Journal of Indian Geomorphology
Volume 8, 2020 ● ISSN 2320-0731
Indian Institute of Geomorphologists (IGI)

Delineation of Landscape and Geomorphic Features Using SRTM DEM and Geological Data for the Darjeeling Himalayan Region

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Abstract: *The objective of this work is to delineate the topographic features of the Darjeeling-Kalimpong districts using geospatial information and GIS application to identify and extract various terrain and geomorphic features using the digital elevation model (30 m) and geological data. The geology and lithology of the region depict that the area had experienced several episodes of tectonic deformation for a long period. Numerous rivers and streams are active in the region. The study area is marked by highly dissected hills and valleys to flattish fans and plains. The landform classes include high altitude rugged topography, flood plain, alluvial fan, terraces, point bars, oxbow lakes, etc. The majority of the region is covered with structural and alluvial foundation. Relative relief of about 28.2% of the area is high, followed by very low (26.9%), very high (22.9%), moderate (13.3%) and low (8.7%). The delineation of terrain and geomorphic units can be applied for planning and management of land use and land cover studies, landslide hazard zonation, and watershed delineation.*

Key words: Terrain, geomorphology, remote sensing, GIS, DEM, Darjeeling.

Introduction

A terrain is the manifestation of vertical and horizontal dimensions of the earth’s surface that form the landscapes. It is generally expressed in terms of elevation, slope, and orientation of landform features. The characterisation of the landscape, on the other hand, is dependent on the properties and shape of topographic features (Klimaszewski, 1982). Landscape assessment evaluates the earth's surface structure and its classification based on surface decoration similarities (Wilson and Gallant, 2000). Physiography, morphometry, lithology, and soil are integral parts of a landscape that directly controls any region's land use and land cover (Saha *et al.,* 2019). Thus, for land use planning, landscape delineation is a significant factor as it demonstrates land suitability. For example, agricultural activity tends to prefer flat and fertile areas with less aesthetic appeal; in contrast, the vicinity to hilly terrain and forested areas prefer recreational and tourism development (Prasad and Sarkar, 2011). In recent decades, various methods of digital terrain analysis have been established for the extraction of terrain parameters and attributes (hydrological, geological, or morphological) from digital elevation data. These include land components like slope, elevation, aspect, curvature and catchment; besides distinctive landscape attributes like cliffs, valley and ridges, saddles, terraces, rivers, and wetlands (Zhou and Chen, 2010).

It is of great importance to delineate geomorphic regions of an area as it offers an insight into geomorphic evolution and hydro-geomorphic character of the area; further, it supports environmental management practices. Geomorphic mapping helps to distinguish the landscape units and also offers insights into the evolutionary roots of a region's landscape. GIS and remote sensing techniques have made it possible to process a vast volume of data cost-effectively, as well as to display and interpret the results.

The altitude distribution of the earth is commonly depicted using the digital elevation model (DEM), which is an essential element in topographic analysis, including its derivative characteristics like slope, roughness, and local relief (Pakoksung and Takagi, 2016). DEM can be defined as a standard gridded representation of a matrix of continuous variation of relief over the surface. Many researchers have used DEM for terrain and geomorphic assessment. Salvacion (2016) delineated terrain of an island using different thematic layers and DEM to get slope, profile curvature, and topographic wetness indices. Saha *et al.,* (2019) categorised terrains based on geo-environmental factors for evaluating land use and land cover in the Bansloi basin, Jharkhand and West Bengal. Das *et al.,* (2017) have done morphometric analysis of the Supin-Upper Tons basin of the Uttarakhand using different elevation models. In the study of Patel and Sarkar (2009), SRTM DEM was used for assessing different morphometric attributes of the Dulung river basin, West Bengal. Thus, DEM is frequently used for delineating terrain and various geomorphic features worldwide.

The selection of DEM is a significant task for terrain delineation as the accuracy of the results and map outputs may be influenced by the type and resolution of the DEM used. According to Elkhrachy (2017), SRTM DEM with 30 m resolution has better vertical accuracy than ASTER DEM. Sefercik (2012) established that ASTER DEM has lower precision in like high mountains, rugged topography and areas with abrupt altitudinal changes. Many other studies suggested that SRTM DEM has more advantages in assessing landscape features than other similar data sets (Ferry and Paul, 2011; Forkuor and Maathuis, 2012; Szabo *et al.*, 2015).

The objective of the present study is to delineate various terrain and geomorphic parameters of Darjeeling Himalayan region and to determine their spatial distribution in terms of area using SRTM DEM and geological data. A total of 14 thematic layers have been prepared and their distribution has been measured using GIS. For the Darjeeling Himalayan region, a comprehensive and detailed mapping related to various geomorphic parameters is critically required for planning purposes including watershed management, landslide hazard zonation and geo-environmental assessment. Therefore, this study is an attempt a detailed mapping of various landscape features of the Darjeeling Himalaya region, which might provide a useful database for further research.

Study area

Darjeeling and Kalimpong districts were selected for the study which are situated at the northern part of West Bengal, extending between 87°59′E–88°53′E and 26°27′N–27°13'N. Both the districts comprise a significant part of Darjeeling Himalaya region and together occupy an area of 3,149 km^2 (Fig. 1). Being a hilly region, the study area's economy includes horticulture, tea production, paddy farming, alongside tourism, trade and commerce (District Census Handbook, 2011).

Darjeeling and Kalimpong districts are famous worldwide for their scenic beauty, tea gardens and famous hill stations. Geomorphologically, the study area comprises of steep hills to flat plains, valleys ridges, forests, and large rivers like the Tista,

