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Hypsometric Analysis Using Microwave Satellite Data and GIS of Naina–Gorma River Basin (Rewa district, Madhya Pradesh, India)

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Abstract

Understanding about the stages of geomorphic evolution and geological development of any river catchment and its proneness to erosional process is important for managing the water resources and loss of sediment. Hence, this work is focused on identification of the growth stage of Naina–Gorma river basin and its sub-basins. Hypsometric curve (HC) and hypsometric integral (HI) have been estimated using microwave satellite data in the geographical information system (GIS) environment. The result shows that the HI value ranges from 0.36 to 0.89, indicating youth to mature stage of geomorphic development for river basin and its 15 sub-basins. Therefore, the sub-basins which are at youth age stage of geomorphic development are of high susceptibility to medium to complex denudational processes, erosion, channel erosion, and mass movement activity. This mass movement is due to variation in tectonic activity, rejuvenation processes, and lithology of the area. It helps to measure watershed health, represent the form, its evolution, and morphology of river basin. The results of the statistical analysis suggest that positive statistical relationship exists between the area and the hypsometric integral groups of the 15 sub-basins. It also plays an important role in explaining the dynamics of surface and subsurface water runoff generation. The results of the study have been validated through field visits and surveys. The findings of the work would help in construction and adoption of appropriate soil and water conservation measures in the rain-fed river system to retard the soil erosion and conservation of water.

Keywords Erosion · Hypsometric analysis · Hypsometric integral · Geomorphology · Relief ratio · Naina–Gorma river basin

Introduction

Hypsometric analysis has been used to understand the various forcing factors on basin topography [16]. It is an area-altitude analysis which helps in understanding the distribution of the horizontal cross-sectional area of a landmass with respect to elevation [38]. It has been used to differentiate erosional landforms of different stages during their evolution [38, 40]. The statistical characteristics of hypsometric analysis include the hypsometric integral (HI), hypsometric curve (HC), and hypsometric skewness [15]. The HI and HC are important indicators of watershed conditions [24] and to represent form and its evolution [30]. The HI is the area beneath the curve and relates the percentage of total relief to the cumulative percent of area and shape of the hypsometric curve which indicates the age of the catchment. Hence, HI and HC explain the degree of basin dissection and relative landform age [37]. The HC expresses the volume of the rock mass in the watershed and the amount of erosion that has been taken place, whereas HI is used as an estimator of the erosion status of a drainage basin and interaction between tectonic uplift and erosion. Both the HI and HC are significant indicators of stages of geomorphic evolution and geological development. The hypsometric analysis involves the measurement of the interrelationships between the altitude of basin and area to understand the influence of climatic, geologic, and tectonic factors on topographic changes.

The drainage basin is classified according to their stages of geomorphic evolution as youth stage (hypsometric curves as convex upward curves and hypsometric integral is ≥ 0.60), equilibrium or mature stage (hypsometric curves as S-shaped which have concave upward at high elevation and convex downward at low elevation and hypsometric integral values

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are $0.30 \leq HI \leq 0.60$), and old or monadnock stage (concave upward hypsometric curves and hypsometric integral value is ≤ 0.30) [38]. The landform evolution processes have been inferred on the basis of the hypsometric curves; the contribution of fluvial and diffusive processes in slope degradation of the river basins was understood [6].

Langbein [13] has developed modern dimensionless form of hypsometry to represent the overall slope and forms of larger drainage basins, while Strahler [38–41] and Ritter et al. [24], Miller [17], and Schumm [27] have extended the methodology to investigate the stages of geomorphic evolution for small drainage basins. The HI is acting as an estimator of the basin erosion status and subsequent prioritization for soil and water conservation activities of a drainage basin [1, 7, 31, 32, 34]. According to Weissel et al. [44], HI also depicted the interaction between tectonic uplift and erosion.

Geographical information system (GIS) is a platform that provides advance tools to obtain hypsometric information and to estimate the other associated parameters of landforms and do the spatial analysis [5, 9, 21, 35]. The satellite data have wide applicability in the fields of watershed [10], erosion [22], evapotranspiration ([23]), groundwater [36], land feature estimation [11], morphometric analysis [9], landscape fragmentation [10], soil conservation [20], and runoff estimation [20]. The hypsometric analyses using GIS and satellite datasets have been performed by several researchers in different parts of the world and dealt with erosional topography ([18, 28, 29, 31–34]). Convex-up curves with high integrals are typical for the youthful stage having un-dissected and smooth landscape, S-shaped curves crossing the center of the diagram characterize mature (equilibrium stage) landscapes, and concave-up curves with low integrals indicate towards old and deeply dissected landscapes [38]. The HI is inversely correlated with total relief, slope steepness, drainage density and channel gradients, these properties of the basin provide a measure of the landform distribution of landmass [38, 41].

In literature, many researchers and scientists have found the relationship between HI and the area of the drainage basin. Willgoose and Hancock [45] employed the Siberia catchment evolution model to explore the bond between catchment process and hypsometry in study area. According to Singh [31], hypsometric analysis is used to assess the erosion status of watersheds and it is an essential pre-requisite for integrated watershed management and prioritization. Kusre [12] has also used the HI values as an indicator of high surface runoff and further used it for prioritizing sub-watersheds. Watershed prioritization is considered as the most important aspect of planning and management [2, 8, 42, 43]. The HI values are considered as a morphological index to predict surface runoff and sediment yields [26]. In this series, D'Alessandro et al. [3] have examined HI values for two groups of watersheds draining into the Tyrrhenian Sea and the Adriatic Sea, Italy. Markose and Jayappa [16] have carried out hypsometric

analysis to evaluate HI and HC for 20 sub-basins of the Kali River, India. Lou [14] employed hypsometric analysis to explore the origin of valley network systems in the Margaritifer Sinus region of Mars in order to infer the underlying processes.

The main objective of the work was to understand the geomorphic stages of the Naina–Gorma river basin for sustainable water resource management through microwave satellite data and GIS. This work will help in identification of the suitable sites for the promotion of groundwater recharge practices and to control the soil erosion in the region by the identification of various stages of landforms, their geomorphic evolution, and the hydrologic response of the all drainage system.

Study Area

The Naina–Gorma river basin is located in the north-eastern part of Rewa district of Madhya Pradesh, India. The extension of location of study area is 24° 35′ 00″ N to 24° 57′ 30″ N and 81° 37′ 30″ E to 82° 15′ 00″ E (Fig. 1). The Naina–Gorma river is a major tributary of the Belan river. It originates from the Kaimur range and passes through the Rewa plateau and the Rewa scarps and joins the Belan river at the north of Rewa district. The boundary of river basin was delineated from Survey of India (SOI) tophosheets of scale 1:50,000. It has a total geographical area of 1425 km^2. The Naina–Gorma river passes through major geomorphologic units such as valley fills, denudational hills, and weathered pediplains. Geologically, the area broadly consists of sandstone and gneissic rock. Soil types are broadly categorized into black to mixed and sandy red soils. Elevation varies from 97 to 463 m approximately from mean sea level. The yearly average annual rainfall is observed as ~ 895 mm in the basin. The sub-basin map is depicted by Fig. 2.

