Landscape variables in the Indian (Peninsular) catchments: insights into hydro-geomorphic evolution

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Abstract:

The river systems in peninsular India are remained unexplored in terms of hydro-geomorphic evolution, though a few works are carried out in order to understand the tectonic and structural evolution with paleoclimate. Morphometric analysis at catchment scale delivers insights into the dynamics, erosion capacity, probability of flood occurrence, lithological and structural control, and genetic response to the tectonics. The present study aimed to characterize the hydro-geomorphic evolution of 12 major catchments in Peninsular India via morphometric analysis. A total 25 morphometric parameters were computed and several statistical analyses performed in establishing the inter-correlation and making classification of Indian rivers. The results indicated that most of the rivers in peninsular India are 7th to 9th order catchments. A high variability of the rainfall was observed in these rivers where the northern catchments experience higher amount of precipitation contrasting to the southern basins. Almost all the basins showed a moderate relief ratio, hypsometric integral, ruggedness etc. Cauvery, Baitarni, and Brahmani showed exceptionally steeper gradient, high relief ratio, LS factor, and ruggedness index which may indicate higher erosion potential. A positive association between erosion rate and hypsometric integral was observed. All these rivers were classified in three categories based on cluster analysis where the medium and large sized catchments formed different groups. Despite of the extensive data and statistical analysis, the outcomes of this study are highly general due to large scale variation in lithology and climate. In foreseeable works dealing with such morphometric variables, a higher resolution sub-catchment scale analysis would be required for a better description of the hydro-geomorphic response of these large catchments in peninsular India.

Keywords: Morphometric analysis; Erosion rate; Cluster analysis; Hypsometric integral; GIS; India

1. Background:

The quantitative methods in modern fluvial geomorphology emerged post-war time period in the United States and Great Britain (Gregory and Walling 1973; Gardiner 1975) is also widely applied in Australia, Canada, India and many other countries (Horton 1945; Gregory 1976; Gardiner and Park 1978; Kale and Rajaguru 1986). According to Chorley (1969), fluvial processes and forms are of utmost significance in virtually all landscapes. Morphometry is an essential component of contemporary geomorphology (Charlier 1968; King 1971; Mark 1975) that manifest a significant comprehension of hydro-geomorphic evolution of a catchment. The development of fluvial morphometric study has a long history wherein numerous assorted and apparently disparate strands of enquire have been woven together to form what is currently a reasonably unified and coherent field (Gardiner and Park 1978).

The early developments of drainage basin morphometry were led by hydrologists. Gravelius (1914) had proposed a methodology of drainage ordering. Later, Horton (1924) took those ideas and analyzed the basin physiography to predict the surface runoff. Horton (1926) argued that quantitative geomorphic factors can be determined easily without any great difficulties if the topographic maps are available.

Ensuingly, the foundation of basin morphometry was the interest in understanding the process of soil erosion and runoff during 1920s and 1930s (Gardiiner and Park 1978) and it continued to find application in land management (Aronovici 1966; Diaz et al. 1968). However, the foundations of modern morphometric techniques were provided by Horton (1945). Horton's (1945) paper demonstrates how the simple measures can be combined into a method which affords a guide to understand how the catchment functions and evolves. The Hortonian theory of drainage basin analysis motivated the use of quantitative methods in geomorphology and helped to ensure that geomorphology was the key subject during quantitative revolution in geography during 1950s to 1960s (Chorley 1969; Gregory 1976; Gardiner and Park 1978). Chorley (1957), Carlston (1966) studied the climatic influences in basin morphometry. Schumm (1966) demonstrated a large number of basin morphometric variables and their influence on the sediment erosion. Comer and Zimmermann (1969), Dingman (1978) indicated the basin characteristics in relation to the stream flow. Ebisemiju and Ado-Ekiti (1985) revealed how spatial scale interacts with the basin morphometry. Kale and Rajaguru (1986) applied several multivariate statistical methods to prepare morphogenetic map in hilly terrains in India.

