



# Geomorphic response of the river basin drainage in seismically active regions of India

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Received: 3 October 2018 / Accepted: 9 August 2019 / Published online: 17 August 2019  
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## Abstract

Over the last few decades, the Indian subcontinent is gradually drifting towards northeast at a rate of 10 mm/year, which is an indication that the areas are actively deforming. Such a gradual rate of drift is expected to bring modifications and changes in the topography, which can be quantified with the help of geomorphic parameters. The current study examines the geomorphological changes in the seismically active areas of different geotectonic provinces of India, i.e., Northeast India and Bhuj region. The geomorphological changes have been estimated with the help of remote sensing and geographical information system modeling by calculating the geomorphic parameters. A total of 39 drainage basins were extracted from both the study areas using Aster GDEM data of 30 m resolution. Geomorphic indices such as stream order, stream length, bifurcation ratio, form factor, asymmetry factor and hypsometric integral were calculated for each drainage basin of the study regions. The geomorphic parameters reveal that the study areas are dendritic in character, even though having different geological formations, both study regions express similar lithological characteristics. With no strong control of structural elements, both study areas seem to be characterized by relatively high permeability and with relatively gentle slope. The extent of the carving of topography reveals that the drainage development and morphologic evolution of both areas have practically reached Late Mature and Old stage of terrain development. Even though the two study areas represent different seismotectonic provinces, it is observed that geomorphologically they are gradually approaching the stage of peneplanation.

**Keywords** Northeast India · Bhuj region · Hypsometry analysis · Geomorphological parameters · Remote sensing · Geographical information system (GIS)

## Introduction

Morphometric analysis applications are widely used throughout the world to understand the influence of active tectonic activity on river basin drainage. In tectonically active regions, drainage pattern seems to be very sensitive for river deviation, drainage geometry and asymmetry of the basin (Sharma et al. 2018). Different geomorphic landform responses are construed from geomorphic indices. The drainage networks are in relation with the structural features, and these features may lead to the development of an orogen, which is tectonically active (Delcaillau et al. 2006; Schlunegger and Hinderer 2001). Earthquakes are responsible for the mobility of landslides, debris flows, erosion, river incision, change in vegetation, change in drainage pattern, etc., and these changes are even more in continuously seismic active regions (Ma et al. 2017; Ren et al. 2017; Roback et al. 2018; Zhang et al. 2015). The deformation in the

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**Electronic supplementary material** The online version of this article (<https://doi.org/10.1007/s12665-019-8547-y>) contains supplementary material, which is available to authorized users.

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landscape may be vertical or horizontal, which constitutes the domain of tectonic geomorphology. Understanding the linkages between tectonic activity, earthquake intensities and drainage pattern is important for evaluating the river basin drainage disturbances.

Drainage basin analysis generally provides the clues to structural features and lithology of the area (Howard 1967). Drainage patterns of diverse characteristic have been defined in the literature: dendritic, parallel, trellis, rectangular, radial/centrifugal, annular, and contorted (Deffontaines and Chorowicz 1991). The deviations from a drainage pattern are considered as drainage anomalies and they can be related to either structural or lithological discontinuities (Pubellier et al. 1994). The drainage basins follow fractal geometry, because these are regarded to represent the self-similar nature of actual substance (Mandelbrot 1983). In drainage analysis, Horton's and Strahler's laws yield scaling properties and are applied to derive characteristic measures of the entire drainage basin. The law of drainage composition has been thought for a long time to be expressed by geometrical progression with the parameters, viz., stream order, stream number, bifurcation ratio, mean bifurcation ratio, stream length, stream length ratio, form factor and asymmetry factor and hypsometric integral (Morisawa 1962; Schumm 1956). From the observations (Walker and Willgoose 1999), the DEM-derived drainage catchments often are significantly different from reality, particularly if the catchments or watersheds are small. A detailed understanding of the drainage evolution and geomorphic signatures of these small catchments can aid in characterizing the hydrogeomorphology of that particular catchment or watershed (Mahesh et al. 2015), which further can be helpful in various watershed or catchment management studies.

The present work aimed to study the drainage pattern characteristics of seismically active regions using Horton's and Strahler's laws. In the present paper, the drainage network has been interpreted from satellite images and has been analyzed to compute different geomorphic parameters. The Indian subcontinent is gradually drifting towards northeast at a rate of about 10 mm/year (Banerjee et al. 2008), which is also an indication that the seismically active study areas are actively deforming. Such a gradual rate of drift is expected to bring out modifications and changes in the topography and they can be quantified with the help of morphometric parameters. For this purpose, the drainage systems in the actively deforming and seismogenic areas of Northeast (NE) India and Bhuj region are selected for the present study to analyze the geomorphic responses. A total of 24 drainage basins have been outlined covering north and south of Brahmaputra River from NE India, 16 of these drainage basins are from north of Brahmaputra River covering Assam, and 8 basins are from south of Brahmaputra River covering the Shillong plateau. From the Bhuj region, 15 drainage basins have been

outlined, and it covers the area in and around the epicenter of the major earthquake of January 2001. There is a lack of studies analyzing the geomorphic indices and understanding the drainage pattern in these seismically active regions of India. The basin drainage assessments focus on understanding and quantifying the geomorphic signatures in these two regions. The study results provide an insight into the river drainage response of continuous seismic activity.

## Materials and methods

### Study area

To examine the geomorphological characteristics of the seismically active regions, two areas have been selected, representing two different tectonic domains, viz., a part of the NE India from the domain of compressional tectonics, which is a site of frequent seismicity and another is Bhuj region in Kutch, India, which had experienced a major earthquake in 2001, that is an example of the intracontinental seismicity. The records of the seismic events from the areas selected for the study have been obtained from the International Seismological Center (ISC) (<http://www.isc.ac.uk/bull>) for the period from 1964 to 2017. According to Scordilis (2006) and Thingbaijam et al. (2008), ISC catalogues are extensive in data volume and estimated earthquake magnitudes are reliable. For NE India, the catalogues contain the data from magnitude ( $M$ ) two and above for the period from 1965 to 2017, while for the Bhuj region, a relatively better record is obtained from 2001 to 2017. The magnitude type considered is of body wave magnitude. The seismicity behavior of the two different seismogenic study areas has been analyzed using these earthquake catalogue data. For NE India, the magnitude of 4.5 and above and for the Bhuj region, the magnitude of 3.3 and above are considered for the analysis (Figs. 1, 2).

### Northeast (NE) India

From Fig. 1, it was revealed that the frequency of events is high in NE India. NE India lies at the junction of the Himalayan arc in the north and the Burmese arc to the east, forming the syntaxial bend, due to which the region is frequented by seismicity, generally of higher magnitudes. The Shillong earthquake of  $M > 8.0$  in 1897 is rather the first instrumentally recorded earthquake and one of the major earthquakes of the world (Ambraseys and Bilham 2003; Rajendran et al. 2004). Another great earthquake, i.e., Assam earthquake of  $M > 8.0$  struck this region in 1950 (Sarker and Thorne 2006). Apart from these two high-magnitude earthquakes (termed to be great earthquakes), it has also been reported that the region has so far experienced nearly 18 large earthquakes of  $M \geq 7.0$ .