Materials and Methods

The Survey of India (SOI) toposheets at 1:50,000 scale and Indian Remote Sensing (IRS) P6 LISS III imagery (24-m resolution) have been used. Shuttle Radar Topography Mission (SRTM) based on Spaceborne Imaging Radar-C/X-band Synthetic Aperture Radar (SIR-C/X-SAR) digital elevation models (DEM; 90 m) was downloaded from USGS site and adjacent DEM was mosaicked together because of some part of basin span across few quadrangles. Figure 3a shows the DEM of the study region that was used for the landscape characterization of the study area and Fig. 3b represents the 3-D perspective view of the study area. The hypsometric analysis was performed in Arc GIS 9.3 using hypsometric extension tool. The drainage network of all the
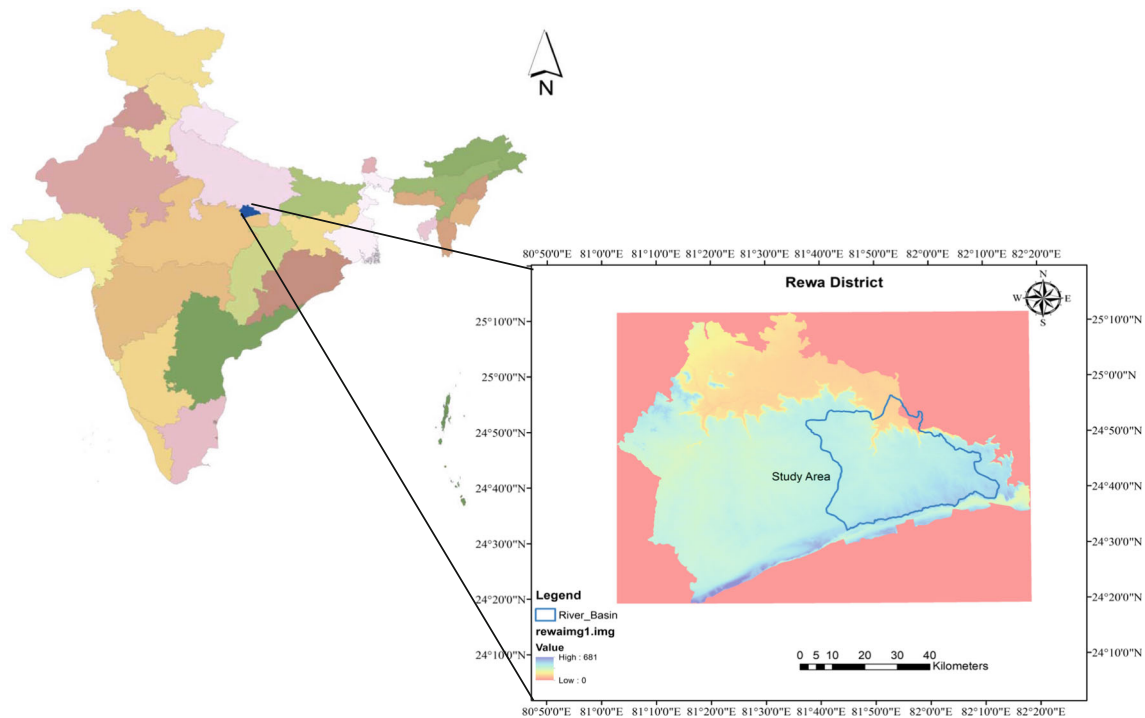
Fig. 1 Study area map depicting the study area shows the Naina–Gorma basin in the north-eastern part of the Rewa district, state Madhya Pradesh, India

sub-basins and basin is extracted from Survey of India toposheets having 1:50,000 scale.

Estimation of the Hypsometric Curve and Hypsometric Integral

The hypsometric analysis develops a relationship between the horizontal cross-sectional area of the river basin and its elevation in a dimensionless form [30, 32]. The hypsometric curve is obtained by plotting the relative area (a/A) along the abscissa and relative elevation (h/H) along the ordinate. The HI is obtained from the hypsometric curve and is equivalent to the ratio of the area. It is expressed in percentage units and is obtained from the percentage hypsometric curve by measuring the area under the curve.

Strahler ([38, 41]) classified a watershed based on the hypsometric curve and HI as a youthful, mature, and old stage. The threshold limits of HI as recommended by Strahler ([38, 41]) as (i) the watershed is at in-equilibrium (youthful) stage if the HI ≥ 0.6, (ii) the watershed is at equilibrium stage if 0.35 ≤ HI < 0.6, and (iii) the watershed is at monadnock stage if HI < 0.35 help in deciding the stage of the watershed.

Integration of the hypsometric curves gives the hypsometric integral (HI) as proposed by Pike and Wilson [19] using eqn. (1).

$$\text{Hi} = \frac{\text{Elev}_{\text{mean}} - \text{Elev}_{\text{min}}}{\text{Elev}_{\text{max}} - \text{Elev}_{\text{min}}} \qquad (1)$$

where E is elevation-relief ratio equivalent to the HI, $\text{Elev}_{\text{mean}}$ is weighted mean elevation of the watershed estimated from the identifiable contours of the delineated watershed, and Elev_{min} and Elev_{max} are the minimum and maximum elevations within the watershed.

The HI is expressed in percentage unit. On the basis of drainage divide, we have calculated the HI of total 15 sub-basins and the overall basin.

Results and Discussions

Results of this research work are discussed in terms of the following sub-headings: topographic analysis, the hypsometric curve shape, the hypsometric integrals, and the statistical relationship between watershed area and hypsometric integral.

Topographic Analysis

The DEM shows the highest elevation as 463 m and lowest as 94 m (Fig. 3a, b). Triangulated Irregular Network (TIN) (Fig. 4) has also represented the topographic view as; like DEM and elevation of the study area, the difference is only that it is vector form of model while DEM is raster model. With the help of DEM, TIN of the study area is generated for better topographic and relief study. It helps to study the landform erosion and watershed management. Figure 5 shows the
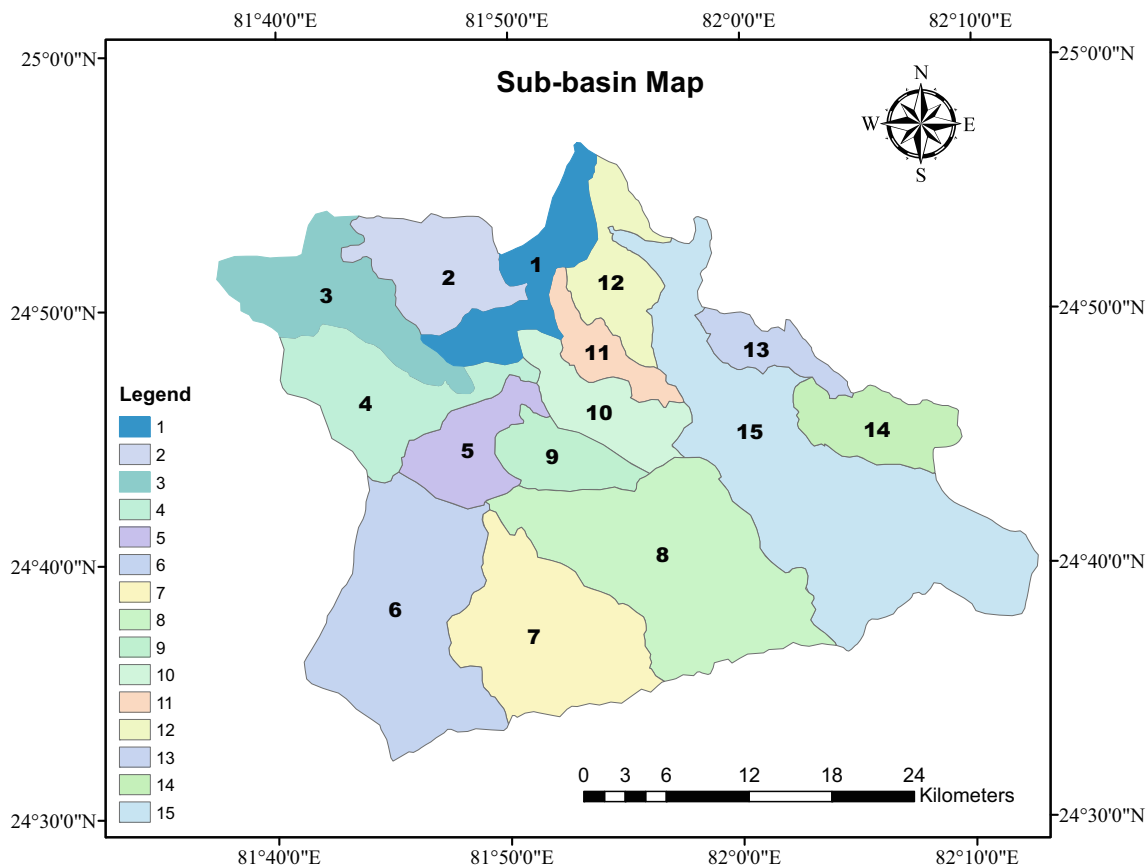
Fig. 2 The sub-basin map of the study area, Naina–Gorma basin is divided into 15 sub-basins according to their drainage

