharge. Thus, areas with less drainage density were assigned higher ranks. The red patches of the drainage density map represent higher stream density, while the yellow and green patches show moderate and low stream density.

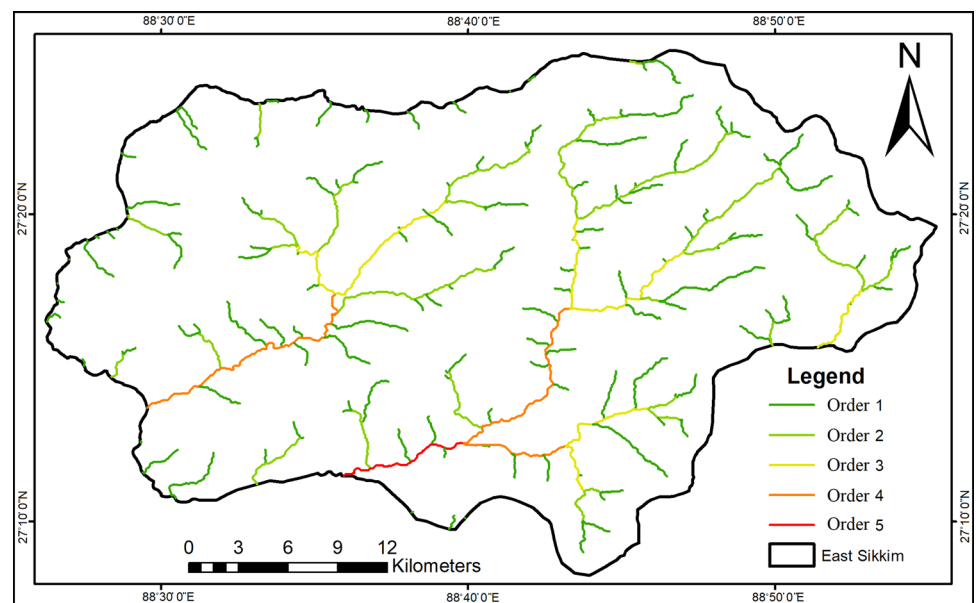Drainage density (DD) is an inverse function of permeability which is shown in Eq. (4)

$$DD = \frac{\sum Di}{A} \qquad (4)$$

where $\sum D$ is the total length of the streams i (km) and A is the surface area (km^2).

Fig. 7 Slope map of East Sikkim
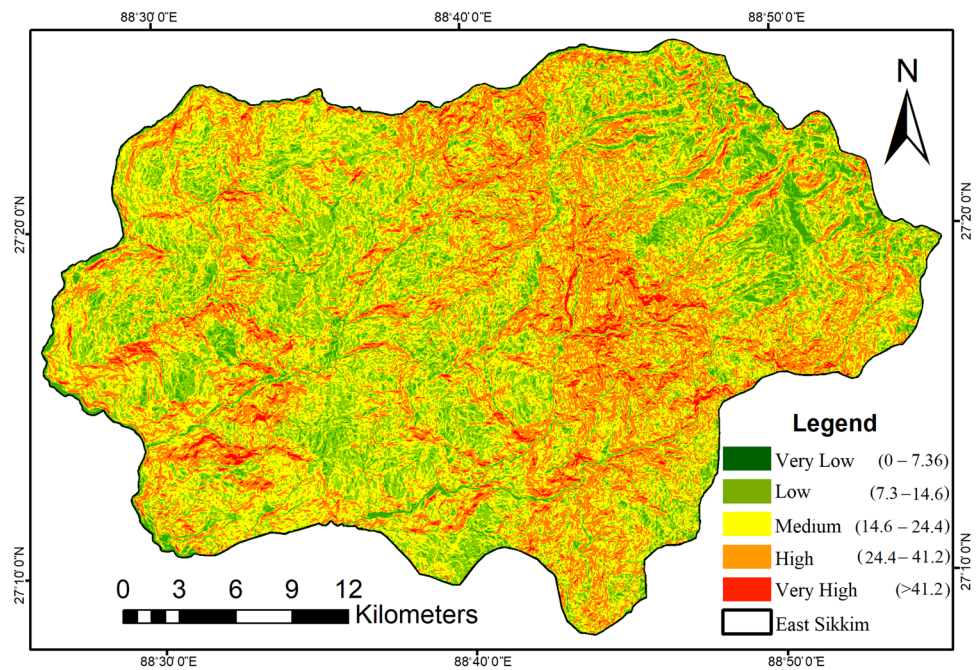
Fig. 8 Stream order map of East Sikkim

Lineaments density

Geological and structural features such as fractures or faults or joints create surficial expressions which are termed as lineament (O'Leary et al. 1976). Lineaments induce secondary porosity and permeability to the formation of a region (Maidment 1993; Freeze and Cherry 1979). In the present study, lineaments were extracted from Landsat 8 images. The extracted lineament map was used for generating lineament density. Lineament density is calculated as the total length of the lineaments to the total area (Edet et al. 1998). The calculation of lineament density (LD) is shown in Eq. (5):

$$LD = \frac{\sum Li}{A} \tag{5}$$

where $\sum Li$ is the total length of all lineaments (km) and A is the area of the grid (km^2).