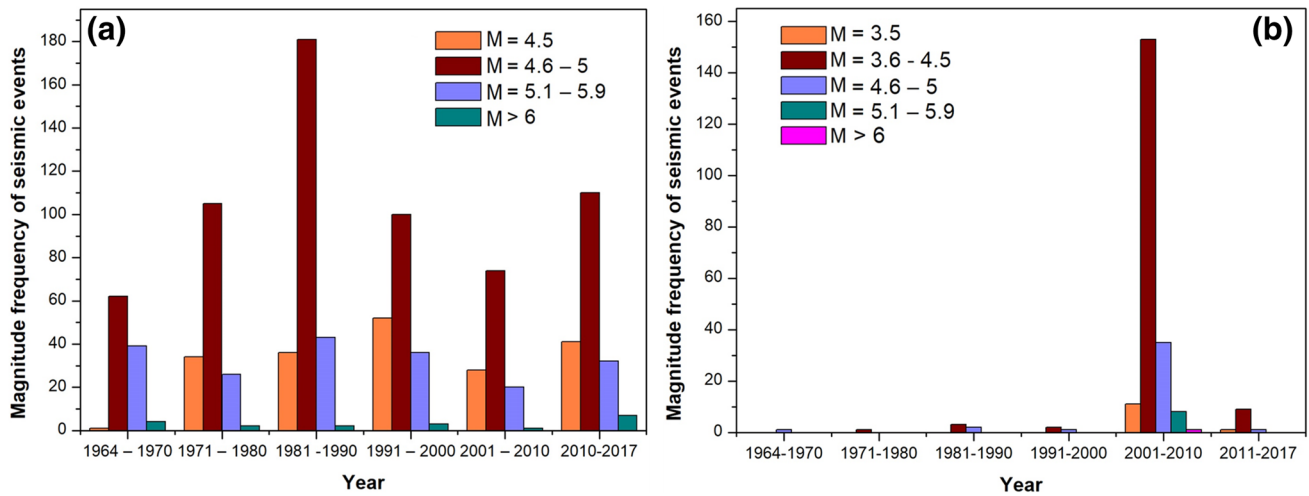


Fig. 1 Decadal frequency and magnitude of seismic events of a Northeast India and b Bhuj regions

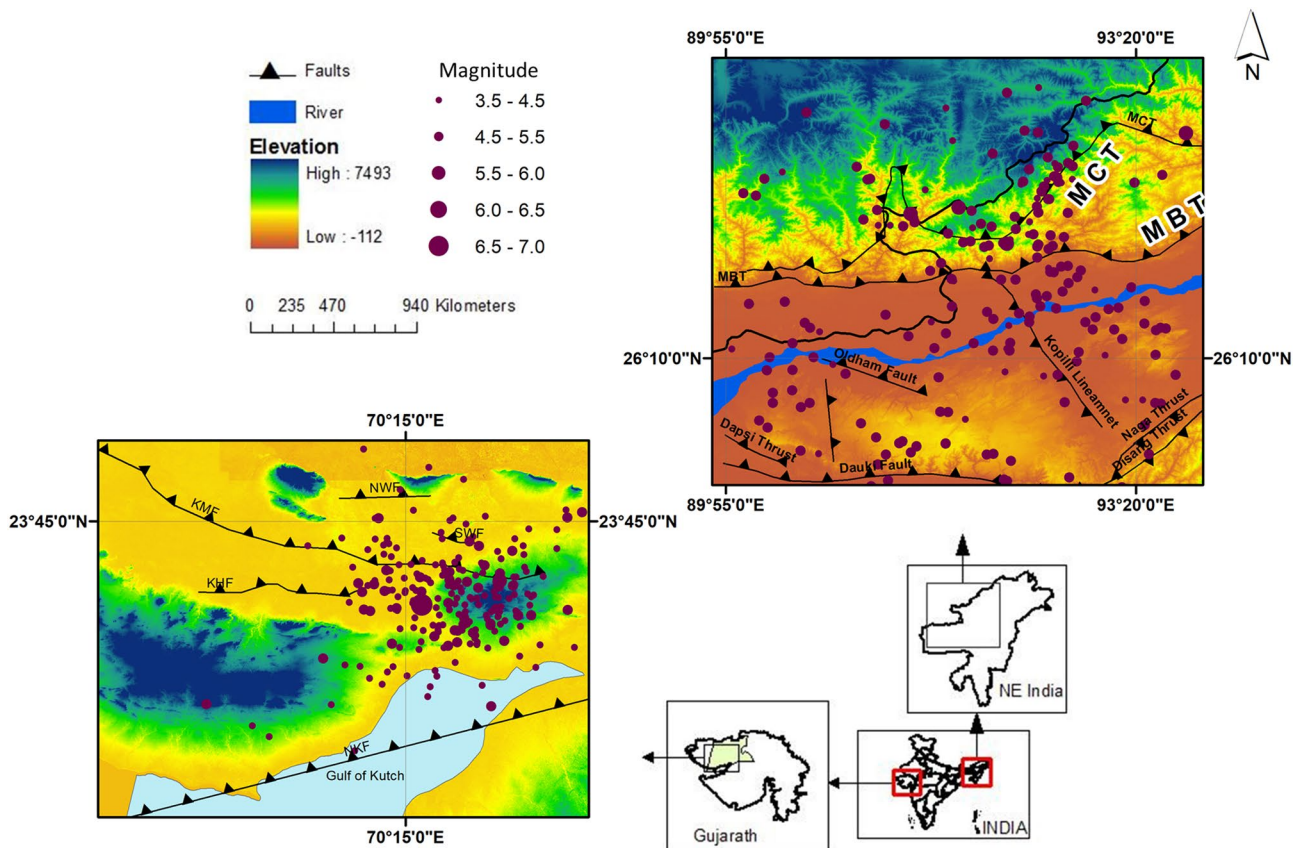


Fig. 2 Location map and major tectonic elements with earthquake epicenters (1964–2017) of the study regions: Northeast India and Bhuj area

The tectonic scenario in the NE India is complex due to the continued convergence of the Indo-Australian Plate and the Tibetan Plate at the Himalayan arc and the subduction of the Indo-Australian Plate below the Burmese arc, causing intensive seismic activity in the region. This situation has

resulted in giving rise to regional tectonic elements such as Main Central Thrust (MCT), Main Boundary Thrust (MBT), Disang Thrust, Naga Thrust, Oldham Fault, Dauki Fault, Kopili Lineament and a number of criss-cross faults and lineaments (Fig. 2). The area comprises crystalline rocks,

including the Archaean gneissic complex and Shillong series, which are intruded by Proterozoic greenstones and Myllem granite and at places capped by the pre-upper Cretaceous volcanics (Krishnan 1949). The shelf and the depression of upper Assam to the northeast are varying in age from late Cretaceous to Pleistocene and demonstrate the older and younger alluvium along the Brahmaputra River. This region is marked by the criss-cross pattern of faults that cut the ancient basement rocks.

### Bhuj region

The Bhuj region has a long history of disastrous earthquakes, and the observed aftershock activity spreads about for a week or more for each seismic event. The Bhuj earthquake in 2001 is one of the high-magnitude earthquakes in recent years (Umamaheswari et al. 2014), and nearly 3000 aftershocks with  $M \geq 1.0$  have been recorded (Kayal et al. 2002). It has been reported that reverse fault mechanism is responsible for each major seismic event of the Kutch basin region (Dimri et al. 2005). For Bhuj earthquake 2001, reverse faults occurred between Kutch Mainland Fault (KMF) and North Wagad Fault (NWF) (Mandal et al. 2004) and thereby implying modifications in the structural fabric of the region after each seismic event.