average slope map of the 15 sub-basins which represent low to high slope in the region in a unit of degree.

Table 1 and Fig. 7 show the results of the hypsometric analysis of the Naina–Gorma river basin. Hypsometric curves show high to medium HI, indicating a youthful to mature stage and old stages of the landscape. Elevation versus area falls off more quickly. Sapping is a lower energy process and so its curve appears rather flat at first and then falls off. It is also observed that there is a combination of moderate convex-concave and slightly S-shape of the hypsometric curves for the Naina–Gorma river basin. This could be due to the soil erosion from the basin and down slope movement of topsoil and bedrock material, washout of the soil mass and cutting of stream banks. The hydrologic response of the drainage basin has near to mature or equilibrium stage, while when studied separately for their sub-basin, it is varying. The HI values for sub-basins of the Naina–Gorma basin varies, viz. sub-basin 1 shows late mature phase or near monadnock stage. Whereas sub-basins 6, 7, and 12 show monadnock stage or old stage, sub-basins 2, 3, 4, 5,10,11, 13, and 15 represent youthful stage or in-equilibrium stage and sub-basin 9 shows late youthful stage. The sub-basin 8 and 14 and whole Naina–Gorma basin represent equilibrium or mature

stage. This condition may be formed due to high to moderate rate of erosion during peak runoff; this will need appropriate soil and water conservation measures. The hypsometric curve expresses medium to complex denudational processes and the linear river morphological changes of this river basin.

All drainage of the study basin is shown on the map (Fig. 6); it depicts that the basin has total seventh stream order. This study suggests that many artificial recharge structures are required at different places to increase the groundwater potential that will help tocontrol the soil erosion. Low hypsometric integral indicates suitable locations for recharge structures and moderate values are suitable sites for preventing soil erosion and runoff. The sub-basins 1, 6, 7, 8, 12, and 14 are having low HI values and indicating the suitable sites for groundwater recharge. These sites also represent monadnock or old stage of landform.

Hypsometric Curves

Previous studies show that convex shape hypsometric curve (HC) indicates the dominance of hill slope processes in small watersheds, whereas concave curves depict the dominance of
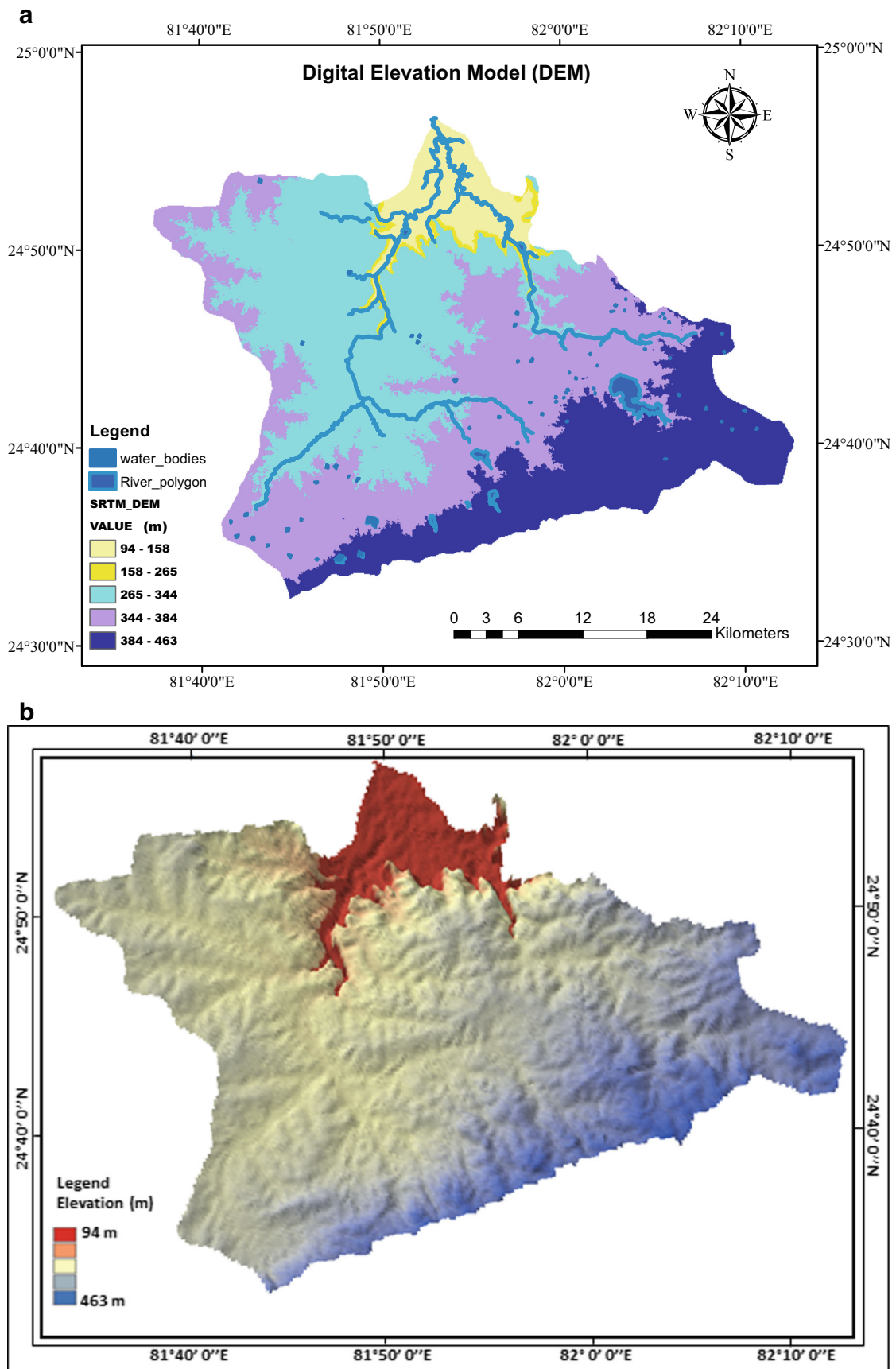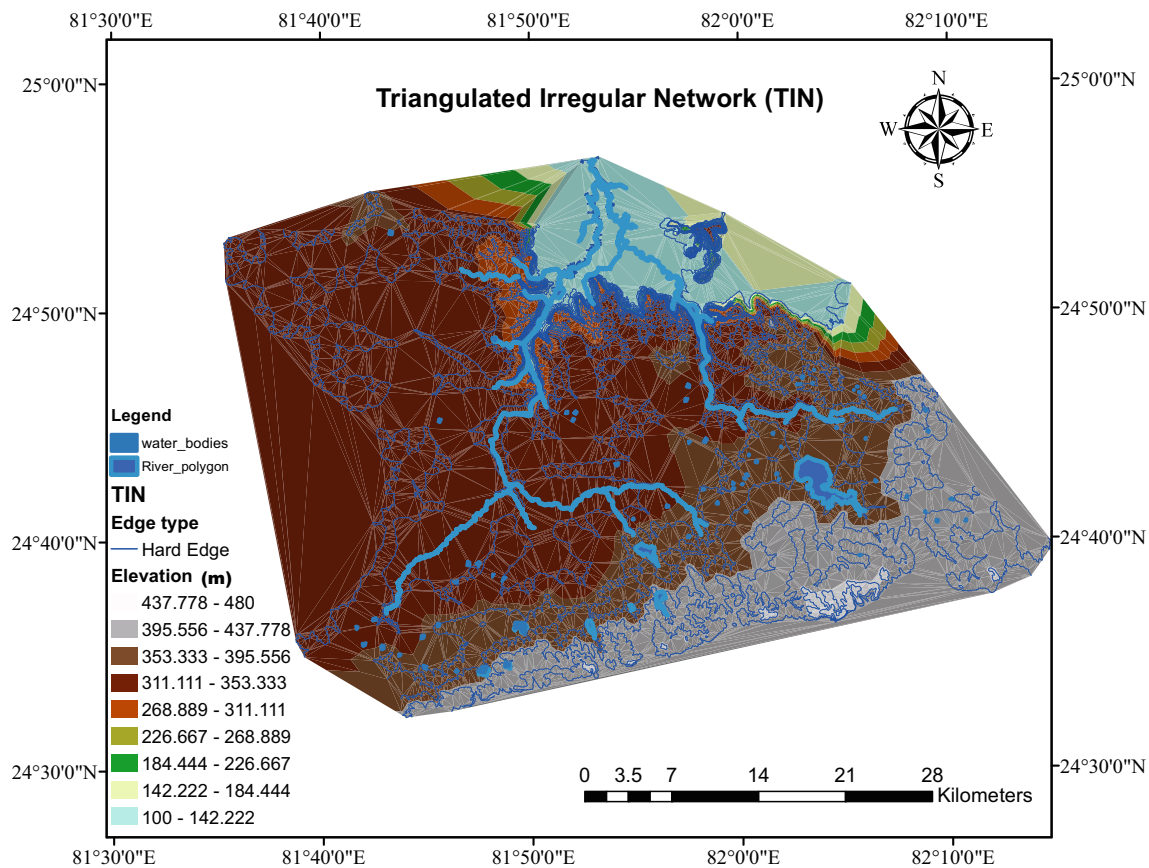
Fig. 3 a Digital elevation model (DEM) of the study area (source: USGS). b 3-D Perspective view of the Naina–Gorma basin