Fig. 9 Drainage density map of East Sikkim
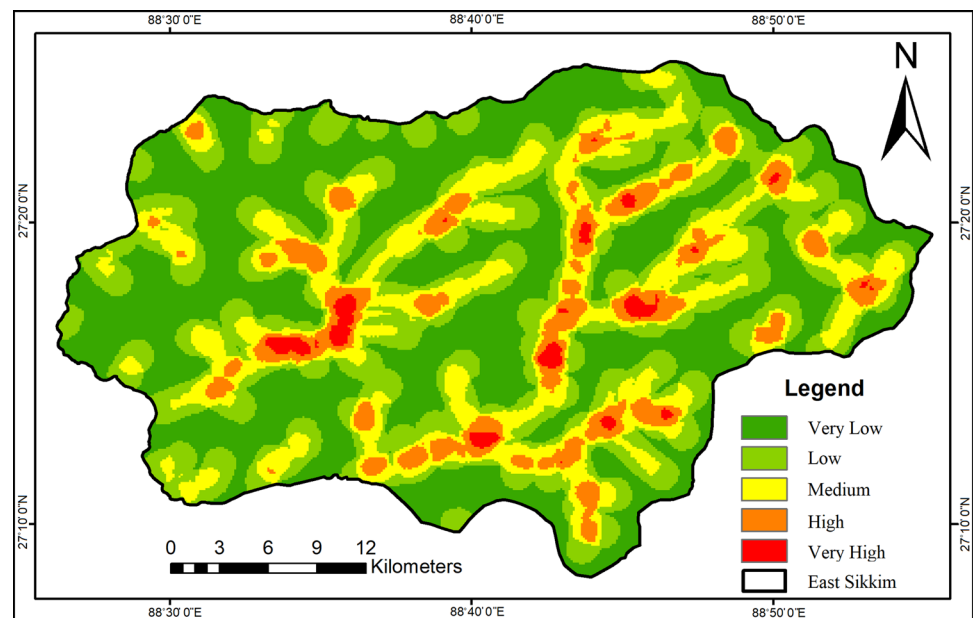
To extract the lineament of the study area, the PCI Geomatica 2013 version was used. PCI Geomatica can extract lineaments from images automatically with the line option (Kocal et al. 2004). The presence of lineaments indicates a permeable zone. Hence, the lineament density of an area can indirectly expose the water recharge potential. The areas with high lineament density offer better conditions for water recharge (Haridas et al. 1998). The linear structure derived was transformed into a lineament density map using the line density tool of Spatial Analyst Toolbox in ArcGIS 10.4.1 (Fig. 10).

Rainfall

Rainfall is an important factor that initiates recharge in any area. The rainfall map is generated from IMD gridded data (0.25×0.25 degree). The NetCDF file is downloaded from the IMD site, and the spatial distribution map of rainfall was prepared by the inverse distance weighted (IDW) interpolation tool in ArcGIS 10.4.1. The total rainfall received in the region ranges from 3123 to 4086 mm/year. The rainfall map has been reclassified into five categories as 'very high' (3893–4086 mm), 'high' (3701–3893), 'medium' (3508–3701 mm), 'low' (3315–3508 mm), and 'very low' (3123–3315 mm). Accordingly, the highest rank (7) is assigned to the region receiving the highest rainfall, and the lowest rank (3) is assigned to the region receiving the least rainfall. The spatial distribution map of rainfall in the study area is given in Fig. 11.