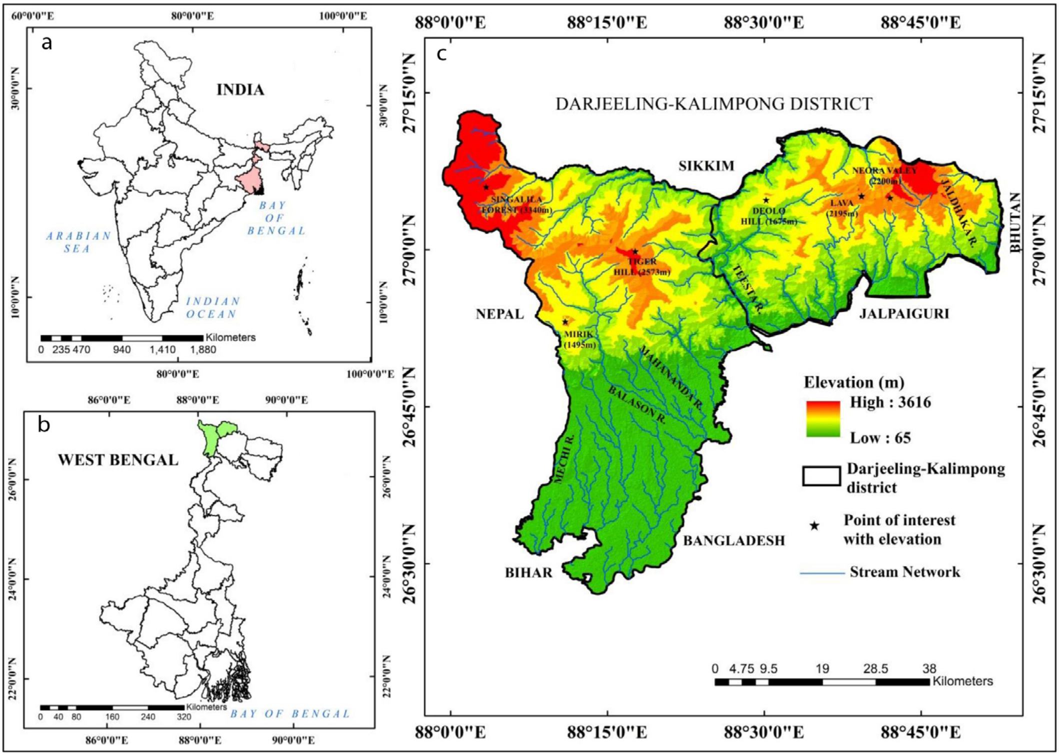

Figure 1. Location of the study area: a) Position of West Bengal in India, b) The location of Darjeeling–Kalimpong district: in West Bengal, c) DEM of Darjeeling–Kalimpong district based on SRTM data (30m×30m)

Mechi, Mahananda and Jaldhaka. It also has a complex geological history.

Data and Methodology

The landscape and geomorphic mapping of the Darjeeling-Kalimpong district were carried out by using the Shuttle Radar Topography Mission (SRTM) and the data collected from the Geological Survey of India (GSI). In this study, 14 different thematic layers were generated in the GIS environment with field knowledge and investigation for assessing terrain and geomorphological parameters. 1 arc-second (30 m) SRTM DEM was downloaded from NASA Earth Data (https://dwtkns.com/srtm30m). In the present study, four data tiles were collected (N26E087, N26E088, N27E087, and N27E088), which were mosaicked in ArcMap v.10.8. For assessing the parameters like (i) geomorphological origin (ii) landforms (iii) geological origin based on chronological order and (iv) lithostratigraphic units, data were collected from the Bhukosh site (http://bhukosh.gsi.gov.in) maintained by GSI. The geospatial layer of fault and fold for the present study was extracted from the same portal. The vector layers collected from the Bhukosh site were pre-processed for area calculation using the calculator geometry option and later converted into percentage. Arc map 10.8 was used for extracting the thematic layers of (i) elevation, (ii) relative relief, (iii) aspect, (iv) slope, (v) dissection index, (vi) ruggedness index (vii) topographic wetness index (TWI) and (viii) drainage network analysis (including drainage density, stream order, stream number and frequency). A total of 433 grids were generated to delineate the

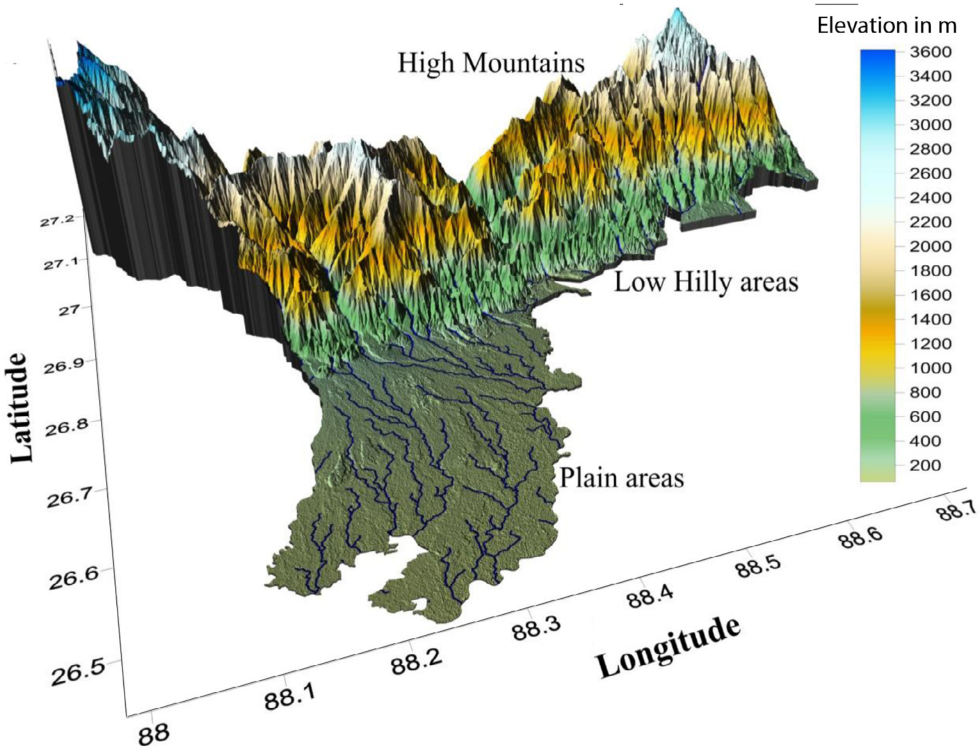

Figure 2. Darjeeling–Kalimpong districts: 3D terrain view (SRTM data, 30m × 30m)

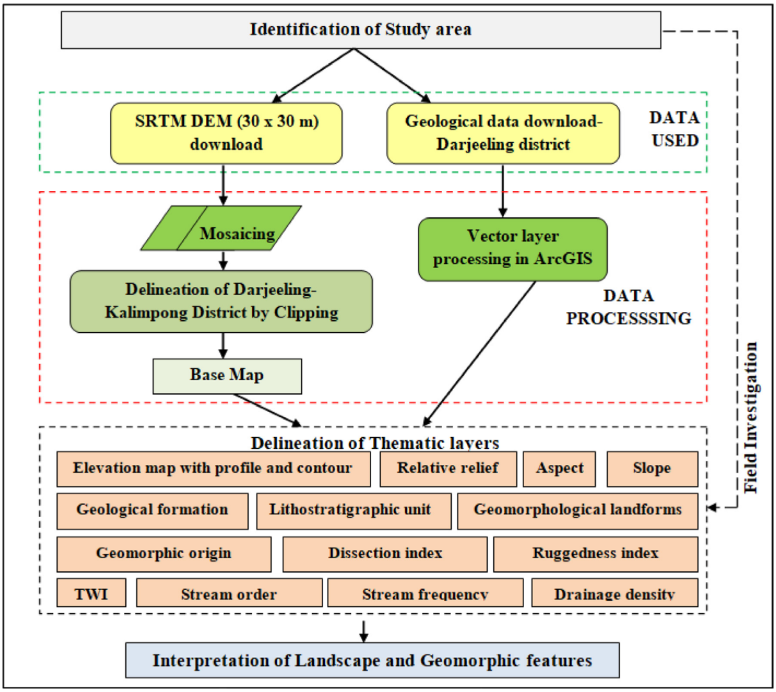

Figure 3. Flow chart showing the steps of data analysis.