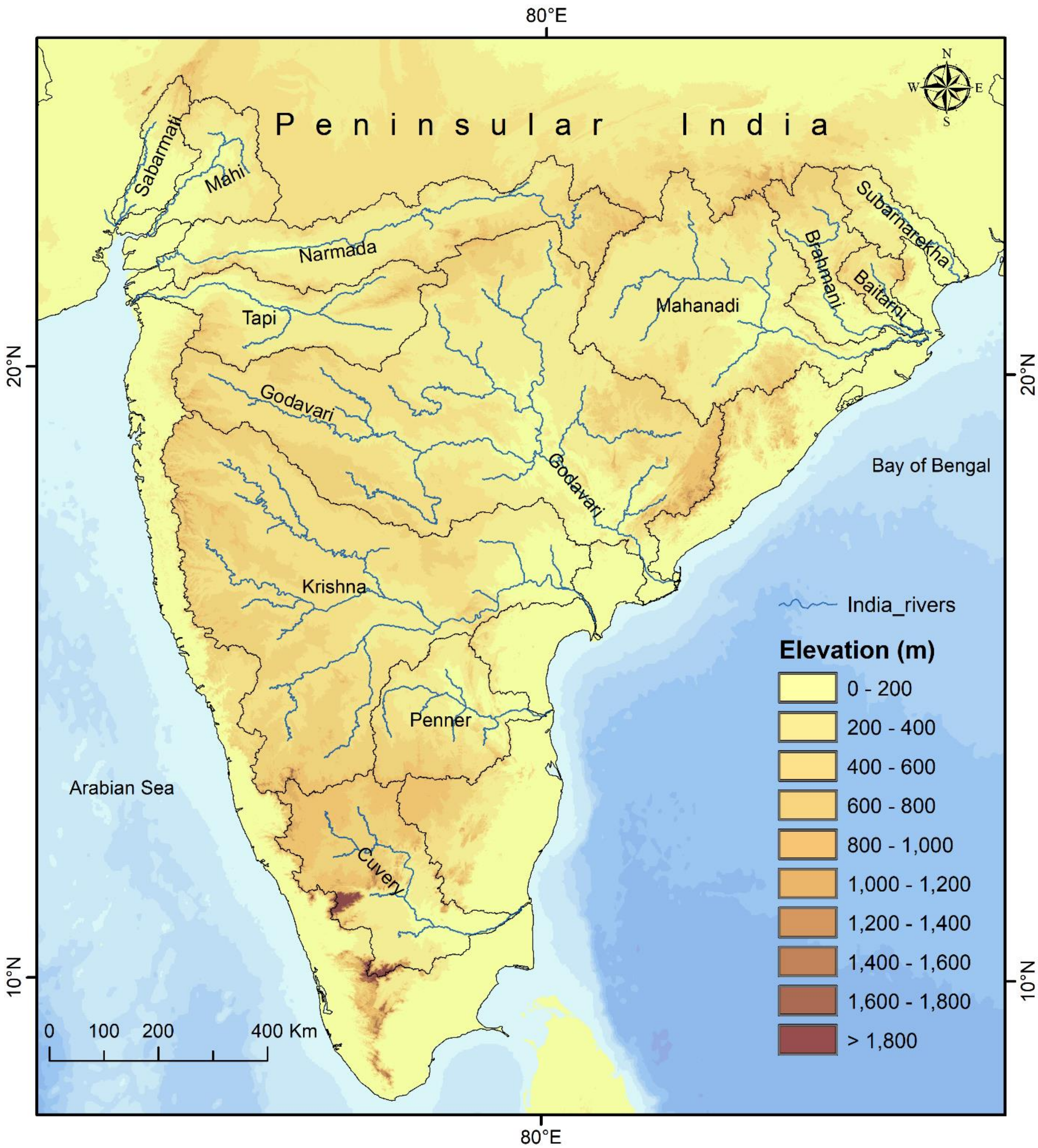


Fig. 1. Major drainage systems in Peninsular India.

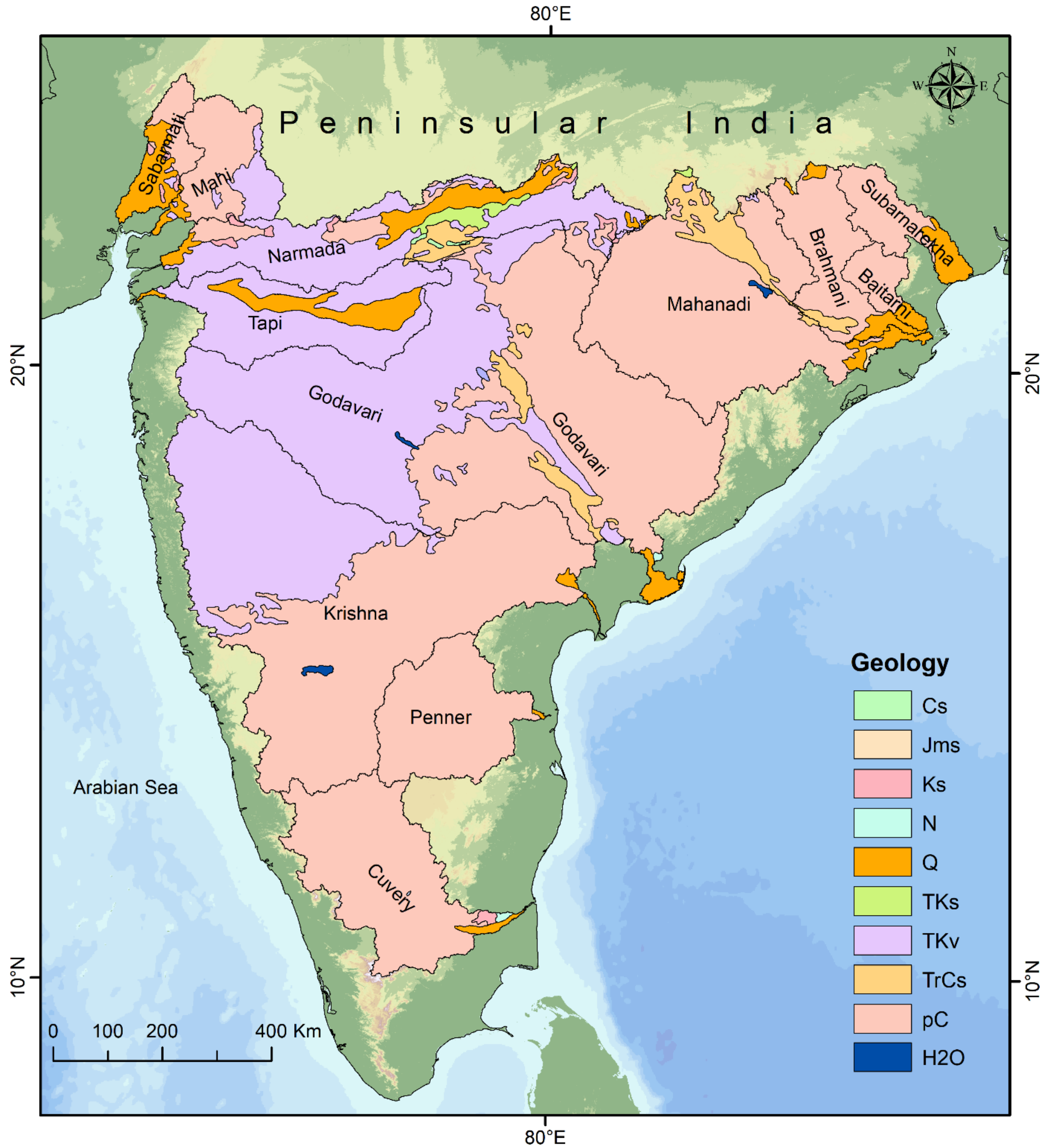
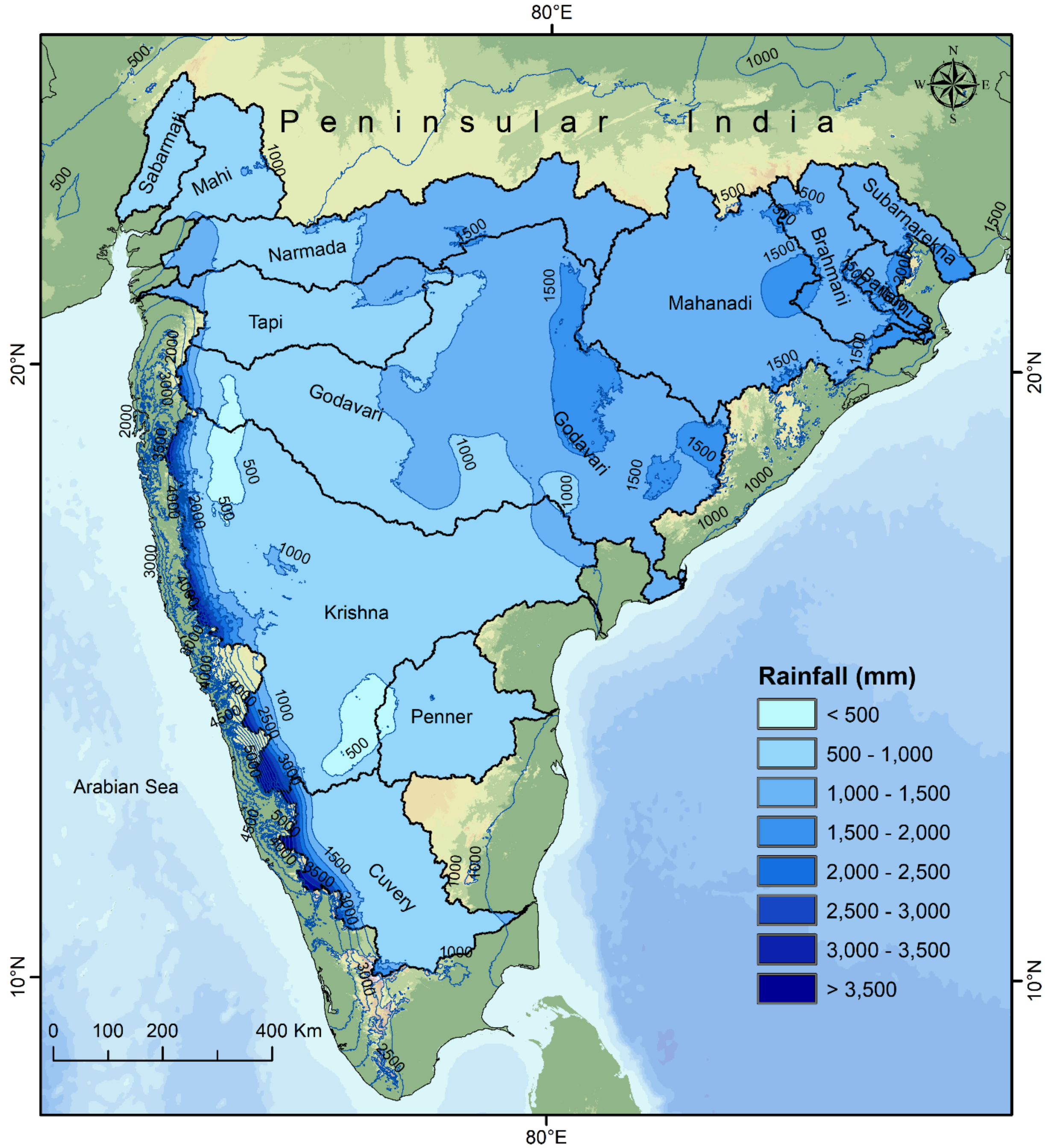