## Groundwater recharge potential map

The groundwater recharge potential map of the study area is shown in Fig. 12, which is the sum of the products of factor percentage influence and the reclassified map. A few significant locations in the study area are labeled on the groundwater recharge potential map. The water recharge potential map shows that high recharge is concentrated in the red sections; moderate recharge areas in yellow; and poor recharge potential in green. The groundwater recharge map is divided into five classes: very good (0.24 sq. km that covers 0.02%), good (13.11 sq. km that covers 1.38%), moderate (515.07 sq. km that covers 54.22%), poor (416.75 sq. km that covers 43.87%), and very poor (4.72 sq. km that covers 0.49%). It is observed that a small region with good and very good groundwater recharge potential is in the central and southwestern parts of the study area which correspond to outcrops of the Chungthang and Gorubathan Formation. The region falls in agricultural area, forest cover, low to very low drainage density, and low to the very low slope. The low to very low recharge potential is in the outcrop of Lingtse Granite Gneiss and Kanchenjunga Gneiss. The zones are spread mainly in the region dominated by high to very high slope, low to very low lineament, and mollisols soil type. The moderate recharge potential zone, which has the maximum spatial cover, occurs predominantly in Chungthang Formation, Gorubathan Formation, low to medium slope, inceptisols, and entisols soil type. In this study, due to the non-availability of field data, validation of the results could not be done. However, the field validation in other studies using the same methodology has proved effective, reliable, and significant for groundwater management and planning artificial recharge (Patil and Mohite, 2014; Abijith et al.

Fig. 10 Lineament density map of East Sikkim
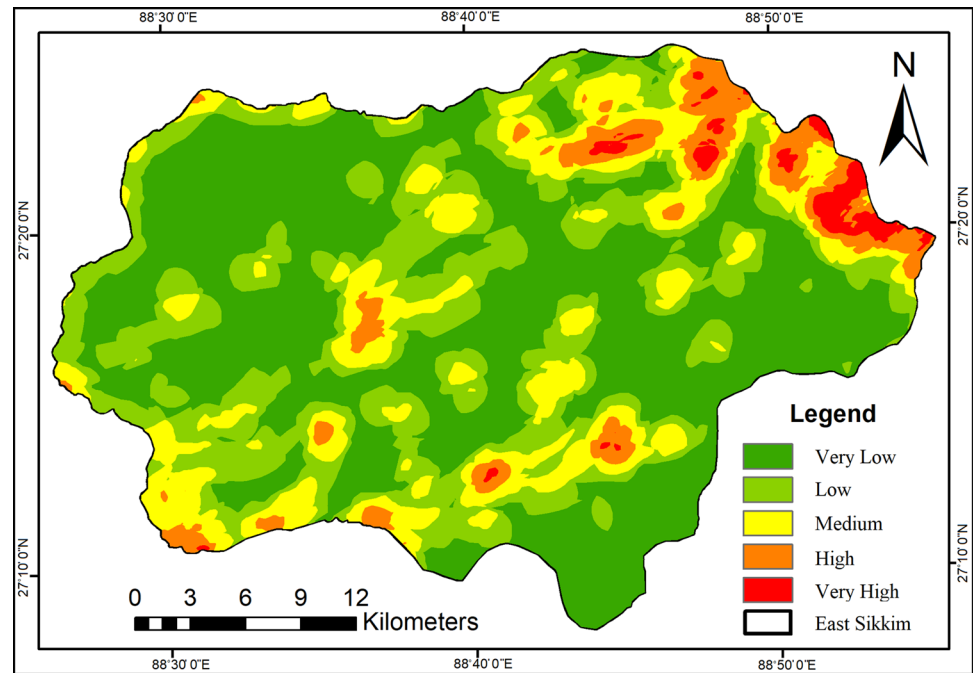

Fig. 11 Rainfall map of East Sikkim
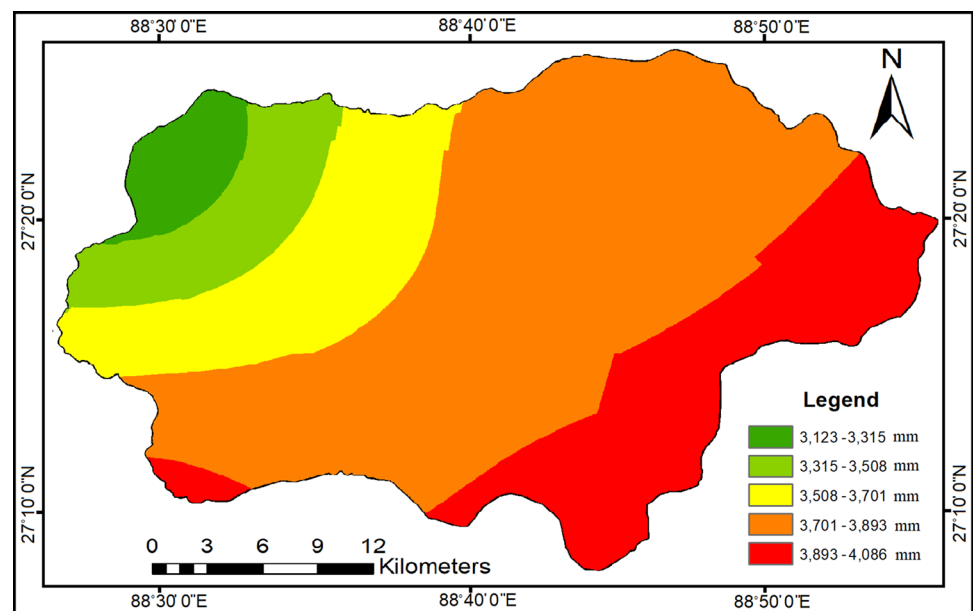
2020; Lentswe and Molwalefhe 2020; Fauzia et al. 2021a, b). Similar studies conducted in Ponnaniyaru watershed, Tamil Nadu, India, and Korba coastal area, Tunisia, were validated with observed well-yield data, water level depth, and predictive precision for AHP, and the observed accuracy was 75% and 75.6%, respectively (Abijith et al. 2020; Zghibi et al. 2020). Another study demarcating potential recharge zone in the Maheshwaram watershed, Telangana, India, gives significant validation results with pre- and post-monsoon water level fluctuations (Fauzia et al. 2021a, b).