The Bhuj region is a rift basin, oriented namely in an east–west direction. Based on its situation, it is classified as a pericratonic basin on a continental scale (Biswas 1987). Development of physiographic features seems to be controlled by geological formations of the region: (1) a widespread surface, forming plains at the lowest level of erosion, of the early Quaternary period, (2) a less prominent late Tertiary surface, (3) remnants of mid Tertiary surface, forming discontinuous ridges and plateaux and (4) the lateritized early Tertiary surface. Geologically, the oldest lithological unit exposed is of the Jurassic period. The progressive groups are sedimentary rocks of the Tertiary period, overlain by the older and younger Alluvium of the Quaternary period. Tectonic evolution of the Bhuj region as a pericratonic basin is mainly guided by the strikes of Aravalli–Delhi in NE–SW direction, the Dharwarian in NNE–SSW direction and the Satpura trend in ENE–WSW direction, paralleling to Son–Narmada–Tapti lineament (i.e., SONATA), which is regarded as a suture. These are the major Precambrian trends in the region. The Kutch basin developed during the Jurassic period due to rifting along the NE–SW trend of the Aravalli to Delhi (Biswas 1987). During the Cretaceous period, rifting along the Dharwarian fractures had taken place, followed by the formation of the Cambay graben during the Palaeocene period. In the early Cretaceous, rifting along SONATA gave rise to the Narmada graben. Of these, the Kutch rift basin is marked by major structural elements such as Nagar Parkar Fault, Island Belt Fault, North and South Wagad

Faults, Kutch Mainland Fault, Katrol Hill Fault and North Kathiawar Fault, along with the major lineaments, viz., Lathi Rajkot Lineament, Chambal Jamnagar Lineament and West Coast Lineament (Biswas 1987) (Fig. 2).

### Detailed methodology of the drainage basin evaluation

The advanced spaceborne thermal emission and reflection radiometer (ASTER) global digital elevation model (GDEM) data used for the research analysis to evaluate geomorphic responses was developed by the Ministry of Economy, Trade and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). ASTER GDEM has along-track stereoscopic image capability of high-resolution digital elevation models (DEMs), which is one arc-second (approximately 30 m) grid resolution (Thomas et al. 2014).

The drainage network extraction methodology was adopted in this study based on the methodological suggestions from the literature (Fairfield and Leymarie 1991; Jenson and Domingue 1988; Morris and Heerdegen 1988; O’Callaghan and Mark 1984; Tribe 1992; Yuan and Luanne Vanderpool 1986). To delineate the drainage source of a watershed or river basin from DEM, a constant threshold area ( $T_a$ ) needs to be defined.  $T_a$  is a minimum area required to form a channel, and in general, the value of  $T_a$  is based on the personal judgment or visual comparison of drainage networks (Helmlinger et al. 1993; Jenson and Domingue 1988). Using a constant threshold value to extract the drainage network from DEM is the most popular method for extracting geomorphological and hydrological information. By visual comparison of networks as observed in the satellite image, a threshold area of 400 m<sup>2</sup> has been considered. Morphometric parameters, namely stream order, stream number, bifurcation ratio, mean bifurcation ratio, stream length, stream length ratio, form factor, asymmetry factor, hypsometric integral and hypsometric curves have been computed using geographical information system (GIS) tools.

#### Stream order

In drainage basin analysis, the initial step is ordering of the streams. The stream ordering is carried out using Strahler’s method (Strahler 1964), and it is a measure of stream position in the hierarchy of tributaries between the stream segments.

#### Stream number

The number of stream segments in each order is known as stream number, and the numbering is given according to Horton’s law (Horton 1945). In other words, it is observed



that in a drainage basin, a number of streams of different orders appear to follow the inverse geometric series, where the first term is unity, and the ratio is expressed as bifurcation ratio:

$$N_{\mu} = R_b \times (K - \mu), \quad (1)$$

and the total number of streams of the basin can be calculated as:

$$\Sigma \mu = R_b \times K - 1/R_b - 1, \quad (2)$$

where  $N_{\mu}$  is a number of stream segments of a particular given order,  $R_b$  is the bifurcation ratio constant,  $\mu$  is the basin order, and  $K$  is the highest order of the basin.

### Bifurcation ratio

Bifurcation ratio ( $R_b$ ) explains the branching pattern of a drainage network and is given as the ratio of a total number of stream segments of one order and next higher order in a drainage basin. It relates to the integration between streams of different orders in a drainage basin and has a dimensionless unit. Horton (1945) and Schumm (1956) considered  $R_b$  as an index of relief and dissection, while Strahler (1952) demonstrated the regions with different environments, unless and until there is a powerful geologic control dominates.

### Stream length

Stream length indicates the chronological development of stream segments including interlude of tectonic disturbances. The characteristic size of components in the drainage network and its contributing surfaces were revealed by the mean stream length (Strahler 1964). The positive exponential function model of stream lengths is:

$$L_{\mu} = L_1 \times R_1(\mu - 1), \quad (3)$$

where  $L_{\mu}$  is the cumulative mean length of the given order,  $L_1$  is the mean length of the first order,  $R_1$  is the constant length ratio, and  $\mu$  is the given order of a stream.

### Stream length ratio

The stream length ratio can be defined as the ratio between the mean stream length of a given order and the mean stream length of next lower order, and it is related to the surface flow and discharge of the basin (Horton 1945).

**Form factor** Form factor ( $R_f$ ) is defined as the ratio of basin area to the square of basin length (Horton 1932), and it is the quantitative expression of drainage basin outline. A lower value of the form factor indicates that the basin is elongated and a higher value suggests that the basin is circular. Circular basins flow for a shorter duration with a high peak,

whereas elongated basins flow for a longer duration with the lower peak.

Thus, the form factor equation can be written as:

$$R_f = A_b/L_b^2, \quad (4)$$

where  $A_b$  is the area of the basin in sq. km, and  $L_b$  is the basin length in km.

**Asymmetry factor** The asymmetry factor ( $A_f$ ) is useful in identifying the tectonic tilting and control over the basin evolution at the regional and local scales.  $A_f$  can be written as:

$$A_f = 100(A_r/A_t), \quad (5)$$

where  $A_r$  is the area on the right side of the river flow in the basin and  $A_t$  is the total area of the basin. Basin is considered to be sensitive if the tilting is perpendicular to the direction of the main river. If  $A_f$  is greater than 50, then there is a shift in the channel towards the downstream left side of the drainage basin.  $A_f$  value less than 50 indicates that the channel has shifted towards the downstream right side of the drainage basin. If the value of  $A_f$  is equal to 50, it expresses symmetric condition and verifies the equilibrium state in the basin. Also, the values far from 50 verify the role of erosion in the right or left banks of the river (Ildoromi 2012; Molin et al. 2004).