Fig. 4 Triangulated Irregular Network (TIN) of the study area

fluvial processes in large watersheds. Figure 7 is used in the hypsometric analysis; considering the river basin area to be bounded by vertical sides and a horizontal base plane passing through the outlet, the relative elevation is calculated as the ratio of the height of a given contour (h) from the base plane to the maximum basin elevation [24, 25]. The hypsometric curves of the majority of sub-basins and entire watershed exhibit remarkably convex

Table 1 Sub-basin wise estimated area, perimeter, length, max and minimum elevation, average slope, hypsometric integral values, ranking, and geologic stage

| Sub-basin	Area (km^2)	Perimeter	Sub-basin length (km)	Max elevation (m)	Min elevation (m)	Mean elevation (m)	Average slope (degree)	HI	Ranking	Geologic stage
1	63.28	56.52	18.96	338	97	217.5	0.069–8.863	0.36	10	Late mature stage or near monadnock stage
2	70.55	41.61	14.04	362	110	236	0.013–7.357	0.82	4	In-equilibrium or youthful stage
3	88.76	58.42	20.24	310	359	334.5	0.024–2.617	0.61	8	In-equilibrium or youthful stage
4	88.13	56.17	19.07	357	134	245.5	0.017–6.663	0.89	1	In-equilibrium or youthful stage
5	50.29	37.46	11.79	352	140	246	0.042–7.317	0.87	3	In-equilibrium or youthful stage
6	177.17	35.36	20.69	432	325	378.5	0.005–2.774	0.28	10	Monadnock stage or old stage
7	132.28	53.76	17.91	456	326	391	0.147–4.059	0.35	10	Monadnock stage or old stage
8	202.34	72.24	27.53	461	325	393	0.001–4.396	0.39	9	Mature or equilibrium stage
9	40.19	29.81	11.53	364	296	321	0.045–4.24	0.64	7	Late youthful stage
10	55.00	40.36	15.17	366	133	249.5	0.009–6.753	0.88	2	In-equilibrium or youthful stage
11	31.00	34.76	13.42	368	105	236.5	0.05–8.575	0.78	5	In-equilibrium or youthful stage
12	56.07	49.20	16.19	367	99	233	0.016–7.467	0.31	10	Monadnock stage or old stage
13	30.14	32.12	12.86	393	131	262	1.032–6.968	0.82	4	In-equilibrium or youthful stage
14	51.69	34.85	11.57	423	347	385	0.139–3.218	0.44	9	Mature or equilibrium stage
15	288.52	119.43	40.79	463	103	263	0.06–8.643	0.73	6	In-equilibrium or youthful stage
Naina–Gorma								0.50		Mature or equilibrium stage
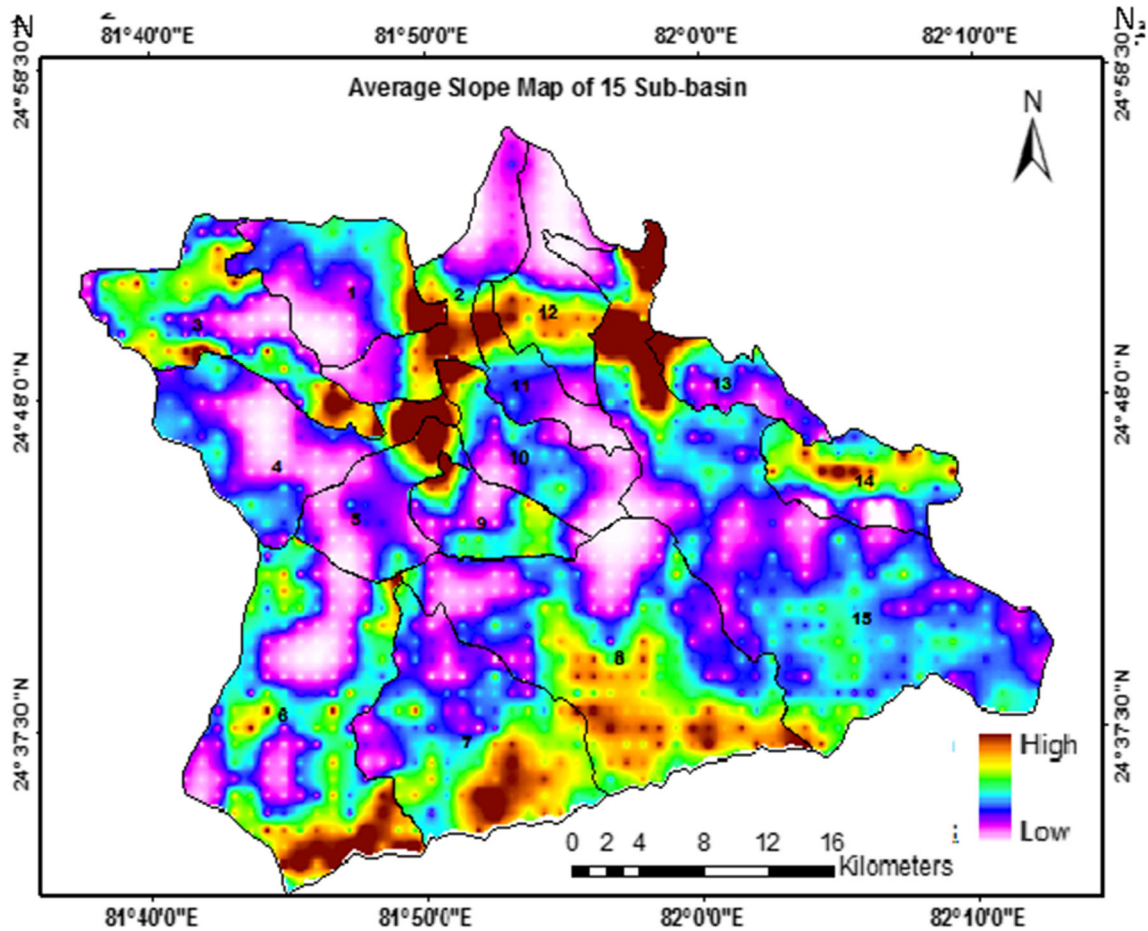
Fig. 5 Average slope map of 15 sub-basins