Fig. 2. Simplified geology map of peninsular Indian catchments. (Cs- Carboniferous sedimentary rock; Jms- Jurassic metamorphic and sedimentary rock; Ks- Cretaceous sedimentary rock; N- Neogene sedimentary rock; Q- Quaternary sediment; TKs- Tertiary and Cretaceous sedimentary rocks; TKv- Paleocene Cretaceous extrusive rocks; TrCs- Lower Triassic to Upper Carboniferous sedimentary rock; pC- undivided Precambrian rock; H2O- waterbodies) (Source: USGS, https://catalog.data.gov/dataset/geologic-map-of-south-asia-geo8ag)



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94 *Fig. 3. Rainfall distribution in the major catchments in Peninsular India. (Source: Worldclim).*

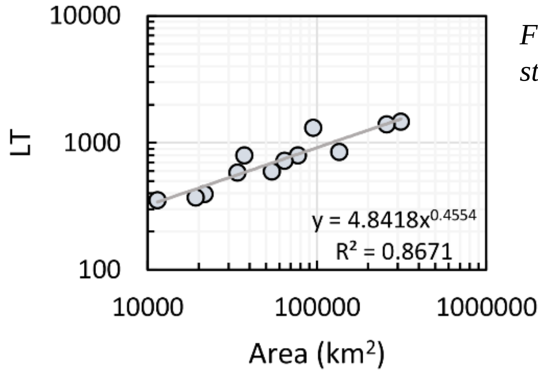

Fig. 4. Association between catchment area and trunk stream length.

In recent decades, with the technological evolution and Geographical Information System (GIS), quantitative geomorphology has become much easier, less tedious and precise (Das 2018). Introduction of high resolution Digital Elevation Models (DEM) made it conceivable to delineate and examine the catchment parameters in programmed manner in GIS environment, which has enabled to explore a large amount of data on landscape variables (Das 2019a, b). Many studies show the characteristic catchment behavior by performing morphometric analysis in GIS environment (Sreedevi et al. 2005; Mesa 2006; Thomas et al. 2011; Magesh and Chandrasekar 2014; Kumar et al. 2015; Pandey and Das 2016; Rawat and Mishra 2016; Dusan et al. 2017; Radwan et al. 2017).

Several factors such as lithology, tectonic, and climate shape the landscape and drainage network (Das and Pardeshi 2018). To understand the dominant role of factors in such geomorphic control, it is essential to establish relationship between the morphometric variables with measured climate, hydrology, and erosion rate data. The geomorphic characteristics of catchments in Peninsular India are not studied extensively, despite a few researches are done at local scale. Therefore, there is a significant amount of knowledge gap about the landscape response to climate and lithological variation. Moreover, there is an unanswered question concerning how the landscape variables are related to the differential erosion rate at peninsular catchments in India. To address such questions, in this study, 25 morphometric parameters were computed for the major 12 large catchments, several statistical analyses were performed for an assurance of the hydro-geomorphic character of catchments in Peninsular India.

2. Study area:

The Peninsular India is a combination of several types of landscapes, characterized by ancient rocks of Proterozoic era, denudational and paleo surfaces, and many tropical large rivers (Fig. 1) (Kale and Vaidyanadhan 2014). The landscapes in Peninsular India are dominated by fluvial processes. This region shows tectonic stability for an extensive period when contrasted with the Himalayan terrain. The peninsular India shows spectacular Western Ghat, which is the origin of almost all the river systems. Deccan Volcanic Province (DVP) a remarkable landscape that formed due to fissure eruption about 65 Ma. ago by Reunion hotspot, while India was sliding towards north (Morgan 1972; Duncan and Pyle 1988). The entire landscape in Peninsular India shows regional complexity in the lithology, geological history and climate.