**Hypsometric curve and hypsometric integral** Area elevation analysis, i.e., hypsometry analysis is useful for understanding the geomorphology and its relation to the tectonic changes. The hypsometric curve is constructed by plotting the relative drainage basin height ( $h/H$ ), that is known as the total basin height ratio against the relative drainage basin area ( $a/A$ ), which is the total basin area ratio (Strahler 1952). The maximum height ( $H$ ) equals the maximum elevation minus the minimum elevation and represents the relief within the basin. The areas in between each pair of adjoining contour lines symbolize the total surface area of the basin ( $A$ ). Area ( $a$ ) is the surface area within the basin above a certain line of elevation ( $h$ ). The relative area ( $a/A$ ) value measures between 1.0 at the lowest point in the basin, where relative height ( $h/H$ ) equals zero, and zero at the highest point in the basin, where relative height ( $h/H$ ) equals 1.0 (Mayer 1990). Determining the hypsometric integral (HI) is the simplest way to characterize the shape of the hypsometric curve for a given drainage basin. Integral values vary between 0 and 1, where a value close to 0 indicates the highly eroded region and value close to 1 is for the slightly eroded region (Pedrera et al. 2009):

Hypsometric integral (HI)

$$= \text{mean elevation} - \text{minimum elevation}/\text{maximum elevation} - \text{minimum elevation.} \quad (6)$$

The hypsometric integral and its relationship to the degree of dissection allow it to be used as an indicator for evaluating the landscape stage in the cycle of erosion. High hypsometric integral values indicate that most of the topography is highly relative to the mean elevation, representing a youthful topography. Intermediate to low hypsometric integral values represents more evenly dissected drainage basin, indicating a Mature stage of development. Depending on the hypsometric integral value, a drainage basin can be classified as Old stage  $0 < HI < 0.3$ , Late Mature stage  $0.3 < HI < 0.4$ , Mature stage  $0.4 < HI < 0.5$ , Late Youthful stage  $0.5 < HI < 0.6$  and Youthful stage  $0.6 < HI < 1$ . The shape of the hypsometric curve and the hypsometric value provide valuable information not only on the erosional stage of the basin but also on the tectonic, climatic and lithological factors that are controlling it (Willgoose and Hancock 1998). Hypsometric curve and the hypsometric integral are evaluated directly from the DEM of the basin. Computation of the hypsometric integral has been performed using CalHypso script of the GIS extension tool (Pérez-Peña et al. 2009).

## Results and discussion

Computation of different geomorphic parameters throws light on the evolutionary trend of geomorphic features in the structurally and tectonically active study regions. The Indian subcontinent is gradually drifting towards northeast at the rate of about 10 mm/year, which has a major impact on both the study regions of actively deforming. Such a gradual rate of drift is expected to bring modifications and changes in the topography that has been quantified with the help of geomorphic parameters.

### Basin characteristics

#### Stream order

The maximum frequency of streams is observed in case of the first order, and it is rather unambiguous in every drainage basin. Furthermore, it is noted that the stream order decreases as the stream number increases. General drainage pattern from both the areas is of dendritic in character, which indicates the homogeneity in geological characteristics and lack of structural control. This pattern is characterized by a tree-like or fern-like pattern with branches that intersect primarily at the acute angles. Development of the same, a similar drainage pattern reveals more or less uniform lithological characters throughout the terrain. Stream ordering in the basins of NE India is with streams of maximum order 8. Out of the 24 basins in NE India, 3 basins are of order 8, 2 basins are of order 7, 14 basins are of order 6, and 5 basins are of order 5. In Bhuj region, out of the 15 basins, 5 basins

are of order 6, 9 basins are of order 5, and only 1 basin is of order 4.

#### Stream length

Stream length is measured from the mouth of the river to drainage divide, and the total length of stream segments is maximum for the first-order streams, which decreases with the increase in stream order. This is a normal trend and indicates that the terrain is characterized by a gentle slope, low relief and homogeneous lithology. The mean stream length of all the basins varies based on stream order, which can be ascribed to variations in slope and topography. In NE India, mean stream length varies from 674.6 to 144,720 m and for the Bhuj region, mean stream length of the basins varies from 97.2 to 51,073.2 m. For any given order, it is greater than that of the lower order and less than that of its next higher order. It is observed that the mean length of the highest order is less than that of the length of the previous order (Table 1). Stream length ratio is another significant hydrological feature of the basin, as it reveals surface runoff characteristics. Streams of relatively smaller lengths are characteristic of areas with larger slopes with finer texture. Longer lengths of streams generally indicate flatter gradient or gentle slope. It has a significant relation with the surface flow and discharge. The highest mean stream length ratio is 3.6 for NE Indian basins (basin 24) and 4.2 for the Bhuj region (basin 6) basins. The total length of streams of every order also reveals a normal trend, i.e., decrease in stream length with the increase in stream order, suggesting thereby that the area is characterized by low relief and gentle slope along with the uniform lithological characteristics. Such topographical characters appear to have favored the dendritic drainage. This inference has been drawn from both the study areas, even though they represent different geotectonic provinces.

#### Bifurcation ratio ( $R_b$ )

Bifurcation ratio ( $R_b$ ) for different regions and environments conveys a small range of variation, except where the geological control dominates. The bifurcation ratio characteristically ranges between 2.0 and 8.0 for basins in which geology is reasonably homogeneous and absence of major structural elements. Variations in the bifurcation ratios of the basins change with different drainage basins. The lower value of  $R_b$  indicates that the basin has suffered less structural disturbance and the drainage pattern is not distorted. Furthermore, low  $R_b$  values signify the high drainage density, low permeability of the terrain and indicate areas with uniform surficial materials, where the geology is reasonably homogeneous. Average of bifurcation ratios of all orders, i.e., mean bifurcation ratio in NE India varies from 3.4 to 5.7

**Table 1** Basin-wise results of stream order, bifurcation ratio, stream length ratio and hypsometric integral for Northeast India and Bhuj regions

Region	Basin number	Stream order	Bifurcation ratio ( $R_b$ )	Stream length ratio ( $R_l$ )	Form factor ( $R_f$ )	Asymmetry factor ( $A_f$ )	Hypsometric integral (HI)
Northeast India	Basin 1	8	3.90	2.30	0.36	49.94	0.28
	Basin 2	6	3.83	2.22	0.47	56.08	0.46
	Basin 3	6	3.78	2.11	0.24	54.52	0.16
	Basin 4	6	3.68	1.94	0.18	46.61	0.23
	Basin 5	6	4.49	3.45	0.30	53.76	0.25
	Basin 6	6	3.93	2.27	0.22	66.93	0.19
	Basin 7	5	4.22	2.69	0.10	48.01	0.24
	Basin 8	5	4.06	2.30	0.14	44.75	0.25
	Basin 9	6	3.64	2.00	0.15	42.95	0.17
	Basin 10	6	4.69	2.58	0.20	38.25	0.24
	Basin 11	5	4.39	2.86	0.03	39.94	0.41
	Basin 12	6	3.79	2.21	0.30	56.29	0.16
	Basin 13	6	3.99	2.20	0.47	38.57	0.51
	Basin 14	8	4.36	2.24	0.47	46.87	0.46
	Basin 15	6	4.18	2.69	0.20	56.45	0.23
	Basin 16	7	3.62	1.90	0.40	40.29	0.38
	Basin 17	8	3.73	2.00	0.59	29.48	0.33
	Basin 18	6	4.04	2.36	0.30	59.69	0.42
	Basin 19	7	3.71	2.08	0.42	43.32	0.35
	Basin 20	5	4.20	2.45	0.28	55.78	0.12
	Basin 21	6	3.60	1.96	0.28	36.48	0.25
	Basin 22	6	3.72	2.07	0.35	64.00	0.35
	Basin 23	6	3.88	2.29	0.41	57.19	0.29
	Basin 24	5	5.31	3.62	0.29	44.73	0.25
Bhuj region	Basin 1	6	3.57	2.11	0.57	44.21	0.32
	Basin 2	5	3.98	2.20	0.22	61.39	0.25
	Basin 3	5	3.65	2.34	0.27	58.48	0.34
	Basin 4	5	3.89	3.12	0.22	48.52	0.26
	Basin 5	5	4.27	2.43	0.23	55.15	0.29
	Basin 6	5	4.34	4.25	0.23	47.61	0.34
	Basin 7	6	3.72	2.19	0.34	55.87	0.22
	Basin 8	6	3.40	2.00	0.27	54.22	0.29
	Basin 9	5	4.16	2.20	0.42	37.68	0.32
	Basin 10	5	3.59	2.47	0.61	51.87	0.38
	Basin 11	4	4.77	2.94	0.42	45.23	0.36
	Basin 12	5	4.09	2.24	0.41	53.01	0.23
	Basin 13	5	4.16	2.06	0.21	56.44	0.18
	Basin 14	6	4.25	2.53	0.13	39.7	0.16
	Basin 15	6	3.91	2.30	0.12	40.17	0.23