upward curves (Fig. 7) except for few sub-basins which exhibit concave surface.

This study is provids a measure of the distribution of landform volume remaining beneath or above a basal area. The Naina–Gorma basin is vulnerable to erosion due to its undulating topography. Figure 7 represents the hypsometric curve of the entire basin and its 15 sub-basins show the different landform stage and its nature while Fig. 8 depicts the river profile of all 15 sub-basins in terms of altitude (m) and flowing distance (m) that cover by drainage of the study area.

By examining the graphical diagram of the HC and HI values, it is revealed that (i) HC of Naina–Gorma basin indicates that the overall basin is in mature or equilibrium stage while HC of sub-basins 2, 3, 4, 5, 10, 11, 13, and 15 shows that these are in youthful or in-equilibrium stage. Hence, sub-basins are at the youth stage to mature stage of geomorphic development (ii) due to variation in tectonic effect, lithology, and rejuvenation processes there are some marginal differences which exist in the basin and the 15 sub-basins.

More or less the entire basin suffers from serious geomorphic hazards condition like slope instability, floods, high sediment yield, and severe soil erosion and the other suffering from anthropogenic effects such as deforestation, overgrazing, land use/land cover changes, and poor conservation measures maximize the soil erosion. Soil erosion from the entire basin and its sub-basins is attributed to topography, rainfall and stage of river and increased from the incision of channel beds, washout of top soil, and undercut erosion of stream banks.

Hypsometric Integrals

Recently, Markose and Jayappa [16] have postulated that hypsometric integral (HI) controls the shape of an HC and thereby used as indicators for the geomorphic evolution of drainage basins. The HI values provide valuable information in deciding the geological stage of the development of the watershed. The HI of the whole river basin is 0.50, which represents mature or equilibrium stage, while the HI for the sub-basin 1 to 15 is varied (Table 1). In the in-equilibrium stage, the watershed is still under development while the equilibrium stage is the mature stage of watershed development, i.e., the development has attained steady-state condition, whereas the monadnock phase occurs particularly, when isolated bodies of resistant rock from
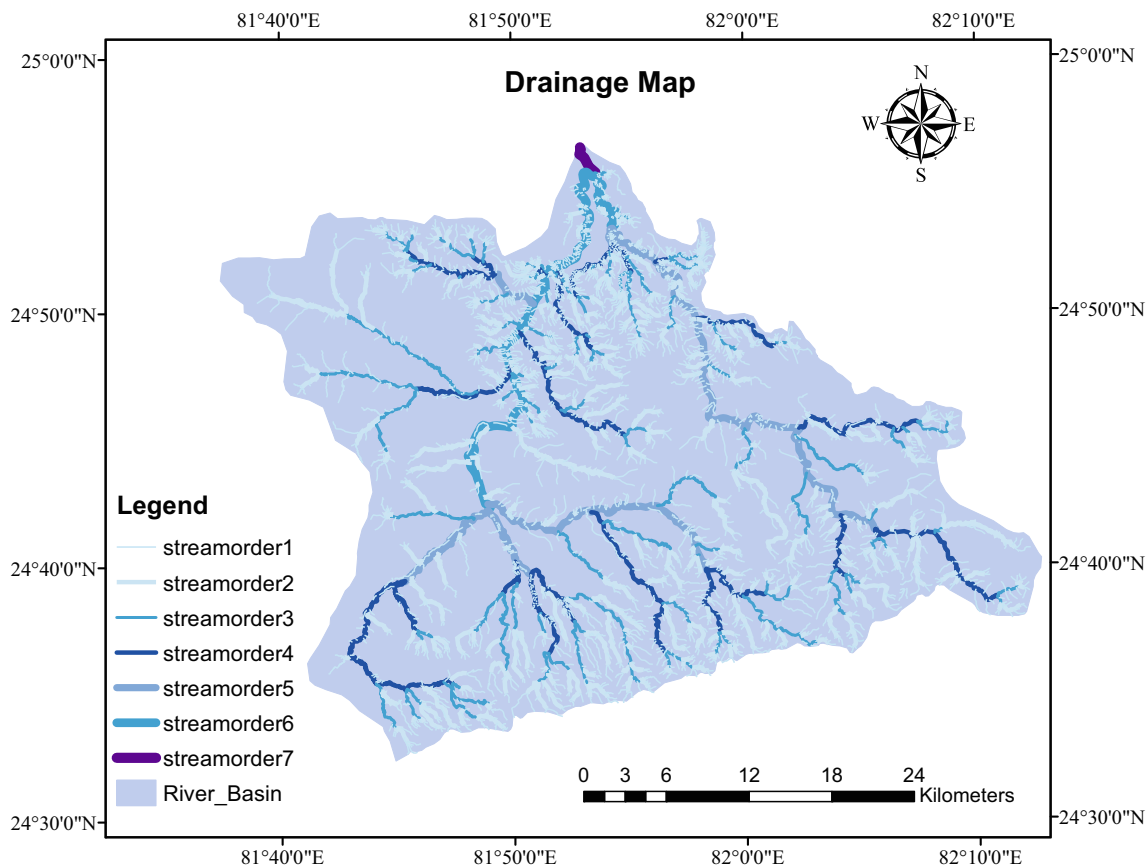
Fig. 6 Drainage map of the Naina–Gorma basin

prominent hills are found above the subdued surface which is indicated by the distorted hypsometric curve. Hypsometric curves show differences, both in sinuosity of form and in the proportionate area below the curve. Stages of youth, maturity, and old age in regions of homogeneous rock give a distinctive series of hypsometric forms, but mature and old stages give identical curves unless monadnock masses are present [38]. The southern side of the basin is relatively mature as compared to the south-western side and north-eastern side. The study revealed that sub-basins number 2, 3, 4, 5, 10, 11, 13, and 15 requires an attention for taking up remedial measures on priority. Since structural measures are not adequate to treat such large river basin; both structural and non-structural measures need to be considered for the Naina–Gorma river basin management. The treatment measures should include water retention structures for moderating flood effect in the downstream areas in rainy season.