Table 1. Data source and techniques adopted for preparation of different thematic layers.

Sl. No.	Parameters	Data used	Sources of data	Techniques	References
1	Elevation	SRTM DEM (30×30m)	NASA (https://dwtkns.com/ srtm30m/)	30×30m digital elevation model	-
2	Relative relief (Rr)	SRTM DEM (30×30m)	NASA (https://dwtkns.com/srtm30m/)	Rr = H–L; H=highest altitude, L=lowest altitude	Smith, 1935
3	Main geological group	Geological map, 2019	GSI (http://bhukosh.gsi.gov.in/)	Using ArcGIS	-
4	Lithostratigraphic units	Lithology map, 2018	GSI (http://bhukosh.gsi.gov.in/)	Using ArcGIS	-
5	Aspect	SRTM DEM (30×30m)	NASA (https://dwtkns.com/srtm30m/)	Aspect = 57.29× atan2($\left[\frac{dz}{dy}\right]$ – $[dz/dx]$)	https://desktop.arcgis.com/en/
6	Slope	SRTM DEM (30×30m)	NASA (https://dwtkns.com/srtm30m/)	Slope degrees = ATAN (rise_run) × 57.29578 Where, rise_run = $\sqrt{([dz/dx]^2 + [dz/dy]^2)}$	https://desktop.arcgis.com/en/
7	Geomorphic features	Geomorphology map, 2018	GSI (http://bhukosh.gsi.gov.in/)	Using ArcGIS	-
8	Geomorphic origin	Geomorphic origin map, 2018	GSI (http://bhukosh.gsi.gov.in/)	Using ArcGIS	-
9	Dissection index (Di)	SRTM DEM (30×30m)	NASA (https://dwtkns.com/srtm30m/)	Di= Rr/H	Nir, 1957
10	Ruggedness index (Rn)	SRTM DEM (30×30m)	NASA (https://dwtkns.com/srtm30m/)	Rn=Rr×Dd	Strahler, 1958
11	Drainage density (Dd)	SRTM DEM (30×30m)	NASA (https://dwtkns.com/srtm30m/)	Dd =L/A, where L=length of the rivers, A=area	Horton, 1932
12	Stream order(U)	SRTM DEM (30×30m)	NASA (https://dwtkns.com/srtm30m/)	Hierarchical Rank	Strahler, 1964
13	Stream frequency (Fs)	SRTM DEM (30×30m)	NASA (https://dwtkns.com/srtm30m/)	Fs = Nμ/A. Nμ=Total no. of streams of all orders, A= total area (km^2)	Horton, 1945
14	Topographic wetness index (TWI)	SRTM DEM (30×30m)	NASA (https://dwtkns.com/srtm30m/)	TWI = ln (As/ tanβ) ln= natural log, As = the cumulative upslope area, tanβ= slope.	Moore *et al.*, 1998

terrain features of the study area.

Various tools and techniques were adopted in the GIS environment like Inverse Distance Weighted (IDW) interpolation, 3D analyst tool, spatial analyst tool (including line density and hydrology) to create different thematic layers. For drainage network analysis, hydrology-based algorithms available in the GIS environment have been adopted. The DEM was first pre-processed in the GIS suite using sink-filling, flow accumulation and flow direction tools. After that, stream order, stream number, stream frequency and drainage density were determined to analyse the various morphometric parameters of the study area.

To find the area distribution of various terrain and geomorphology classes, each thematic layer was first digitised and georeferenced in UTM projection (WGS 1984, Zone 45N) and then tools like Reclassify and Zonal Statistics were applied. To prepare the 3D terrain model of the study area, the mosaicked SRTM DEM was processed using the 3D surface option in Golden Surfer v.13 (Fig. 2).

For a better understanding, the methodology of the present study, a flow diagram was constructed (Fig. 3) showing the four work stages: (i) Data used for the study, (ii) Data processing, (iii) Preparation of thematic layers for evaluation of terrain and geomorphic parameters, and (iv) Interpretation of results. All the techniques and data sources used for preparing different thematic layers are given in Table 1. Further, all the terrain and geomorphic analysis results, including its classes, percentage of area coverage, range, mean and standard deviation, have been summarised in Table 3.

Result and Discussion

Major Geological formations

The exploration of geology for Darjeeling Himalaya and the adjoining region began in the mid-19th century. J.D Hooker gave a detailed report regarding the geology of the Darjeeling Himalaya in 1854 based on his extensive field investigation during 1848–49 (Mili, 2012). Since then, many contributors documented their findings regarding the geology of the Darjeeling Himalaya (Mallet, 1874; Gansser, 1964; Pawde and Saha, 1982; Banerjee *et al.,* 2019). These have been summarised in Table 2.

This study classifies the geology of the Darjeeling Himalayan region using information from the Geological Survey of India (GSI), based on recent data (Fig. 4a). It shows that geologically the study area can be divided into nine major classes with six chronological groups — (i) The Kanchenjunga gneiss is the oldest geological class deposited during the Archean period and it covers mainly the northeastern and central-western parts (Fig. 4a). As per the chronological order, the other formations are: (ii) Buxa formation, (iii) Reyang formation, (iv) Gorubathan formation, and (v) the undifferentiated Darjeeling-Kanchenjunga

Table 2. Geological succession of Darjeeling Himalaya (Source: Mallet, 1874; Gansser 1966; Pawde and Saha, 1982).