and for the Bhuj region, it varies between 3.4 and 4.8. The highest value of mean bifurcation ratio, i.e., 5.7 and 4.8 is found in basin 24 of NE India and basin 11 of Bhuj region, indicating structural control in the area and low permeability, whereas the other basins with low bifurcation ratio are geologically homogeneous. Bifurcation ratio has significance in understanding the possible presence or absence of structural control in the development of a drainage pattern.

Values of the bifurcation ratio computed for NE India show much variation, though its values for most of the basins are in the lower range except for one basin. Such values suggest no strong structural control, uniform lithological characters and relatively high permeability character of the terrain, supporting the inference drawn earlier from total stream lengths of respective stream orders. A similar observation can be made from the variations in the values of the bifurcation

ratio about the drainage development from the Bhuj region. The area is nearly plain, and the drainage that has developed indicates geological formations have rather similar lithological characters, no strong control of structural elements and the region also seems to be characterized by relatively high permeability.

### Form factor

The value of the form factor would always be less than 0.75 for perfectly circular basins, and the basin is more elongated in shape if the form factor value is small. A basin or watershed with high form factor value will tend to have a high peak flow for a shorter duration, whereas elongated basin with low form factor ranges from 0.54 indicating them to be elongated in shape and flow for longer durations (Pareta and Pareta 2011). In NE India basins, form factor values vary from 0.03 to 0.59, and in Bhuj region basins, the values range from 0.12 to 0.61 (Table 2). It reveals that the basins from NE India are all elongated basins and flow for longer durations. Flood flows of such elongated basins are easier to manage than those of circular basins. In the case of the Bhuj region, values indicate that all the basins are elongated except basin 10 and they flow for a longer duration. Basin 10 indicates that it is nearly a circular basin and which have high peak flows for a shorter duration.

Based on the classified arbitrary scale (Table 2), it is observed that from NE India, out of 24 basins demarcated, 12 basins fall in the category I, 11 basins fall in the category II, while only 1 basin, i.e., basin number 17 is in category III, indicating short elongation and therefore, steeper slope (Fig. 3a). Thus, form factor values of the basins from NE India characterize the area as nearly plain, supporting the inference derived from the values of the bifurcation ratio. In the Bhuj region, out of the 15 basins outlined, 9 basins fall in the category I, 4 basins fall in the category II, while 2 basins are of category III (Fig. 3b). This categorization also indicates most of the study area is characterized by relatively gentle slopes, except that of the basins 1 and 10.

### Asymmetry factor

Asymmetry factor ( $A_f$ ) is a quantitative expression of the form of the basin expressed in percentage. Therefore,  $A_f$

value 50 suggests symmetrical basin, which is considered as stable phase and the basin is in an equilibrium condition. In the present study, the symmetry of the basin is considered with a deviation of  $\pm 5$ , i.e., the value of  $A_f$  between 45 and 55 is regarded for the basin to be in an equilibrium state. The value of  $A_f$  more than 55 indicates that the area to the right of the trunk stream than that to the left, while its value less than 45 indicates that the area to the right of the trunk stream than that to the left and the basins with these characters have been subjected to tectonic tilt.

The results from NE India reveal that the  $A_f$  value ranges from 29.48 to 66.93 and basin 17 shows the higher form factor value than other basins in the region, whereas the  $A_f$  value is low for basin 17. NE India basins 2, 3, 5, 6, 12, 15, 18, 20, 22 and 23 are showing  $A_f$  value far from 50, so the erosion in these basins is comparatively higher than the other basins and tilted due to the strong morpho-dynamic activities. However, the value of  $A_f$  less than 50 indicates less erosion. Basins 1, 4, 7, 8, 9, 10, 11, 13, 14, 16, 17, 19, 21 and 24 are among those basins in which the erosion and the morpho-dynamic activities are more evident. For the Bhuj region, basins show the values vary between 37.68 and 61.39 and the basins 2, 3, 5, 7, 8, 10, 12 and 13 are highly eroded, and basins 1, 4, 6, 9, 11, 14 and 15 are less eroded. Accordingly, it is seen that out of the 24 basins outlined from NE India, 8 basins appear to be in stable phase, i.e., nearly in an equilibrium condition. The remaining 16 basins seem to be unstable and subject to tectonic tilt environment. Out of these 16 basins of unstable character, 9 basins have less area to the right of the main trunk stream, and 7 basins have more area to the right of the main trunk stream than that to the left (Fig. 4a). In case of the basins from the Bhuj region, it is observed that out of the 15 basins, 6 basins seem to be in stable phase and are in an equilibrium condition, while the rest nine basins are not in the equilibrium state. Out of these nine unstable basins, five basins have less area to the right of the main trunk stream, and four basins have more area to the right of the main trunk stream than that to the left, thereby indicating that they are subjected to tectonic tilt (Fig. 4b).

### Basin stage

The extent of the carving of the topography carried out by the streams in the basins of the two study areas is estimated by the hypsometric analysis, expressed in terms of hypsometric integral. Constructed hypsometric curves based on hypsometric integral are divided into three types of curves: concave, convex and S-shaped curves, depending on the shape of the curve. The value of hypsometric integral varies from 0.12 to 0.51 in the case of NE India. Out of these values, between 0.24 and 0.35 show convex hypsometric curves, whereas 0.12–0.24 values show concave curves. The S-shaped curve is noted for the values between 0.41 and

**Table 2** Defined basin categories based on form factor and basin characteristics

Category	Form factor value	Basin characteristics
I	<0.30	Elongated, gentle slope
II	0.30–0.50	Less elongated, gentle slope
III	>0.50	Short elongation, steep slope