Statistical Analysis (Hypsometric Integral Versus Sub-basin Area)

The statistical relationship between the area and the hypsometric integral groups of 15 sub-basins shows positive relationship between the area and HI. Regression analysis reveals that HI and area have a positive correlation in small basins, which means for small sub-basins, the area and HI have a direct relationship with each other (Table 2). Whereas as the basin area increases, the relationship becomes poor and shows the indirect relationship (R^2 ranges from 0.99 to 0.07; Table 2). This confirms that the hypsometric integral is controlled by the basin area in small sub-basins rather than in large ones. According to Girish et al. [6], basins with the lesser area (< 100 km^2) were found to have a positive correlation between hypsometric integral and basin area, whereas for large basins, no such correlation exists. Area variations between the 15 sub-basins are not large; therefore, regression analysis was conducted on three HI value classes (0.70–0.80, 0.80–0.85, and > 0.85) and the entire set of data (the 15 sub-basins). Further, analysis reveals that poor correlation exists in overall basin, where R^2 for the whole basin is 0.07 and groups 1 and 2 exhibit strong correlation $R^2 = 0.99$ and 0.99 while group 3 shows good correlation $R^2 = 0.84$ (Fig. 9), which matches with the results reported by earlier workers [4, 16]. Indicative literature [4, 7, 16, 45] has suggested that in small catchments or sub-basins, the hypsometric curve is generally convex and the value of the hypsometric integral approaches towards unity (denoting the dominance of hillslope processes). However, large basins and watersheds exhibit concave curves, and the integral approaches towards zero (dominate fluvial processes). However, the study conducted by Markose and Jayappa [16] has employed a regression analysis to further investigate the scale dependency, i.e., the
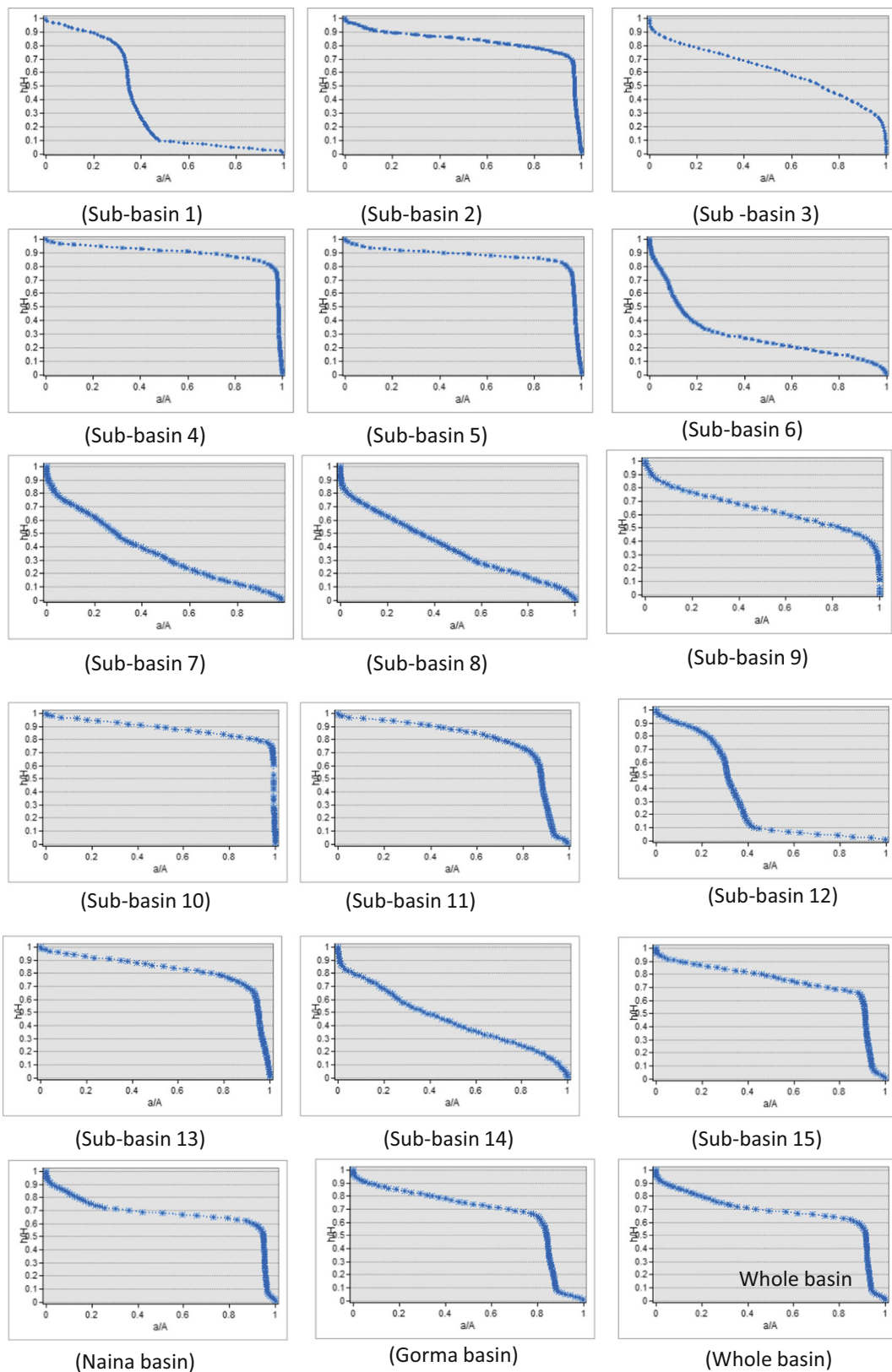
Fig. 7 Hypsometric curves of the Naina–Gorma basin and 15 sub-basins

relation between basin area and hypsometric integral; in their work, the area of the basin was varying with the existence of