Geologically, Peninsular India is made up of several Precambrian cratonic blocks bordered by rifts and Proterozoic fold belts (Kale and Vaidyanadhan 2014). Fig 2 shows the simplified geology map of Peninsular India. Major lithology in Peninsular India are Precambrian rock, Cretaceous extrusive volcanic rock (Deccan basalt), lower Triassic to upper Carboniferous sedimentary rocks and Quaternary alluvium. Peninsular India is having a great tectonic history during geological past. The entire landscape, during Mesozoic was a part of Gondwana and located in between Africa and Antarctica. Later, it was broken apart and drifted northward and ultimately collided with the Eurasian plate in early Cenozoic period (Gunnell and Radhakrishna 2001). The major geomorphic landforms in Peninsular India are block mountains, plateau, mesas, cuestas, steep escarpments, valleys (Kale and Vaidyanadhan 2014).

The major east flowing drainage systems in Peninsular India are Subarnarekha, Baitarni, Brahmani, Mahanadi, Godavari, Krishna, Penner and Cauvery draining into the Bay of Bengal. Sabarmati, Mahi, Narmada and Tapi are the major west flowing rivers draining to the Arabian Sea. Among these 12 major rivers, Godavari as the largest catchment and Krishna as 2^{nd} largest catchment, together drain more than 0.5 million km^2 area.

The Peninsular India shows several different major climatic regions as moist sub-humid in the east and along the Western Ghats, large part of the Peninsula indicates dry sub-humid conditions, the central and south-central part show semi-arid condition, and the western section characterized by arid climate (Gadgil and Joshi 1983). A high variation in precipitation can be seen in Fig. 3. The regions along the Western Ghats experience more than 3000 mm rainfall, while the central part shows less than 500 mm rainfall on an annual scale.

3. Data and methodology:

Geographic Information System (GIS) be governed by computer programs are often used for ease analysis of large geo-spatial database for saving, controlling information about the modern sciences of geography, geology and environment (Sabins 2000; Abboud and Nofal 2017; Das 2018). Shuttle Radar Topographic Mission (SRTM) derived Digital Elevation Model (DEM) of 3 arc-second (90 m) data was acquired from CGIAR official portal (http://srtm.csi.cgiar.org/). SRTM data has been preferred in this study because of its higher vertical accuracy (Forkuor and Maathuis 2012; Sun et al. 2003; Das and Pardeshi 2018). The average annual rainfall data were obtained from the worldclim data hub (https://www.worldclim.org/). The generalized lithological map of peninsular India was downloaded from United States Geological Survey official website (Geology map of South Asia). The discharge and sediment load data of major peninsular Indian catchments were collected from Water Resource Information System of India (WRIS-India) and Central Water Commission (CWC 2015) annual data book.

Since Peninsular India comprises a large number of scenes, ArcGIS 10.1 was used to mosaic, removing artificial sinks, delineate the catchments and drainage network. Later the catchment variables were exported to the Microsoft excel for further analysis (see Table 1 for the morphometric indices and their corresponding formulae). Few landscape variables such as slope-length factor, topographic ruggedness index and topographic wetness index were computed directly in SAGA GIS environment.

Cluster analysis has been frequently applied in small catchments for management strategies (Flores et al. 2007; Andrade et al. 2008; Yunus et al. 2014). This method specially designed for grouping the variables of similar features into similar categories (Raux et al. 2011). Bivariate correlation analysis and cluster analysis were performed under XLSTAT (2016, Addinsoft) to discriminate the catchments based on morphometric variables.

4. Results:

The present study presents hydro-geomorphic evolution of the 12 major tropical river basins in Peninsular India by attributing a large number of landscape variables and their interrelationships with the hydro-climatic properties. The results of the landscape variables are described below in detailed manner.

4.1. Morphometric analysis:

4.1.1. Stream order:

In a catchment, drainage network is a set of numerous stream segments which are naturally organized in a systemic manner. According to the stream's position in a catchment, the stream hierarchy is assigned as a sequence number which delivers a significant amount of information about the hydro-geomorphic character of the catchment. Horton (1945) introduced the concept of stream ordering which gives a major emphasis on the internal composition or the overall network geometry. Later, Strahler (1952) modified the Horton's method for simplification by assuming no triple junction condition in a drainage network by involving rules as: (i) The channels in the head stream or source are order 1; (ii) the junction of two same order streams form a subsequent order. Stream order is a useful and simple index that describes the size of catchment.

In this study, Strahler's (1952) method of stream hierarchy was employed to evaluate the stream order in Indian rivers. Godavari and Krishna, being the largest drainage system in Peninsular India, classified as 9^{th} order basins (Table 2). However, the other catchments mostly belong as 7^{th} and 8^{th} order drainage network.

4.1.2. Basin area, perimeter, length:

Table 2 shows the numerical attributes of the basin area and perimeters in the peninsular catchments in India. Godavari and Krishna comprise the maximum basin area and perimeter. Mahanadi also indicate a considerable large catchment area compared to the other catchments.

Schumm (1956) described the basin length as the maximum length measured of the catchment parallel to the principle drainage line. The maximum basin lengths are observed in Godavari, Krishna and Narmada (Table 2).

4.1.3. Length-area relation:

A direct proportionality between two variables i.e. drainage area and stream length against drainage order lead to build the concept of a constant of channel maintenance (Schumm 1956). The concept implies that a minimum drainage area is required for channel initiation, in a given set of environmental conditions. Later, the length-area association of a catchment has been extended by Hack (1957) by establishing an empirical relationship of the length of trunk stream to the basin area. This index provides a significant clarification about the changes in basin length in terms of drainage network evolution.

In the present study, the maximum Lr values are recorded in Godavari (2,774), Krishna (2,472), Mahanadi (1,680), Narmada (1357), Cauvery (1199) and Tapi (1073) (Table 2). Although, the calculations are made using the equation given by Hack (1957), the relationship (see Fig. 4) between area (A) and trunk stream length (LT) in the present study establish a new equation for Peninsular Indian catchment is:

$$L = 4.84A^{0.46}$$

4.1.4. Fitness ratio:

Fitness ratio is a critical measure of topographic fitness which can be calculated by measuring the ratio of trunk channel length to the catchment perimeter (Melton 1957). Baitarni (Rf=0.45) and Mahi (Rf=0.42) show the maximum fitness ratio, which indicate the trunk channels are relatively long compared to the basin perimeter.