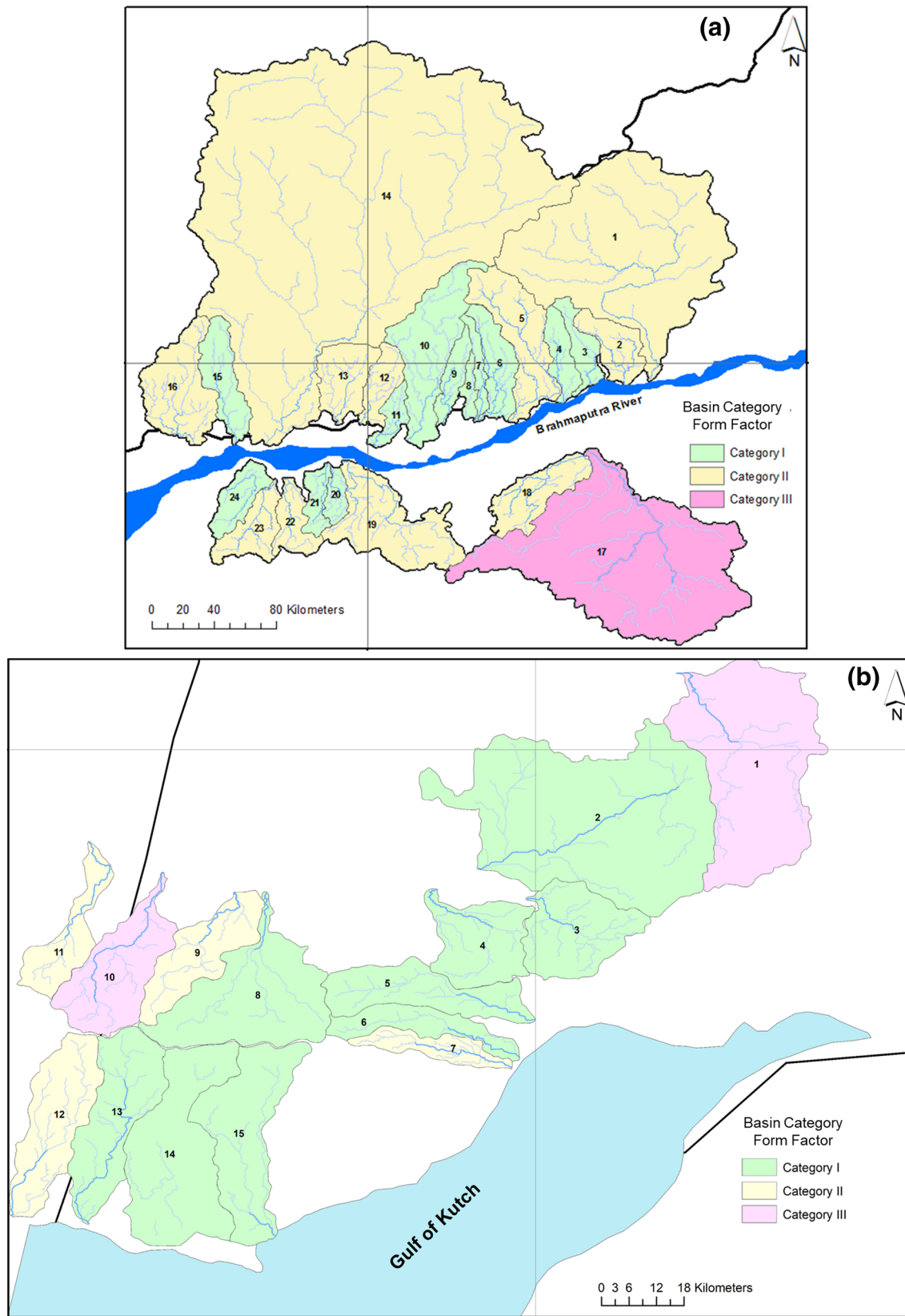
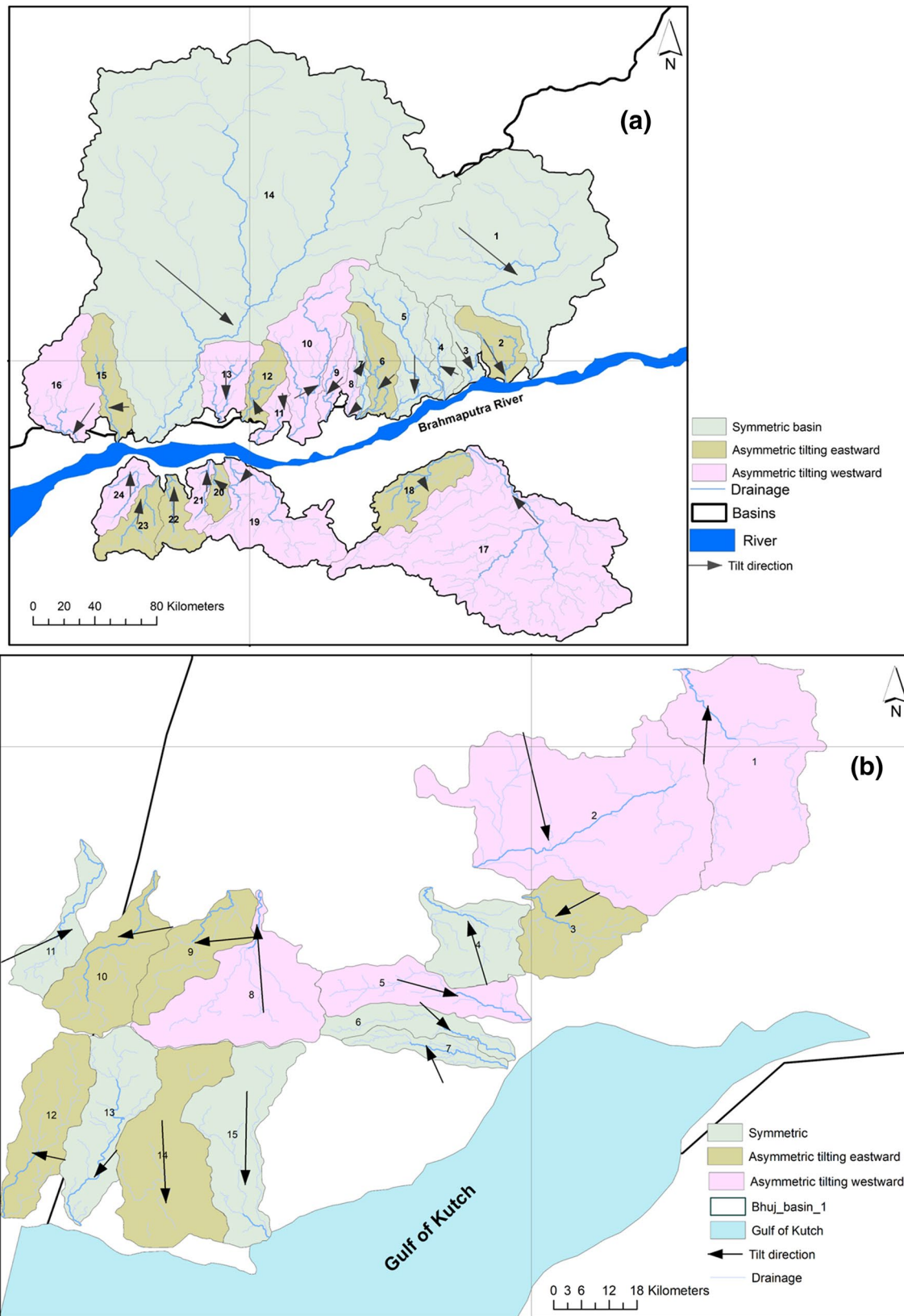


Fig. 3 Categorization of the basins based on form factor in a NE India and b Bhuj region



**Fig. 4** Asymmetry factor distribution with the direction in the spatial map with main basin drainage **a** NE India and **b** Bhuj region

0.46 (Fig. 5a). For the Bhuj region, hypsometric integral values vary from 0.16 to 0.38. The value of HI for the convex curve is 0.25–0.28, concave curves HI is 0.16–0.23 and for S-shaped curves, the HI value is 0.32–0.38 (Fig. 5b).