Age	Series	Lithological Characters
Recent (Holocene) Pleistocene	Alluvium	Younger flood-plain deposits of the rivers composed of sand, gravel, pebble, etc. and soil covering the rocks sandy, clay, gravel, pebble, boulders etc. representing older fluvial deposits
Himalaya Front Tectonic Line (HFTL)		
Miocene	Siwalik	Micaceous sandstones with salty bands, seams of graphitic coal, silts and minor bands of limestone
Main Boundary Fault (MBF)		
Permian	Damuda Series (Lower Gondwana)	Quartzite sandstones with salty bands, carbonaceous shale's, seams of graphitic coal, lamprophyre sills and minor bands of limestone
Thrust Fault of Nappe Outlier		
Precambrian	1) Darjeeling gneiss 2) Daling gneiss	Golden-silvery mica schists; Slate, chlorite-sericite schist, chlorite- quartz schist

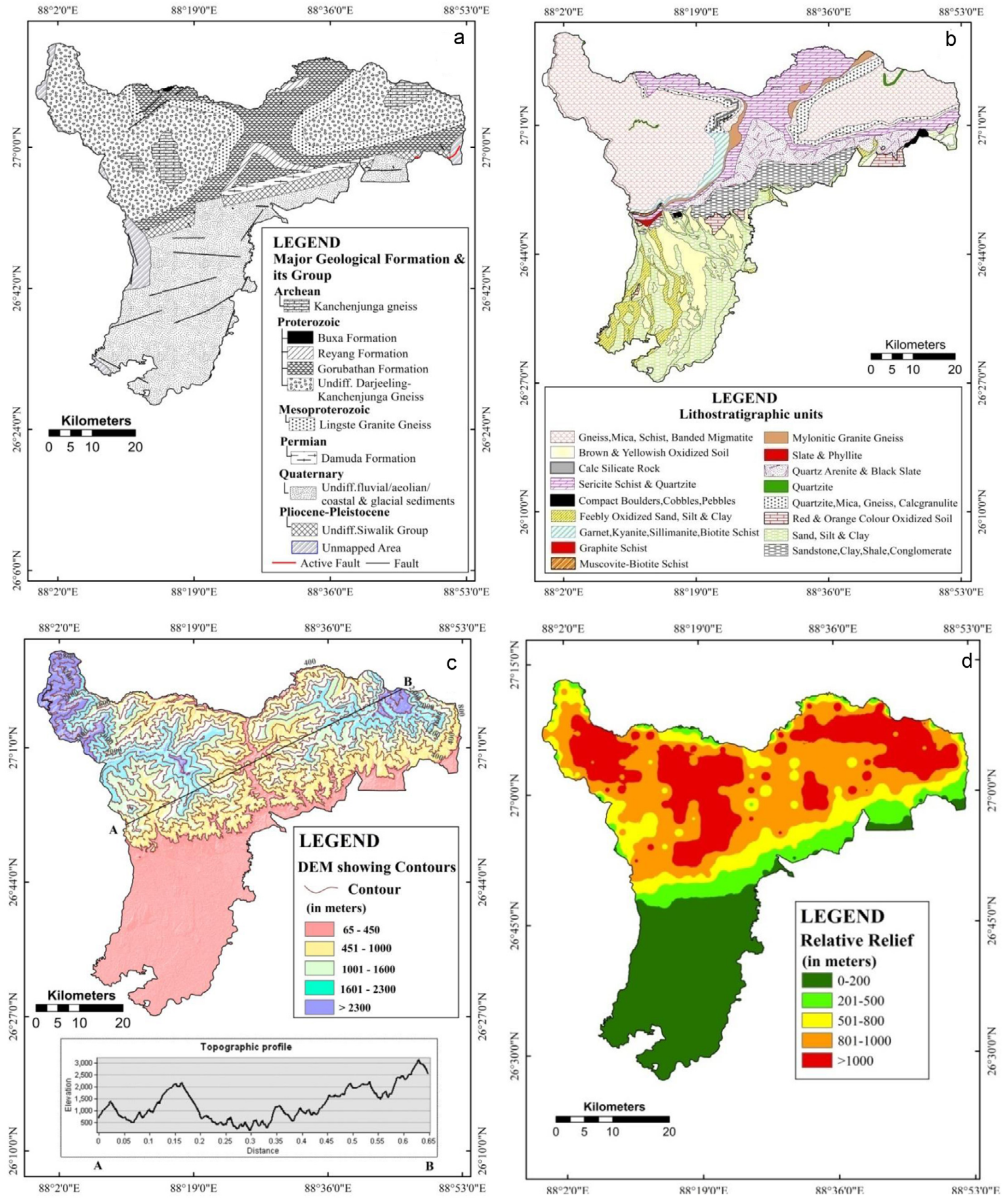

Figure 4. Darjeeling–Kalimpong districts showing: (a) Major geological units, (b) Litholostratigraphic units., (c), Elevation with contour and topographic profile (d) Relative relief

Gneisses. All these belong to the Proterozoic era. Subsequently, (vi) Lingste Granite Gneiss (Meso-Proterozoic era), were deposited in central eastern and western parts and (vii) Damuda formation (Permian period), covered a small section in the central part. The majority of the Darjeeling-Kalimpong district is covered by (viii) undifferentiated fluvial sediment (Table 3), which was deposited during the recent Quaternary period and spreads mainly in the southern part, preceded by (ix) undifferentiated Siwalik group (Plio-Pleistocene) which mainly extends from western to eastern part in a linear form.

The study area has faced major tectonic movement in the past as indicated by faults, folds and extensive depositions. Many faults are found in the Darjeeling-Kalimpong district, among which active faults are noticed in the northeastern part of the study area (Table 3).

Lithostratigraphic setting

Landscape development is an outcome of numbers of factors such as geological past, climate and tectonics, which endow the energy that is required for the geomorphic processes to work. Hence, lithology is the significant aspect that controls wearing and tearing of the earth surface (Sklar and Dietrich, 2001). Lithologic features are essential for understanding the terrain as it controls the erosion and weathering and also set limits to the development of various geographic parameters (Ott, 2020). The local hydrology, soil fertility and its chemistry were significantly influenced by the texture and composition of rocks (Anderson, 1988). Many pioneering works regarding the lithology and its deformation in Darjeeling Himalayan region have been done and different contributors provided different names for the same lithological settings of the region (Lahiri, 1973; Chawla *et al.,* 2019).