4.1.5. Form factor:

Form factor is simply the ratio of the catchment area to square of the catchment area (Horton 1932). The basin length is not necessarily the maximum length, but should be measured from a point on the catchment-line opposite the head of the trunk channel. For a given catchment with a side outlet the length can be less than the average basin width (Horton 1932). Form factor is an index that has been extensively used in connection with the maximum flood-discharge formulas. In general, lower form factor values are an indicative of elongated catchments that experience shorter peak flow for long duration. In case of higher form factor values the catchments may experience a higher peak flow for a small duration. However, according to Horton (1932), this index is only sensitive to the catchments which are long and narrow such as catchments occupying the rift or synclinal valleys, indicate the flood regime. For catchments which are more irregular shape, particularly underlined by permeable soils, this factor does not have any practical values in terms of understanding the hydrologic characteristics.

In the tropical rivers of Peninsular India, Penner (Ff= 0.52), Krishna (Ff= 0.47), Cauvery (Ff= 0.38), and Mahi (Ff= 0.37) show a considerably high form factor (Table 2).

4.1.6. Circularity ratio:

Miller (1953) introduced the circularity ratio as the ratio between the catchment area to the area of the circle having the exact same circumference as the perimeter of the basin. This index is mainly controlled by several natural factors such as the lithology, structure, relief, gradient, precipitation, the coverage of natural vegetation etc. Low, medium and high circularity values generally indicate the young, mature and old phases of the life cycle of the watersheds which may be referred in terms of relief, shape, discharge and soil characteristics.

Almost all the peninsular rivers in India indicate circularity ratio less than 0.3. The highest circularity ratio is observed in case of Penner (Rc= 0.26) and lowest in Narmada (Rc= 0.10).

4.1.7. Elongation ratio:

Elongation ratio is an index that delivers significant information about the catchment shape. The elongation ratio can be expressed as the ratio between the diameter of a circle with the same area as the basin and the maximum length of the basin (Schumm 1956). High elongation ratio values generally indicate more circular shape of catchment.

In Peninsular catchments, Penner (Re= 0.81) shows the most circular shape while Narmada (Re= 0.39) is the most elongated shape (Table 2).

4.1.8. Compactness coefficient:

Gravelius (1914) introduced the compactness of coefficient as the ratio of perimeter of a catchment to the circumference of circular area which is equal to the catchment area. The compactness of coefficient depends on the degree of gradient while it is absolutely independent on the size of catchment.

The maximum compactness of coefficient has been observed in Narmada (Cc= 3.13) while the lowest is recorded in Baitarni (Cc= 2.05).

4.1.9. Relief:

Relief is simply the difference between maximum elevation and minimum elevation of a given catchment. Among 12 major catchments in peninsular India, maximum relief has been recorded in Cauvery (R= 2629) while the lowest has been observed in Mahi (R= 1011).

4.1.10. Relief ratio:

The morphological evolution of the area related to relief is expressed as a relief ratio in the work of Schumm (1956), where he contended that this index is simply the height of the catchment divided by the length. Relief ratio is a reliable factor to compare geomorphic characteristics of catchments within one topographic unit or the areas having dissimilar but homogeneous lithology. Schumm (1956) observed a close correlation between the relief ratio and stream gradient. Relief ratio can be practically used to estimate the sediment loss. A direct relation between relief ratio with the sediment loss has been observed in many areas such as Utah, New Mexico and Arizona (Schumm 1956). In a homogeneous lithological condition, higher relief ratio indicates a higher sediment yield.

The maximum relief ratio has been observed in Baitarni (Rr= 6.15) while Narmada (Rr= 1.48) shows the least relief ratio among other major catchments in peninsular India.

4.1.11. Relative relief ratio:

Relative relief ratio is a modified version of relief ratio, which considers the basin perimeter for the calculation. The interpretation is more or less same as relief ratio as both of these factors are highly correlated.

Similar to the relief ratio, the maximum relative relief ratio has been recorded in Baitarni (Rrr= 152.38) while the lowest is found in Godavari (Rrr= 32.74).

4.1.12. Hypsometric curve and integral:

In fluvial landscape, the hypsometric curves and integrals are widely studied to understand the complex evolution of the topography. Hypsometry is very often computed using the hypsometric curve, the cumulative histogram of elevation within a catchment or a region (Strahler 1952; Brocklehurst and Whipple 2004; Egholm et al. 2009; Das 2018). The hypsometric integral is the area lying below the hypsometric curve. The hypsometric integral is a measure of stage as it expresses the percentage of mass of the catchment remaining above a basal plane of reference

(Strahler 1952; Schumm 1956). The main advantage of hypsometric analysis is that due to its normalization effect, catchments draining different magnitude of areas can easily be compared. Hypsometric curves and integrals can be significantly influenced by the lithological variation, tectonic setting and climatic control on the fluvial erosion. The convex hypsometric curves with high integral values indicate youthful inequilibrium where a dominant fluvial erosion often occurs. The hypsometric curves of the mature catchments show a sigmoid shape. In steady-state equilibrium, after reaching the maturity stage, the curve generally tends to stabilize.

Fig. 5 shows hypsometric curves plotted for all the major catchments in Peninsular India. Almost all the hypsometric curves show a concave up shape. Strong irregularity on the curves are observed in case of Suabrnarekha, Baitarni, and Cauvery catchments. The stare alike curves in Baitarni and Cauvery indicate influence of different base levels on the topographic evolution. Maximum integral values are observed in Baitarni (HI= 0.32), Brahmani (HI= 0.31), and Narmada (HI= 0.31) while Sabarmati (HI= 0.19) shows the lowest integral value (Table 2).