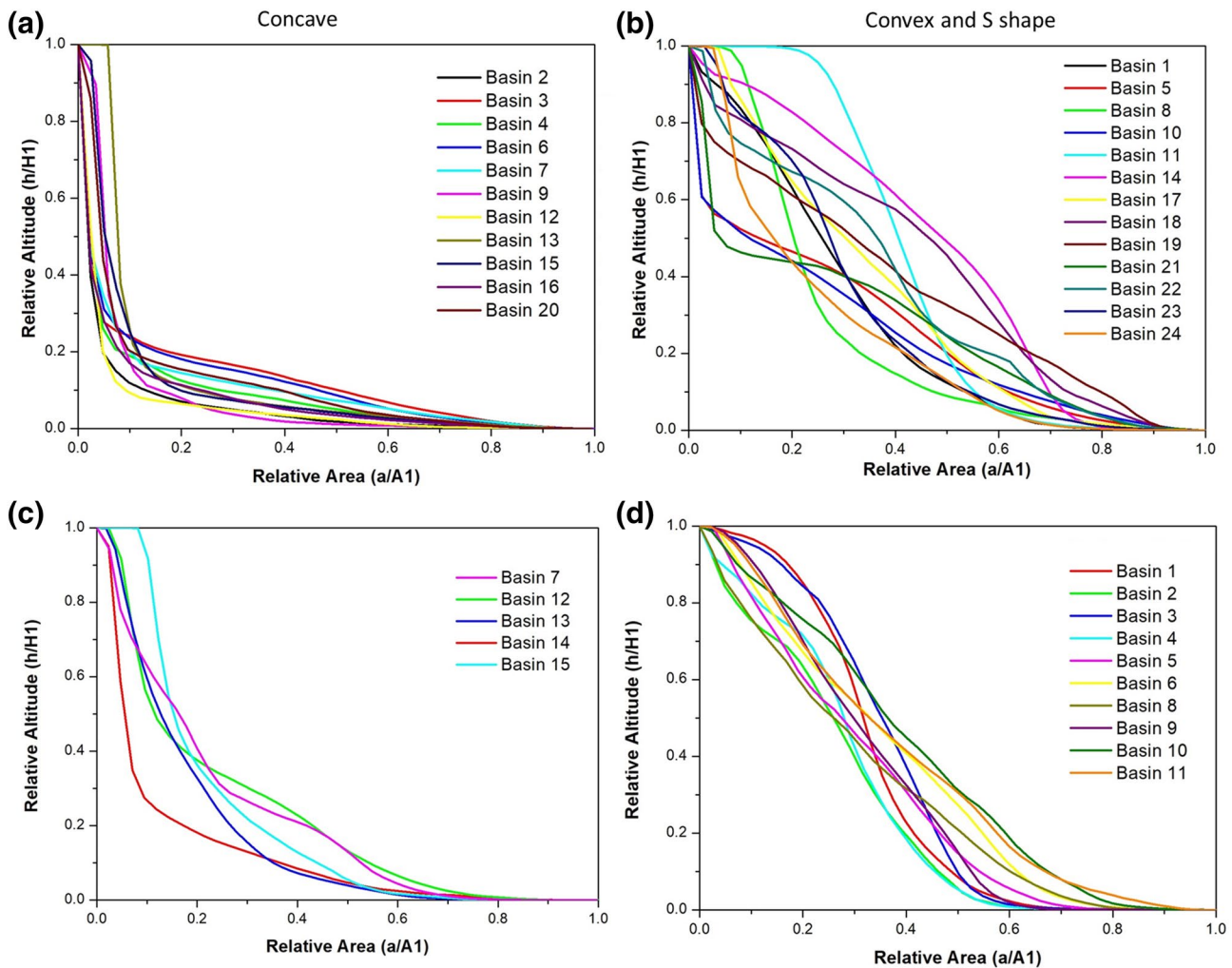
Hypsometric integral explains Youthful stage or Mature stage or Old stage of evolution of the topography in the study regions. The lesser the value of the hypsometric integral, the further the dissection of the topography is, and that suggests an advanced stage of morphologic evolution. At the same time, if the value is more, it means that the dissection of topography is relatively less, and therefore, it is in the initial stage of evolution. Thus, as stated earlier, the drainage basin stage from both the areas based on HI has been classified according to Table 3. It is observed that HI value in NE India varies between 0.16 and 0.50 for the basins north of Brahmaputra River, while for those south of Brahmaputra River, it varies from 0.12 to 0.41. Accordingly, out of the 24 basins from the area, 15 basins represent the Old stage,