However, very few mapping of the lithostratigraphic setting of the Darjeeling Himalayan region have been done earlier; hence this paper attempts to delineate the lithostratigraphic units, which is very important for understanding the landscape (Fig. 4b). The mapping was done in the GIS environment based on the data of GSI. It reveals that the configuration of the lithological settings of the Darjeeling Himalayan region composed of a variety of rocks and it can be classified into 17 classes (Fig. 4b). Among these 17 classes, three groups dominate in the study area — (i) gneiss, mica-schist and banded migmatite (37.4%); followed by (ii) sand, silt and clay (16.9%) and (iii) sericite schist and quartzite (11.5%). The gneiss, mica-schist and banded migmatite are mainly foliated metamorphic rocks with a banded appearance. This group covers mainly the eastern and western parts of the area, distribute over Darjeeling Phulbazar, Mirik, Jorbunglow, Gorubathan and parts of Kalimpong, Kurseong and Rangli Rangliot. It depicts that this area has undergone high-grade metamorphism in the geological past. Subsequently, the sand, silt and clay group, comprising the alluvial material is mainly found over areas of Matigara, Naxalbari, Khoribari and Phansidewa, located in the southern part of the region. This group reveals that the area has experienced episodes of extensive fluvial activity together with intensive agricultural practices. The next group of sericite schist and quartzite, covers mainly the north-central parts of Kalimpong, Darjeeling Phulbazar and Rangli Rangliot, indicating tectonic compression that the area experienced. Apart from these three major groups, which cover more than 65% of the study area, there are (i) brown-to-yellowish coloured highly oxidized soil (7.4%) occupying mainly the fertile areas of Matigara and Naxalbari, (ii) quartz arenite and black slate (7.1%) distributed over lower Kalimpong and Gorubathan, followed by a group of (iii) sandstone, clay, shale and conglomerate (6.6%) occupying lower Kurseong and upper Matigara regions. Besides these, there are other lithostratigraphic units as well, shown in Figure 4b and Table 3. This reveals that the area has faced multiple phases of tectonic activity and deformation, which is evident from the diversity of lithostratigraphic units.

Table 3. Terrain and Geomorphological indicators of Darjeeling-Kalimpong District

Terrain & geomorphological parameters	Classes	Range	Area covered in %	Min	Max	Mean	SD
Elevation	Lowland & plain area	65–450	37.0				
	Low altitude plains	451–1000	22.2				
	Moderate altitude hills	1001–1600	20.6				
	High altitude hills	1601–2300	13.9				
	Highest altitude hills and mountains	>2300	6.4	65	3616	931	778
Relative relief	Very low	0–200	26.9				
	Low	200–500	8.7				
	Moderate	500–800	13.3				
	High	800–1000	28.2				
	Very high	>1000	22.9	1.7	1512	647.2	418.1
Aspect	Flat	–	0.2				
	N	0°–22.5°, 337.5–360°	5.8				
	NE	22.5°–67.5°	11.6				
	E	67.5°–112.5°	14.3				
	SE	112.5°–157.5°	16.9				
	S	157.5°–202.5°	17.1				
	SW	202.5°–247.5°	13.4				
	W	247.5°–292.5°	10.7				
	NW	292.5°–337.5°	10.2	–1	359	172	101
Slope	Flat	0–5°	28.8				
	Gently sloping	5–10°	4.8				
	Moderately sloping	10–15°	7.5				
	Strongly sloping	15–20°	12.9				
	Moderately steep	20–25°	15.7				
	Steep	25–30°	14.0				
	Very steep	>30°	16.3	0	71	17.1	12.2
Dissection index	Very low	0–0.1	50.01				
	Low	0.1–0.2	21.19				
	Moderate	0.2–0.3	10.16				
	High	0.3–0.5	12.51				
	Very high	>0.5	6.13	0	0.83	0.16	0.15
Ruggedness number	Level land	0–0.1	29.5				
	Slightly rugged	0.1–0.2	14.2				
	Moderately rugged	0.2–0.3	20.9				
	Highly rugged	0.3–0.4	22.3				
	Extremely rugged	>0.4	13.2	0	0.6	0.18	0.13
Drainage density	Very low	0–1	40.4				
	Low	1–3	32.3				
	Moderate	3–5	15.8				
	High	5–7	7.8				
	Very high	>7	3.7	0	12.6	1.9	1.8

Elevation

The elevation map of the study area has been prepared using digital elevation model (DEM). The elevation map is crucial to identify the various terrain features of any region. Based on the elevation, which ranges from 65 m to 3616 m, the study area can be classified into five physiographic zones (Table 3). These five zones are (i) lowland and plain areas (65–450 m), (ii) low altitude plains (451–1000m), (iii) moderate altitude hills (1001–1600 m), (iv) high altitude hills (1600–2300 m) and (v) highest altitudinal hills and mountains (>2300 m). For understanding the nature of the landscape and its surface configuration, altitudinal profiles always provides an insightful perception (Singh and Gupta, 2009). Thus to understand the nature of the topography, profile A-B was constructed. The profile depicts that there are steep hills and ridges with valleys running from east to west (Fig. 4c). It is clear from Figure 4c that the study area represents highly dissected mountains and undulating terrain in the north-central part, which gradually became almost flat plain land towards the south. Also some of the high altitudinal sites of tourist interest like Tiger hill (2,573 m), Kurseong (1505 m), Mirik (1495 m) and Kalimpong (1247 m) located in the study area.

Relative relief

Relative relief is defined as the variation between maximum and minimum elevation within the given area (Chawla *et al.,* 2019). It is an important parameter for representing and understanding the morphological distinctiveness of any landscape (Gayen *et al.*, 2013). Relative relief is a function of a variety of factors like slope, lithology, structure, climatic condition, geomorphic process, as well as vegetation cover (Khakhlari and Nandy, 2016). Thus, for landscape evaluation relative relief is a vital geomorphic indicator to understand the topography of any area.

A relative relief map of the study area was prepared using SRTM DEM in the GIS environment. The relative relief of the study area can be categorised into five groups (Table 3, Fig. 4d). The eastern and west-central part falls under high relief zone (>1000 m), which means the topography is immature with steep hills. The values rapidly reduce to below 200 m in the southern part, characterised by flat terrain with numerous network of rivers, adequate for agriculture activity. The maximum and the average relief of the study area are 1512 m and 647 m, respectively.

Slope aspect

Slope aspect can be defined as the direction to which a surface slope faces. Aspects also have a close influence over the flora-fauna as well as climatic characteristics of a region. It is mainly due to the changing inclination and concentration of sun rays with respect to the slope (Magesh *et al.,* 2012; Lama and Maiti, 2019). Aspect plays a vital role in determining the landscape structure (Khakhlari and Nandy, 2016).

The Figure 5a shows the direction of the slope aspect ranging from 0° to 360°; where 0° represents geographic north, 90° eastern direction and so on. Based on the slope aspect the study area is divided into ten categories. Table 3 indicates almost uniform distribution of NE, E, SE, S, SW, W and NW facing slope in the northern part of the study area due to its hilly terrain. However, most of the north-facing slope is located on the northern part of the region. This variation of aspect reflects the diversity of features like rate of erosion, a mixture of vegetation as well as diverse topographic form governs in this area. The table reveals that the south-facing slope is maximum (17.6%), followed by SE (16.9%), E (14.3%) and SW (13.4%).