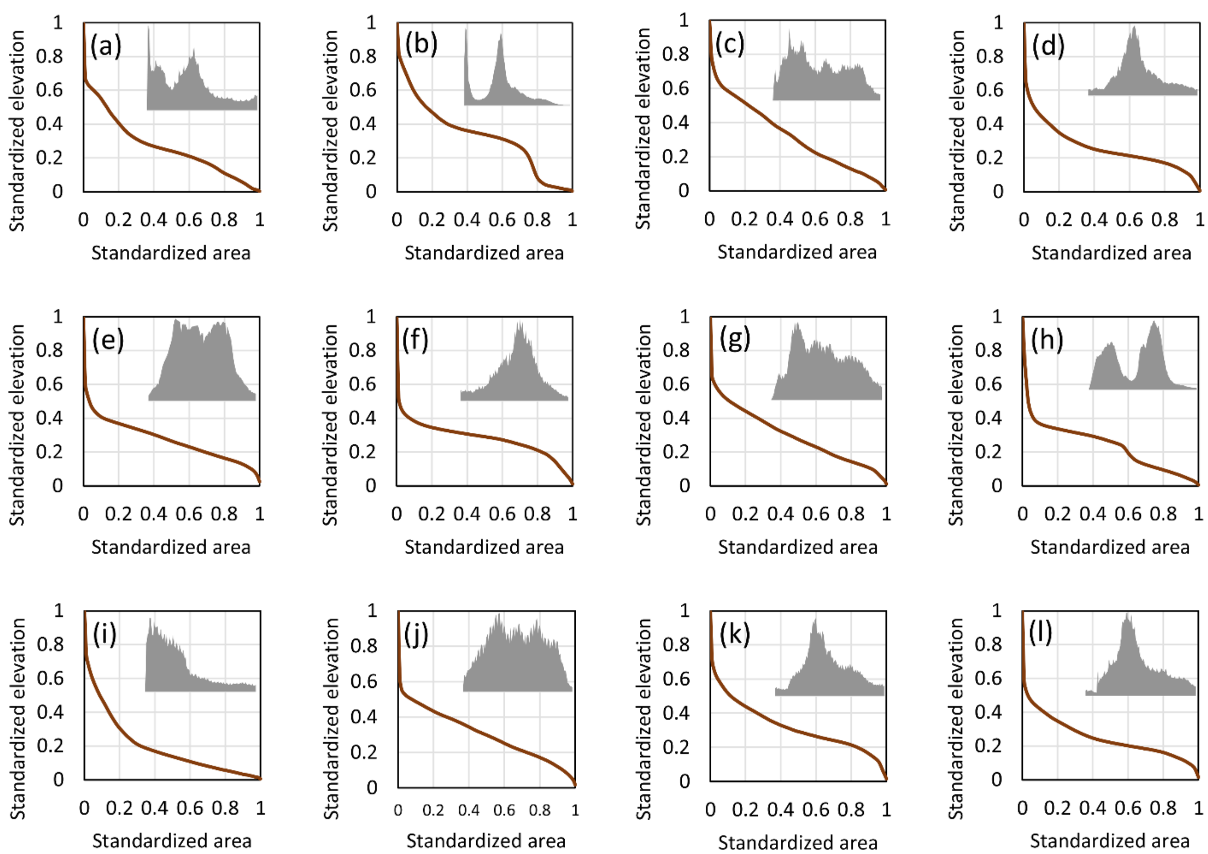

Fig. 5. Hypsometric curves of the major catchments in Peninsular India. The inset graphs indicate the distribution of pixels with respect to elevation.

4.1.13. Relative gradient:

Relative gradient is the ratio between relief and the basin length of a given catchment. Relative gradient of a catchment delivers a critical understanding about the steepness of the basin and therefore potential erosion capacity.

The maximum relative gradient is recorded in Baitarni (Rg= 6.15) basin while the minimum is found at Narmada (Rg= 1.48).

4.1.14. Plan and Profile curvatures:

Plan curvature is perpendicular to the direction of the maximum slope while profile curvature denotes the parallel direction of the maximum slope. A positive plan curvature value indicates the sideward convexity while a positive profile curvature indicates upward concavity of the surface. Recent days, with the advancement of GIS, calculation of plan and profile curvature is very easy and these indices are considered as significant landscape variable due to strong correlation between sediment yield (Zhang et al. 2015; Das 2019a).

Almost all the catchments in peninsular India indicate negative plan and profile curvature values. The values imply that all the catchments are longitudinally convex and sidewardly concave.

4.1.15. Slope-length factor:

Slope-length factor in an important landscape factor which has a great influence on sediment erosion worldwide (Panagos et al. 2015). The S-factor measures the effect of the steepness of slope while the L-factor indicate the impact of slope-length. Slope-length factor is a common variable that has been evaluated extensively to calculate soil erosion in various places around the world (Prasannakumar et al. 2012; Sinha and Joshi 2012; Abdulkareem et al. 2017). Few studies reveal a strong association between the LS-factor and erosion rate. A higher LS-factor generally yield higher amount of sediment if all the environmental conditions are homogeneous.

In peninsular Indian catchments, Cauvery show the maximum average LS-factor (LS= 3.70) while the lowest is found in Godavari (LS= 1.81) (Fig. 6).