**Table 3** Basin stage of the watersheds in NE India and Bhuj region based on hypsometric integral (HI) values

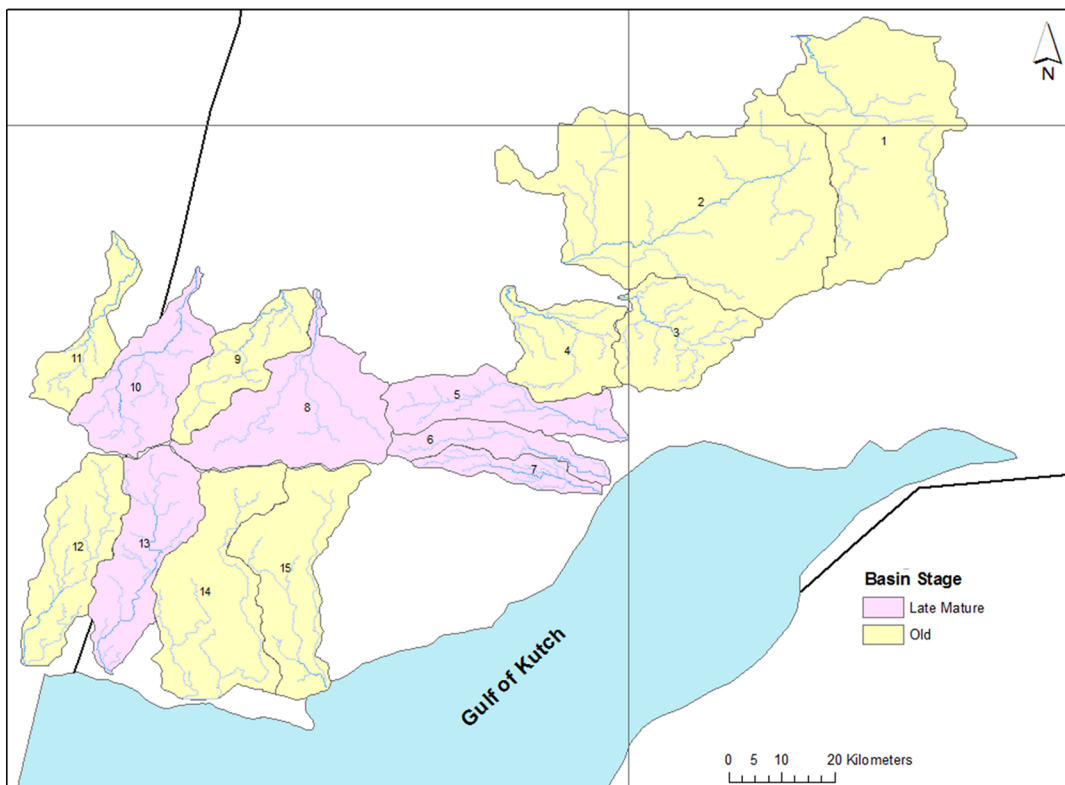
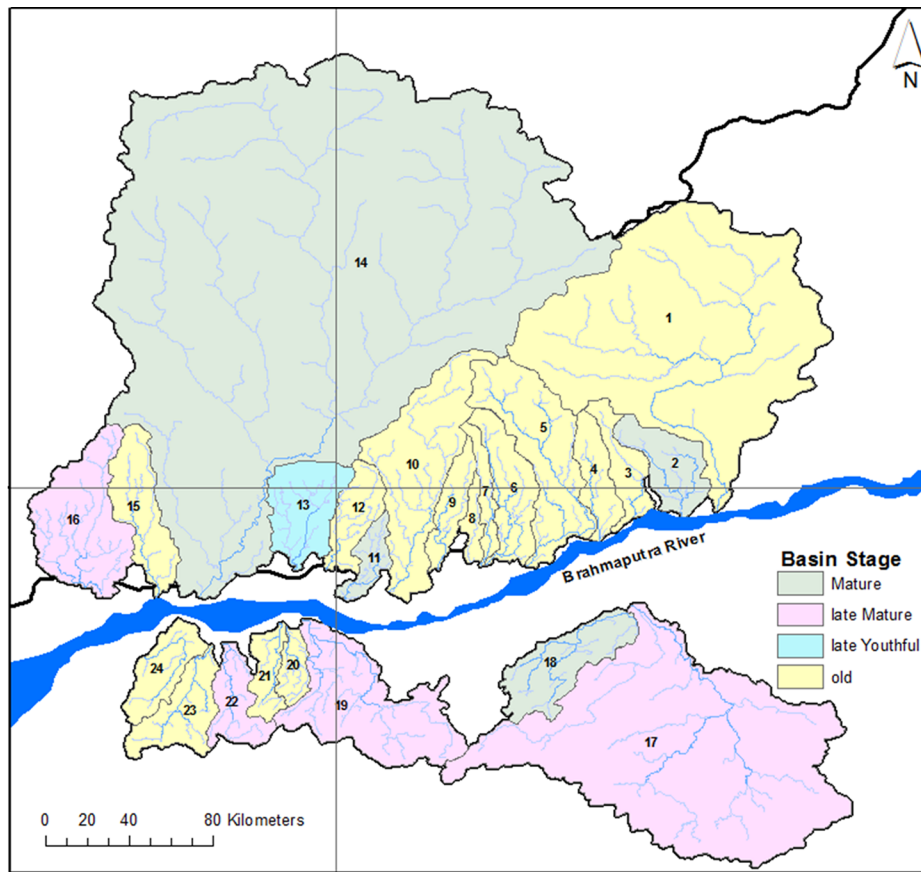
HI value	Stage	NE India	Bhuj region
0.6–1	Youthful	–	–
0.5–0.6	Late Youthful	1	–
0.4–0.5	Mature	4	–
0.3–0.4	Late Mature	4	6
<0.3	Old	15	9

4 basins indicate the Late Mature stage and 4 basins are of the Mature stage, while only 1 basin is characterized by late Youthful stage. It reveals relatively higher erosion in the upper part of the Brahmaputra River than the lower southern part of the Brahmaputra River.

Out of the 15 basins in the Bhuj region, only basin 10 is characterized by a highest HI value of 0.38, representing



**Fig. 5** Hypsometric curves of each basin, a, c are of a concave shape and b, d are of convex and S shape for Northeast India and Bhuj region, respectively





◀**Fig. 6** Basin stage based on hypsometric integral in NE India and Bhuj region. Evolution stage of the landscape: Youthful stage, characterized by deep incision and rugged relief; Mature stage, where various geomorphic processes operate in near equilibrium; Old stage, distinguished by a landscape that reached near base level with very subdued relief

the Late Mature stage. The remaining nine basins are characterized by HI values ranging from 0.16 to 0.29, indicating Old stage and six basins indicate Late Mature stage. From this classification, it is evident that the drainage development and morphologic evolution of both areas are rather in advance stage. Though NE India constitutes a part of the Himalayan orogenic province, out of the 24 basins that have been outlined, 23 basins have reached Mature stage (Fig. 6a), of which 15 basins are in Old stage of evolution, whereas in case of the Bhuj region, 15 basins that have been outlined, have practically reached Late Mature and Old stage (Fig. 6b). Geomorphic indices were calculated and the seismic activity information of the two regions revealed that most of the tectonic activity is associated with the basins of Mature, Late Mature and Old categories.

### Impact of tectonic activity on the river network disruption

The continuous seismic activities in both regions have diverse impacts on river network distribution and distortion. From the study results, it is evident that irrespective of the number of seismic events or high magnitude of earthquakes, most of the basins of both regions are of Late Mature and Old basin stage. A number of seismic events over the years in NE India compared to the Bhuj region have triggered to develop several basin stages also under Mature and Late Youthful stage categories. From the study results of asymmetry factor and form factor, it was evident that the drainage basin disruption tends to be slow in the basins of lower reaches and foothills of Himalayan basins and Bhuj region basins, which agree with the results of Yang et al. (2015). However, even though we have discovered several factors that influence the river network distortion, it is still uncertain how the seismic events or high-magnitude earthquakes impact the basin drainage (Mahmood and Gloaguen 2012).

Earthquakes directly connected to different activities including landslide movement and sediment dynamics (Roback et al. 2018) can also impact the river channel mobility. Similar patterns of the river channel evolution and bed mobility identified by Hsu and Hsu (2009) in Taiwan were induced by a high-magnitude earthquake. The current study will benefit the local policy makers by helping them to understand the geomorphic signatures in these active tectonic regions. The current research also helps to understand river drainage distortion, which can help local decision makers to

prevent flood-induced losses. Use of more high-resolution DEM datasets for the analysis can help increase the accuracy of river basin drainage delineation, channel evolution and river bed mobility (Andreani et al. 2014). Even though the study results are effective in basin planning, for a more clear understanding of earthquake impacts, future research should focus on temporal distribution and changes in river basin drainage network with the influence of different levels of seismic events.

### Conclusions

Two study areas, NE India and Bhuj region, represent different seismotectonic provinces. The drainage network of these intensive seismic activity regions has been outlined, and various geomorphic parameters/geomorphological characteristics are studied and analyzed with the help of remote sensing data. The investigated geomorphic parameters revealed the similarity in geomorphic straits and geomorphic evolution within the two regions. Morphotectonic analysis indicates that the development of dendritic drainage pattern from both the areas and suggests uniform lithological characteristics. Both the study regions are characterized by gentle slopes and low relief from the relation between stream order and respective stream length and form factor calculations, which also support the same observed patterns in the drainage basins. On the other hand, the asymmetry factor indicated tilting of most of the basins in both study regions due to morpho-dynamic activities. Constructed hypsometric curves to examine the extent of stream dissection reveal that both the study regions are attaining Late Mature and Old stages of terrain development. The river basin drainage network gradually evolved over the years in both the study areas depending on the number and intensity of seismic events occurred. In conclusion, geomorphologically both the study areas of different seismotectonic provinces are progressively moving towards the stage of peneplanation. The study results provide valuable insights and geomorphic characteristics of the drainage basin spatial patterns, and we suggest that future studies should focus on the temporal evolution of the drainage network with the impacts of seismic activity.

**Acknowledgements** This research work is carried out with the support of the Head of the Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, Pune, Maharashtra, India. Special thanks to Space Application Center, Ahmadabad, India for the funding and encouragement.

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