an asymmetric distribution of the area of sub-basins across the study area. Hence, basins having a lesser area were found to have
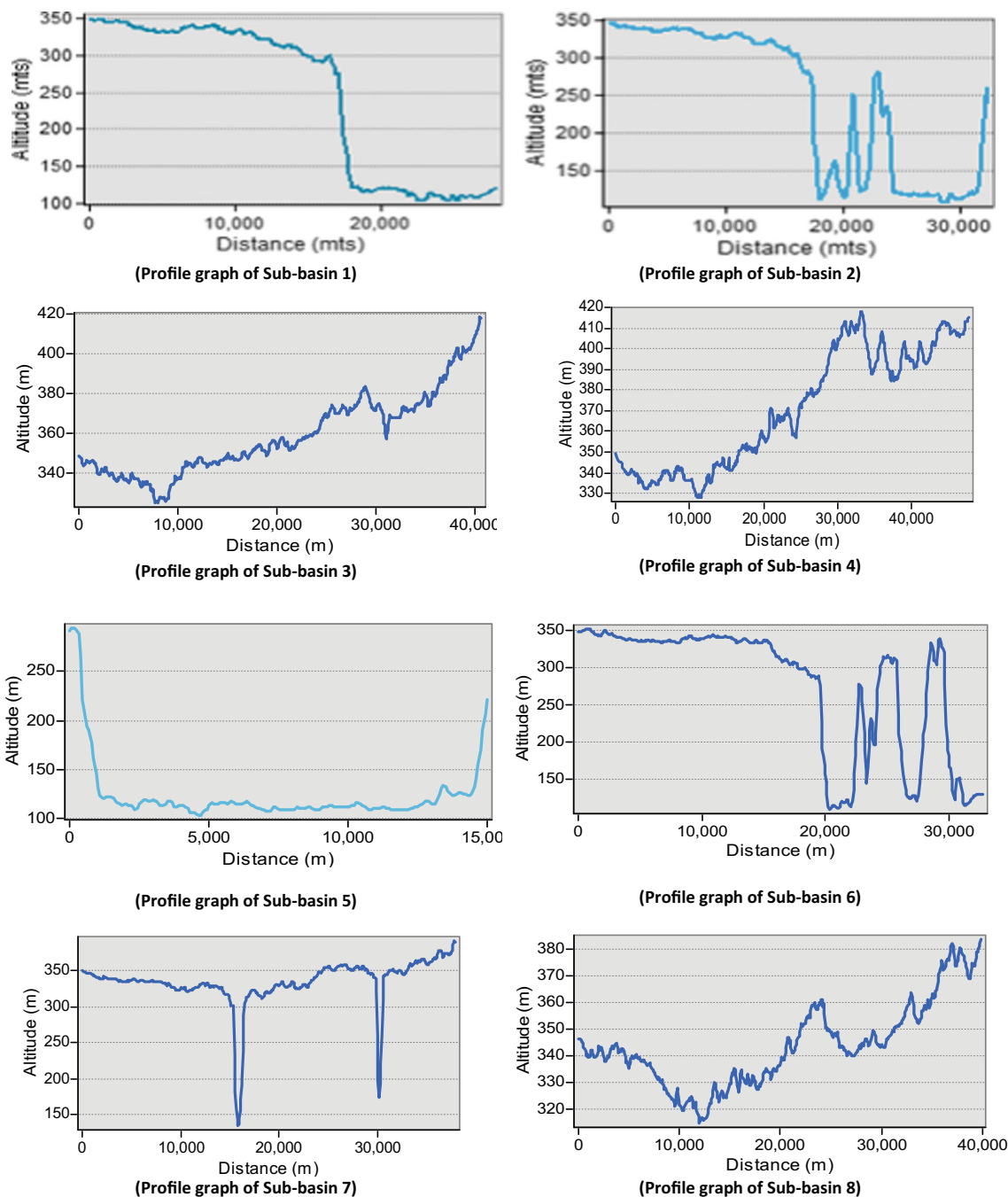
(Profile graph of Sub-basin 1)

(Profile graph of Sub-basin 2)

(Profile graph of Sub-basin 3)

(Profile graph of Sub-basin 4)

(Profile graph of Sub-basin 5)

(Profile graph of Sub-basin 6)

(Profile graph of Sub-basin 7)

(Profile graph of Sub-basin 8)

Fig. 8 Profile graph of Naina–Gorma river basin and 15 sub-basins

a positive correlation between HI and basin area, whereas for large basins, no such correlation exists. Based on the study, river basins can be prioritized for the appropriate conservation measures [6].

Conclusion

The hypsometric analysis was performed for the Naina–Gorma river basin and 15 sub-basins to identify the

geomorphic stage, the age of landforms, and erosive processes in the studied watershed. Functional parameter, i.e., hypsometric integral, is a quantitative assessment and intended to assess the erosion and rejuvenation processes. In the study basin, the majority of hypsometric curves are upward convex and less than 50% sub-basins have HI values 0.73–0.89, highlighting the youth age stage of geomorphic evolution. HI values for all sub-basins vary and represent the geomorphic evolution of landscape accordingly; sub-basin 1 shows near monadnock stage, while sub-basins 6, 7, and 12 show
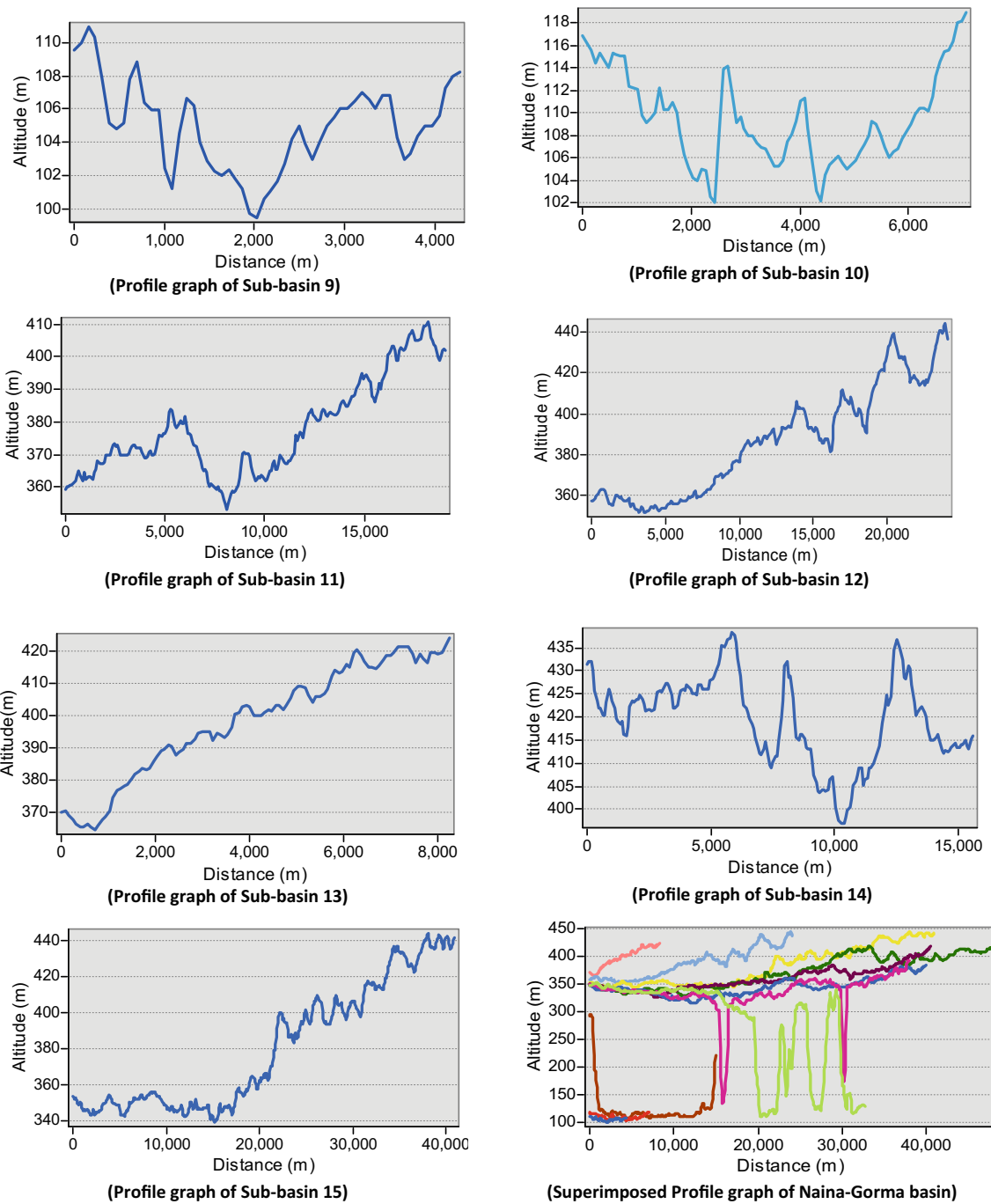
(Profile graph of Sub-basin 9)