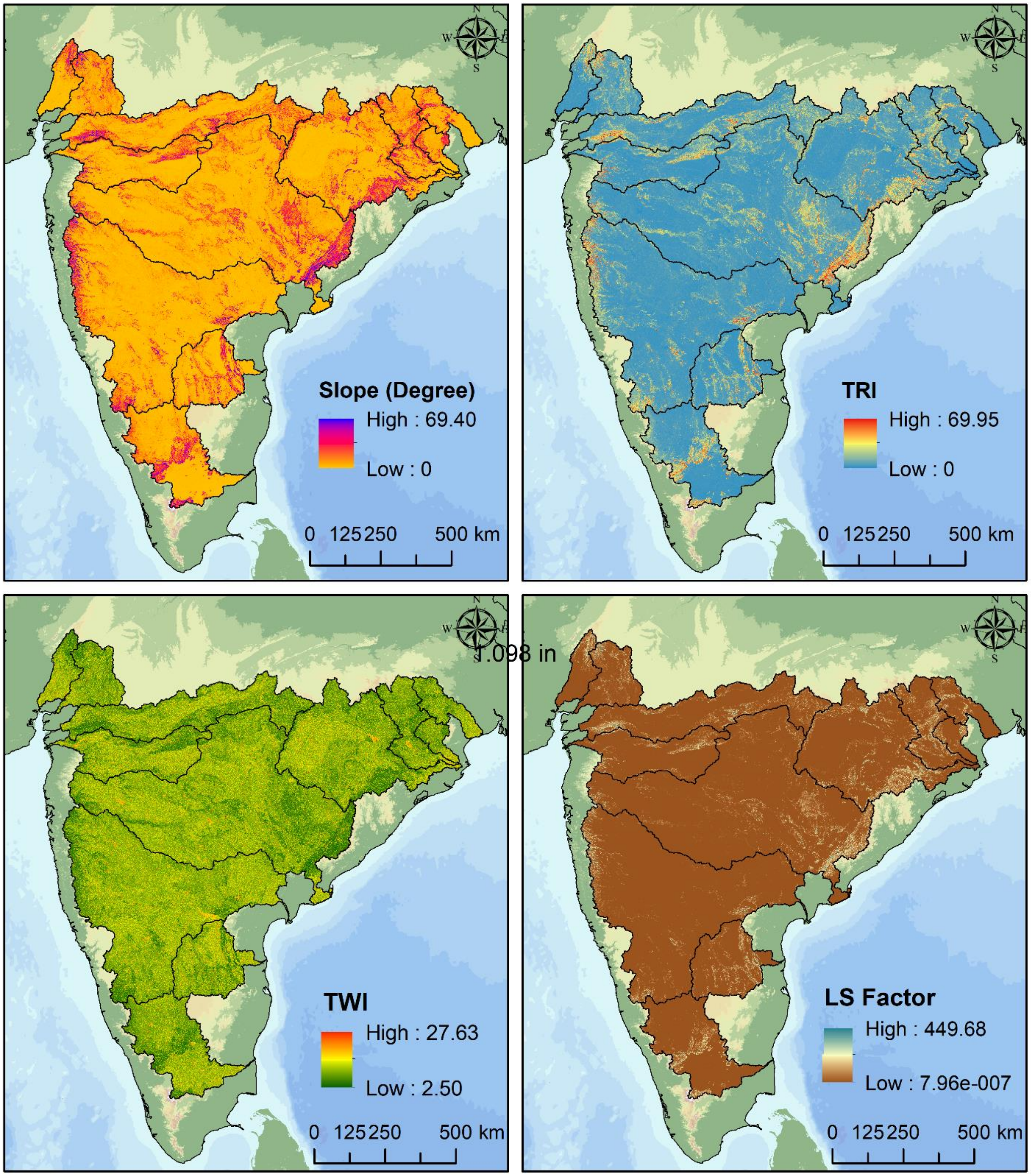

Fig. 6. Maps indicate different topographic parameters which are directly related to catchment hydrologic and erosion characteristics. (a) slope; (b) topographic ruggedness index; (c) topographic wetness index; (d) slope-length factor.

4.1.16. Topographic ruggedness index:

Riley et al. (1999) introduced topographic ruggedness index as the homogeneity in the elevation of a given landscape. Topographic ruggedness index is a good index to understand whether the landscape is smooth flat terrain or rugged. Higher values of this indicate higher rugged topographic condition.

Among the 12 major catchments in peninsular India, Brahmani show the highest ruggedness value (TRI= 5.49) while Krishna shows the lowest ruggedness value (TRI= 2.79) (Fig. 6).

4.1.17. Topographic wetness index:

Topographic wetness index of a catchment represents two types of measurements, are hydrographic positions and the flat lands (Papaioannou et al. 2015; Das 2019a). This factor is a physical representation of areas having higher potential. In general, higher topographic wetness index can be found in the floodplain regions in a catchment (Adam and David 2011).

The maximum average TWI is found in Krishna (TWI= 9.90) while Brahmani (TWI= 8.98) shows the minimum TWI (Fig. 6).

4.2. Bivariate correlation among landscape variables and cluster analysis:

Table 3 presents the mathematical inter-correlation among the 25 landscape variables in peninsular Indian catchments. A strong correlation among the stream order, main stream length, basin area, perimeter, perimeter ratio, basin length is observed in Indian catchments. Geomorphic factors such as cicularity ratio, relative relief, hypsometric integral, slope, relative gradient, curvature, ruggedness index and LS factor are negatively correlated with basin area.

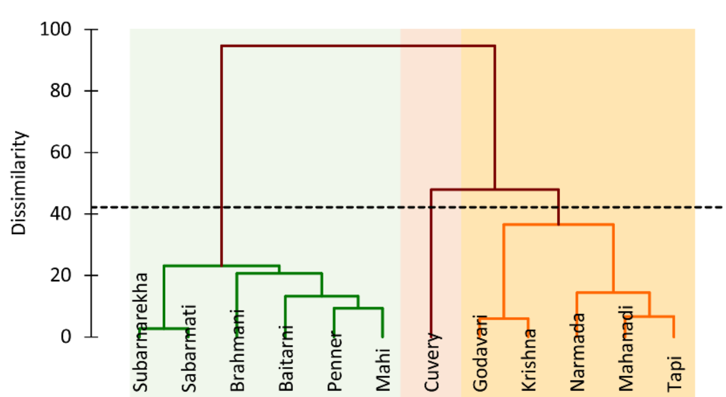

Fig. 7 shows the dendrogram, calculated based on 25 parameters in Indian rivers where the dissimilarity is given in percentage. Total three clusters are observed in the dendrogram where medium sized rivers such as Subarnarekha, Brahmani, Baitarni, Penner, Sabarmati, and Mahi form a group; the second group includes the major large rivers in peninsular India (Godavari, Krishna, Mahanadi, Narmada, and Tapi); Cauvery stands alone in the third group.

5. Discussion:

It is more than a century that the landscape variables of catchments or watersheds are of the major interests to the geoscientists through morphometric analysis to understand the geomorphic and hydrologic characteristics (Schumm 1956; Chorley 1957; Mather and Doornkamp 1970; Raux et al. 2011; Yadav et al. 2014; Abboud and Nofal 2017; Das and Pardeshi 2018; Kabite and Gessesse 2018; Charizopoulos et al. 2019). This paper compares 25 landscape variables in 12 major tropical large rivers in peninsular India to understand the influence of lithology, climate on the hydro-geomorphic variability. Moreover, the impact of these geomorphic factors in the erosion rate in peninsular catchments is assessed. Later on, the Peninsular Indian rivers are grouped based on cluster analysis.

Most of the catchments in peninsular India are classified as 7th to 9th order streams (Table 2). Godavari and Krishna are the largest catchments in Peninsular India. The east flowing rivers in the north (Subarnarekha, Baitarni, and Brahmani) are draining comparatively less area. Except Narmada and Tapi, most of the basins show a circular or semi-circular shape. The southern catchments indicate a higher relief which may indicate higher potential of erosion.