Slope

A slope can be defined as the angular

inclination of the surface relative to the horizontal plane (Khakhlari and Nandy, 2016). Slope is a fundamental parameter of terrain evaluation applied in many studies (Saadat *et al.,* 2008). A slope map is crucial for road development, planning of built-up areas, upgrading agriculture activity and groundwater zonation (Sreedevi *et al.,* 2005). Thus the slope map of the study area was delineated and classified into seven categories (Fig. 5b). It reveals that the angle of slope ranges from 0° to 71° and the mean slope ranges between 17° (Table 3). About 41.1% of the study area in the Darjeeling Himalayan region varies from gentle to moderate, which is mainly found over the southern part and this area. This is a zone of high density of population with high agricultural activity and large built-up areas. High to very steep slope (58.9% of the area) covers mainly the northern part of the study area with highly dissected hill and rugged topography. This

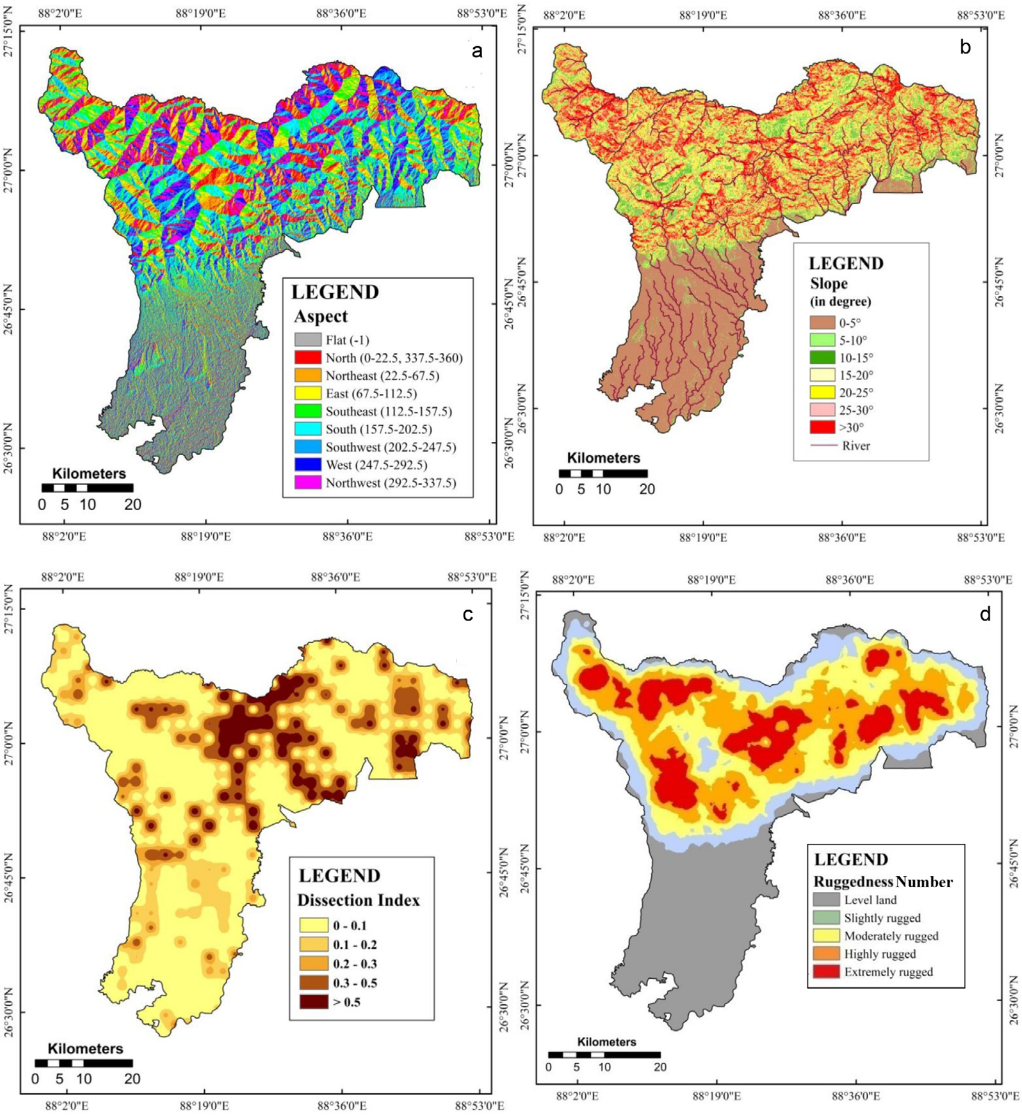

Figure 5. Darjeeling–Kalimpong districts showing: (a) Slope aspect, (b) Slope, (c) Dissection index, (d) Ruggedness number

zone of high slope of Darjeeling Himalayan region is structurally controlled, which gradually decreases towards the southern part, where the slope is a product of fluvial activity (Fig. 4f, Table 3).

Dissection index

The dissection index (DI) formulated by Dov Nir in 1957 is simply the ratio between relative relief and absolute relief, which is essential for understanding the extent of dissection or rate of vertical erosion of the terrain (Baghmar and Mustak, 2011). DI indicates the evolutionary stages of any specific terrain and represents vertical cutting. For understanding the phases of erosion, i.e., youth, mature and old stage, dissection index is an essential geomorphic indicator. The value of DI ranges from '0' (which means absence of vertical erosion and the terrain is almost flat and plain); in contrast, '1' indicates (vertical cliffs or steep slopes with active erosion). The preparation of DI was done manually on ArcGIS using IDW interpolation module.

Thus, DI was computed on the basis of SRTM DEM data for the study area to understand the dissection rate as a vital parameter of terrain evaluation. It reveals that higher DI prevails in the northern and eastern parts of the study area, signifying high erosion (in youthful stage) and instability due to steep and rugged terrain (Fig. 5c). Lower DI mainly prevails in the southern parts (almost in the old stage), having erosional remnants with low relative relief, and flat terrain, covered by deposited sediment. In the western part the DI value is low mainly due to vertical cliff, resistant rock and lack of streams, which restrict erosion. The DI value of the study area is categorised into five classes (Table 3).

Ruggedness number

For understanding the unevenness of the terrain, Ruggedness index (Rn) was computed for the study area. Rn is the result of constant interaction among the roughness of local relief and the extent of available drainage density with other environmental indicators, i.e., slope, weathering, soil and vegetation. Rn is calculated using relative relief and drainage density (Chorley and Kennedy, 1971; Selvan and Ahamed, 2011). The Rn parameter was calculated in the ArcGIS environment using raster calculator. The Rn mapping was done based on the previously calculated layers of relative relief and drainage density.