(Profile graph of Sub-basin 10)

(Profile graph of Sub-basin 11)

(Profile graph of Sub-basin 12)

(Profile graph of Sub-basin 13)

(Profile graph of Sub-basin 14)

(Profile graph of Sub-basin 15)

(Superimposed Profile graph of Naina-Gorma basin)

Fig. 8 (continued)

monadnock stage or old stage. The sub-basins 2, 3, 4, 5, 10, 11, and 15 represent youthful stage or in-equilibrium stage and sub-basin 9 shows late youthful stage, whereas sub-basins 8 and 14 and whole Naina–Gorma basin represent equilibrium or mature stage. The sub-basins 1, 6, 7, 8, 12, and 14 have low HI values and indicate the suitable site for groundwater recharge. The study revealed that sub-basins 2, 3, 4, 5, 10, 11, 13, and 15 require attention for taking up remedial measures on priority. Regression analysis was conducted on three HI classes (0.70–0.80, 0.80–0.85, and > 0.85) versus area and

the entire set of data (the 15 sub-basins) to know the existing relationship.

The study shows that poor correlation exists in overall basin due to a large area of the basin, where R^2 for the whole basin is 0.074 and groups 1 and 2 exhibit strong correlation $R^2 = 0.99$ and 0.99 while group 3 shows good correlation $R^2 = 0.84$. The profile graph is drawn for every drainage of the study region to know the hydrological response and to study the altitude and distance that covered by the particular drainage. The southern part of the
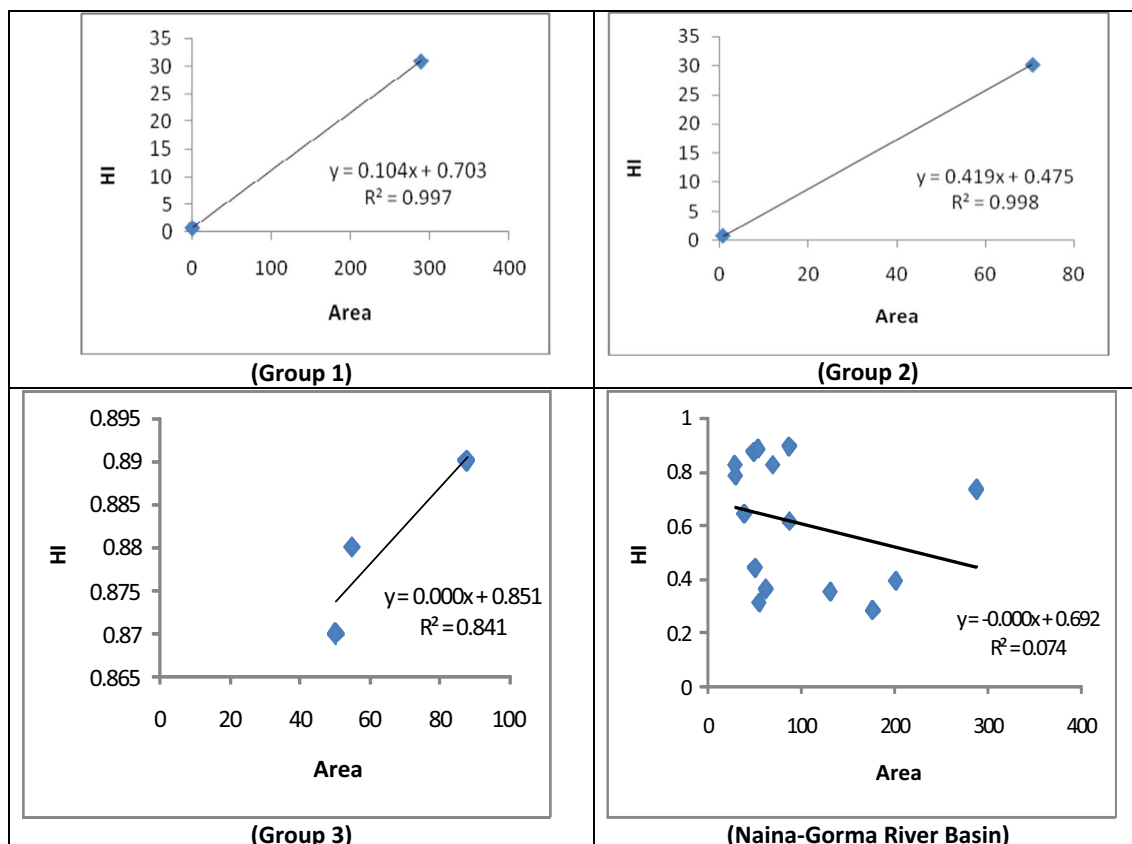
Table 2 The relationship between area and hypsometric integral and the geomorphic stage of different sub-basins. HI are indicators for geomorphic evolution of drainage basins

Sub-basin	Area	HI	HI range	Group	Geomorphic stage
15	289	0.73	0.70–0.80	1	Hypsometric curves are of convex upward shapes. Late youth stage of evolution
11	31	0.78			
2	70.6	0.82	0.80–0.85	2	Slightly sharp convex upward hypsometric curves shape. Demonstrating significant influence of rejuvenation associated with severe incised erosion and active slope processes
13	30.1	0.82			
4	88.1	0.89	> 0.85	3	Very sharp convex upward shape hypsometric curves. Youth age stage of geomorphic evolution. High total runoff with subsurface processes as the major geomorphic processes and high susceptibility to erosion, incised channel erosion, and mass movement
5	50.3	0.87			
10	55	0.88			

Naina–Gorma basin is inaccessible and only these terrain-based indicators can aid in indicating the hydrologic nature.

Study indicated that Naina–Gorma river basin is relatively matured and erosional processes have been stabilized while surface runoff is the dominant process in the entire river basin, thereby contributing significantly to the floods in the downstream areas. Hypsometric analysis is helpful in rainwater harvesting practices and its management at suitable locations for controlling further erosion, reducing the runoff, increasing the groundwater potential in various stages of landform processes in the Naina–Gorma river basin. The hypsometric curve is a concise, but important and powerful tool that encloses the necessary features to represent the form of a drainage basin and its evolution. Profile graph of drainage and HC depicted the

Fig. 9 Statistical relationship between the area and the hypsometric integral (HI) groups of the 15 sub-basins. Groups 1, 2, and 3 have high positive correlation (as basin having smaller area shows positive correlation) whereas the overall basin has poor positive correlations (as basin having larger area shows poor correlation)

hydrologic behavior of a river basin through a set of parameters related to the shape of the curve.

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