Conclusion

Springs and streams are the main water resources of East Sikkim which is one of the most populated districts of Sikkim. Although springshed development has been initiated in Sikkim, no such scientific study has been conducted in the region. This study is an attempt to identify potential zones for underground water recharge using GIS and RS approaches. Remote sensing data, meteorological data, and existing maps were used to create eight thematic maps,

Fig. 12 Groundwater recharge potential map of East Sikkim
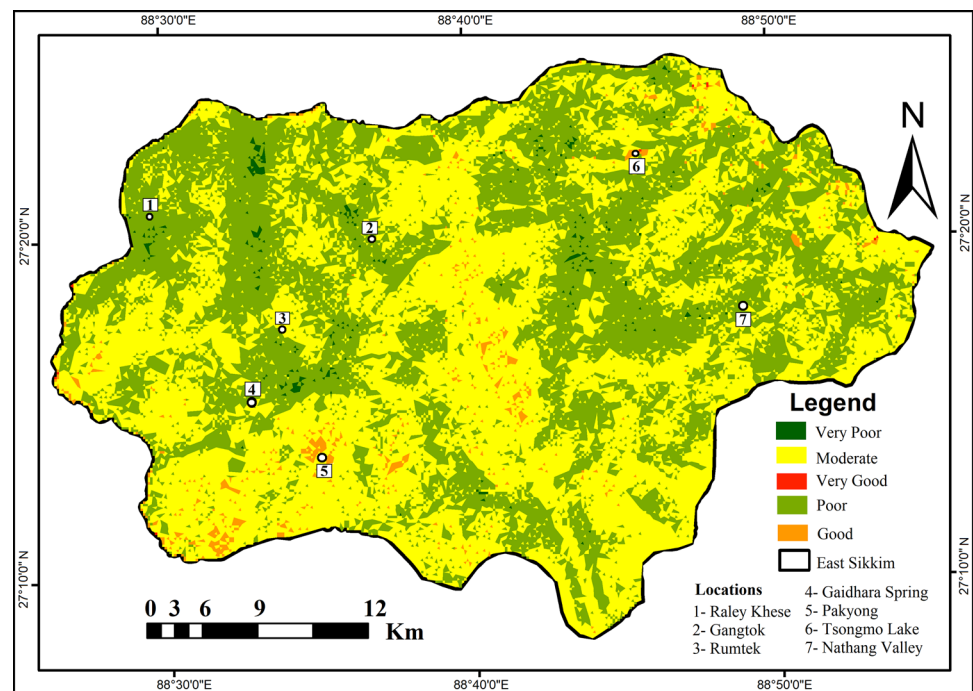
which were then combined in a GIS model using AHP and weighted overlay analysis to produce five categories of GWPZs. The study demonstrates the following conclusions:

1. The delineation of potential watershed recharge zone using the Weighted Overlay method show that most of the major habitat settlements (e.g. Gangtok, Rumtek, Singtam, etc.) fall under moderate (54.22%) and poor (43.87%) recharge potential zones. However, due to the non-availability of groundwater data and spring discharge, validation of the results is beyond the scope of this study.

2. Construction of rainwater harvesting structures, especially pits, trenches and surface check dams, to recharge the groundwater will be more effective in the central and southwestern zones of East Sikkim, especially the Pakyong settlement area.

3. This study highlights the various groundwater recharge potential zones which are necessary to revive the springs as well as make them perennial for sustainable livelihood.

Declarations

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