Low Rn prevails mostly in the southern part where the terrain is flat and the landscape has already reached the old stage (Fig. 5d). Moderate to extremely rugged terrain occur in the north-central part where the terrain is still in its youthful stage, with deep valleys and steep convex slopes. The roughness of the study area has been divided into five classes; where 29.5% of the area has low undulating terrain, followed by highly rugged area covering 22.3% of the area.

Topographic wetness index

The topographic wetness index (TWI), also called compound topographic index (CTI), refers to the spatial distribution of wetness and regulates overland water flow (Samanta *et al.,* 2018, Ali *et al.,* 2019). The TWI map describes the impact of terrain on the amount of wetness to form runoff and is considered an effective method for investigating flood potential (Haghizadeh *et al.*, 2017). It reflects the pattern of water accumulating at a given point and shows the influence of local slope over water flow (Pourali *et al.*, 2014).

For the present study, TWI is measured using the SRTM DEM based on upslope contributing area and slope raster map. It has been calculated in the GIS environment using the equation mentioned in Table 1; where As (flow accumulation) is the cumulative upslope area per unit contour length and $\tan\beta$

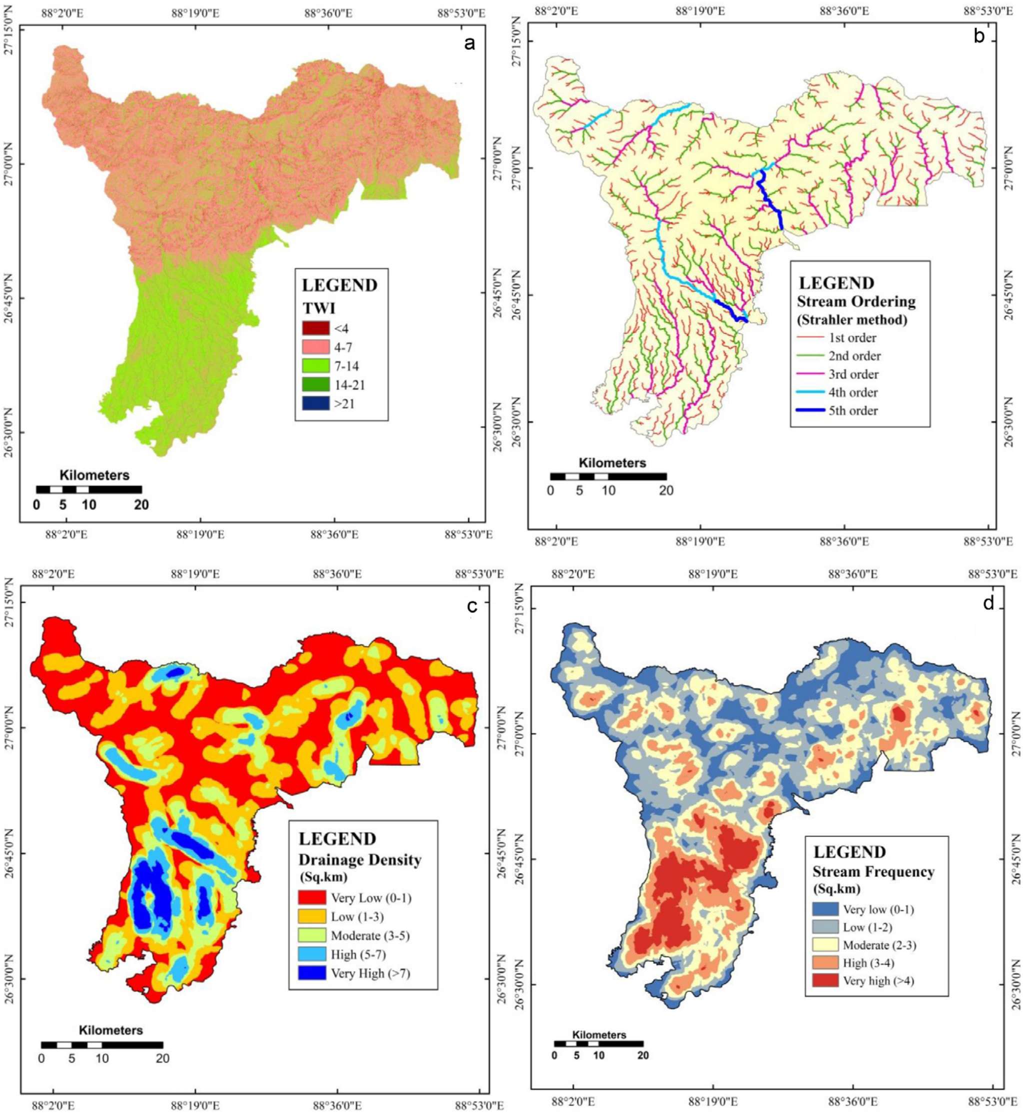

Figure 6. Darjeeling–Kalimpong districts showing: (a) Topographic wetness index (TWI), (b) Stream order after Strahler, (c) Drainage density, (d) Stream frequency

is the surface slope gradient. For the present study area in the Darjeeling Himalayan region, the mean TWI is 6.6, and it varies from 2.3 to 23.2. Figure 6a depicts that the TWI is high mainly in the southern part while it declines towards the northern section of the region. A landscape with greater upslope contributing area and gentle slope would result in high TWI values, indicating higher runoff tendency (Thomas *et al.,* 2016). TWI is, therefore, an appropriate measure to define relative runoff propensities in the landscape surface, to understand the concentration of water and to analyse stream erosion.

Drainage network

The drainage network of any area controls the terrain and topography of that area. A small change in the drainage network due to climatic variables can result in the transformation and modification of local topography (Chougale and Sapkale, 2017). Thus for identifying the drainage network of the study area, which has close relation with the terrain, (i) drainage density (Horton, 1932), (ii) stream frequency (Horton, 1945) and (ii) stream ordering (Strahlar, 1952) was adopted.

Darjeeling Himalayan region is blessed with many great rivers — Tista, Mahananda, Mechi, Balason, Gish, Chel, Great Rangit, Murti and Jaldhaka. Hence a strong drainage network prevails in this area. To understand the stream network, stream ordering based on Strahler's method was done based on SRTM DEM data (Fig. 6b). The streams of the study area can be categorised into 1st to 5th order. Based on the DEM data a network of 848 streams can be identified. Among these 848 streams, 474 are 1st order, 215 are 2nd order, 128 are 3rd order, 23 are 4th order and 8 are 5th order streams.

According to Langbein (1947), the mean drainage density (DD) can vary from 0.55 to 2.09 km km^{-2} in a humid tropical region. The mean DD of the study area is 1.9 km km^{-2} (Fig. 6c). However, according to Figure 6c, low DD mainly covers the northern part characterised by short length of streams, high vegetation density and hilly terrain. Moderate to high DD is mainly found in the southern part of the area. Drainage density has a close relationship with the lithology, climatic variables and topographic factors (Reddy *et al.,* 2004). The average stream frequency (Fs) in the study area is 1.59 km^{-2} and the overall Fs varies from 1 to 4.55 km^{-2} (Fig. 6d). The stream frequency (Fs) map shows a strong association with the drainage density map, indicating an increase in stream frequency with an increase in drainage density and vice-versa (Fig. 4k and 4l).

Landforms and their geomorphic origin

Landform features

A major portion of the study area comprises of hills with moderate elevation (38.1%) followed by high hill and valleys (30%) which reveals that the area is unstable and geomorphologically immature. Due to its instability and highly dissected terrain, the study area as a part of the Darjeeling Himalayan region, is susceptible to landslides

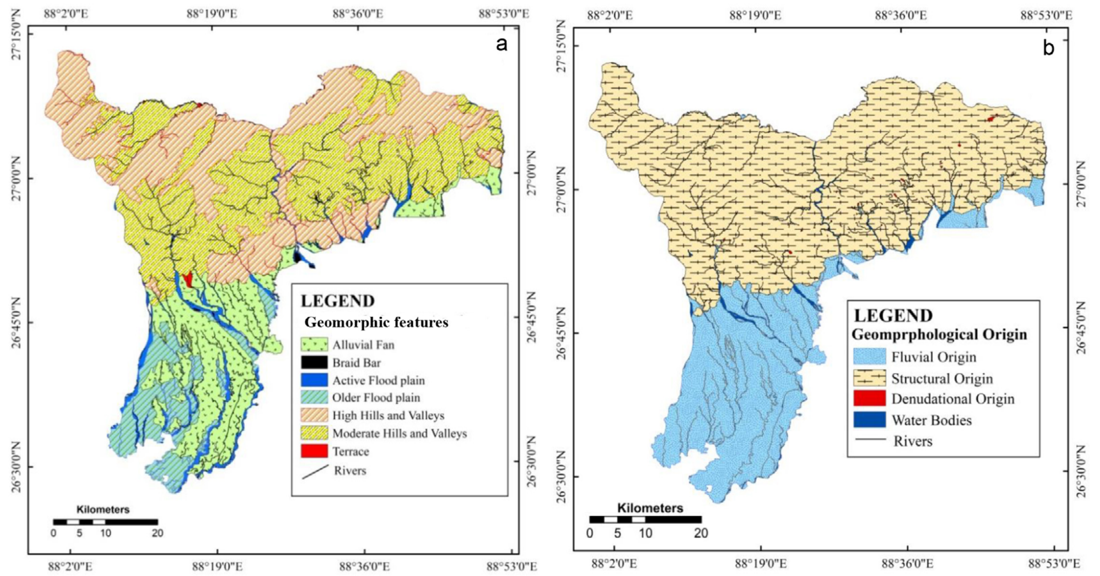

Figure 7. Darjeeling–Kalimpong districts showing: (a) Geomorphic features, (b) Geomorphic origin.

(Chawla *et al.,* 2019; Roy *et al.,* 2019). Thus the study is required to develop proper mitigation strategies for landslide hazards.

The alluvial fans covering 17.6% of the study area is evenly distributed in the southern part. It has already been mentioned that the southern part is of fluvial origin and thus alluvial deposits (sand, silt and clay) is widespread. Two categories of flood plain can be identified in the study area – Active flood plain (3.5%) and the older flood plains (8.1%). Active flood plains are mainly found in the area that experience recent river inundation and they still receive sediment load during the seasonal floods. The older flood plain on the other hand, depicts former fluvial course and are slightly elevated than the younger flood plain (Fig. 7a). Braided channel bars, river terraces, point bars, ox-bow lakes, meander bends and channel islands are also identified from the figure. Thus the area possesses a variety of geomorphic features complimenting both the high altitude mountainous part and the gently undulating foothill zone.

Geomorphic origin

According to its geomorphic evolution the Darjeeling-Kalimpong area can be divided into four classes — (i) area principally of structural origin, (ii) area formed due to fluvial activity, (iii) area principally of denudational origin and (iv) area occupied by waterbodies (Fig. 7b). Majority of the study area is of structural origin (68.1%) with high altitude and rugged terrain. These are mainly the hilly areas of Darjeeling, Mirik, Kurseong and Kalimpong which covers the entire north-central part. The southern part of the study area with the lowest altitude is principally formed due to fluvial activity (28.5%), and is suitable for cultivation and built-up-areas. These southern parts are dominated by agricultural fields, where mainly paddy and jute are extensively cultivated. The area of denudational origin covers only 0.1% of the study area. The areas occupied by waterbodies are found along all the river courses.

Conclusions

Geomorphological research based on landscape mapping and its evaluation along with geospatial application, are well known methods for managing natural resources. In the present study SRTM DEM (30 m resolution), along with geomorphic and geo-lithological data, presented a detailed picture of the landscape of Darjeeling-Kalimpong District. A large amount of data was compiled for qualitative as well as quantitative geomorphic mapping of the area.

The Darjeeling-Kalimpong district's geology and lithological features can be categorised into multiple classes, which reveal that the area has undergone several phases of tectonic movements, which helped to evolve diverse terrain and geomorphic features. Some faults were also identified based on the geospatial mapping. Most of the region owes its origin to structural characteristics and tectonic movements, followed by areas with alluvial foundation. The study shows that the northern portion of the area is marked by high elevation with dissected topography, valleys and ridges. In contrast, the southern part is dominated by flat fertile plain with an elaborate stream network. The area's elevation and slope gradually decrease from north to south and the mean elevation of 931 m and relative relief of 647.2 m reveal that most of the area is of moderate altitude with high relative relief. The landforms found in the Himalayan region include dissected hills and valleys, while the fluvially dominated part mostly includes alluvial fans, terraces and other common floodplains features. Knowledge and methods presented in this paper would be beneficial for terrain analysis and landscape suitability studies. The findings can be used by future researchers to manage land resources and geo-environmental planning.

Acknowledgement

The author thanks NASA Earth Data (https://dwtkns.com/srtm30m/) and Geological Survey of India for providing free data. The author also expresses gratitude to the anonymous reviewer and the editor for their insightful suggestions and comments which helped to improve the paper.

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Date received : 27 November 2020
Date accepted after revision : 31 December 2020