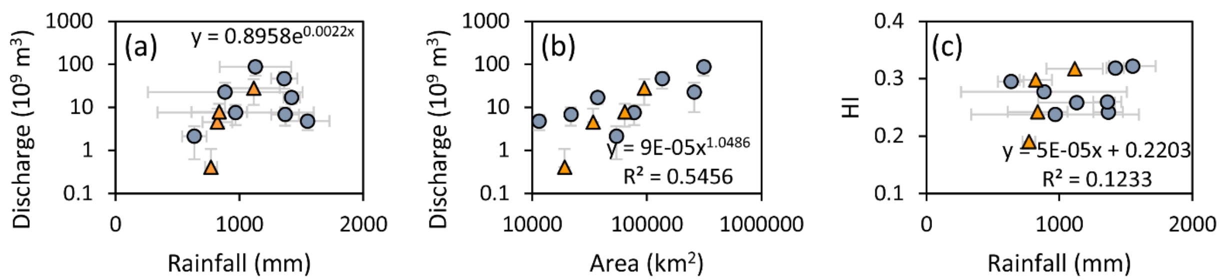

Fig. 8. Relationship among climatic, hydrologic, and topographic parameters. (a) rainfall-discharge relationship; (b) area-discharge relationship; (c) rainfall-hypsometric integral relationship.

The water and sediment discharges are regulated by runoff, which in turn controlled by precipitation. Fig. 8 show the rainfall-discharge relationship in peninsular river. As rainfall is the only source of water in the catchments of peninsular India, a positive relation is found in both east flowing as west flowing rivers. The northern catchments show a higher amount of rainfall and it gradually decreases towards south. Many studies suggest that with an increasing in area, discharge significantly increases (Leopold and Maddock 1953; Leopold et al. 1964; Knighton 1984; Mitchell 2000). The significant association between area and discharge in the present study agrees with the early literature (Fig. 8). In case of variation of discharge in a single catchment as with increasing area, tributaries transport an additional amount of water towards downstream (Das 2018; Das and Pardeshi 2018).

Rainfall has a significant control in the erosion of landscape in rivers where rain is the only source of water. Hypsometric integral is a useful index that delivers a significant amount of information about the catchment erosion by various agents (Sternai et al. 2011) and it has been widely applied to understand the evolution of the landscape (Perez-Pena et al. 2010; Flores-Prieto et al. 2015; Mathew et al. 2016; Baumann et al. 2018). Therefore, a relationship has been established to check if there is any significant association between the precipitation and HI in Indian catchments. It was expected that the catchment with higher rainfall should show a lower HI value. However, a positive significance is observed in case of west flowing rivers, but the east flowing rivers do not indicate any significant association. This is probably due to the heterogeneous lithological variation in Indian catchment. Additionally, most of the Indian catchments show Precambrian bedrock which is hard to erode. Therefore, rainfall creates a minimum significance in the hypsometric integral.

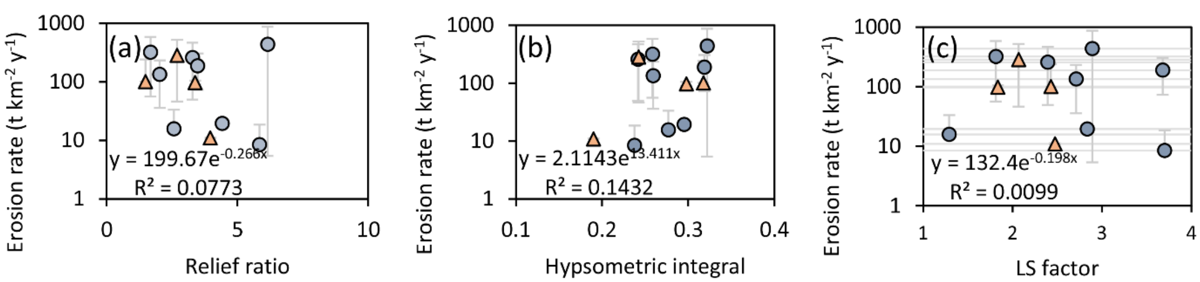

Fig. 9. Bivariate relationship between topographic variables and erosion rates in Peninsular Indian catchments. (a) relief ratio- erosion rate relation; (b) hypsometric integral-erosion rate relation; (c) slope-length factor- erosion rate relation.

Later on, several morphometric parameters are compared with the erosion rate in Indian rivers (Fig. 9). Relief ratio shows a negative association with the sediment yield in Indian catchments. Schumm (1956) mentioned in his paper that "one practical application of the relief ratio is in estimation of sediment loss". Moreover, relief ratio is the only geometric element that is having a relation to the lithology, structure, stage, vegetation and climate (Schumm 1956). The Indian rivers suggest that with increasing relief ratio the sediment yield decrease. The result of this study show absolutely opposite relation which is shown in Schumm's (1956) paper. The main reason is that

Indian catchments are highly heterogeneous, show a significant variation in lithology, climate, natural vegetation etc. It is previously discussed that south Indian catchments yield a very low sediment which is probably due to the lower precipitation and Precambrian bedrock. In contrast, the northern rivers yield higher sediment due to considerable area is made of alluvium and Deccan basalt. Hence, though the relief variation is higher in southern catchments, they yield a significantly low sediment. Thus relief ratio shows a negative association with sediment yield. Similar to this study, the correlation between area, elevation, streamflow, erosion rate, precipitation have already described in earlier studies (Milliman and Syvitski 1992; Einsele and Hinderer 1997).

Hypsometry, the frequency distribution of elevation has been widely applied to resolve the problem of dissimilar erosion rates, tectonics and lithology control in fluvial as well as glacial landscapes (Strahler 1952; Montgomery et al. 2001; Brocklehurst and Whipple 2004; Walcott and Summerfield 2008; Pedersen 2010; Perez-Pena et al. 2009; Das 2018). This index is more complex than it describes. If catchments exhibit a high mean elevation and slope, then this may involve that catchments with smaller area should have a greater erodibility (Raux et al. 2011). In homogeneous lithology and climatic condition, the landscapes which are actively uplifting generally show a higher hypsometric integral values (Perez-Pena et al. 2009; Baumann et al. 2018). The same index may show an opposite behavior in the regions with resistant lithology, where hypsometric integral indicates a higher value, but the region yields less sediment if the amount of precipitation is same. Thus, while making interpretation about hypsometric integral, a careful inspection of lithology, climate and the tectonic history is essential. A strong positive association between hypsometric integral and erosion rate is observed in peninsular Indian catchments. It implies that despite of resistant lithology, climate and other factors make a significant influence on sediment erosion rate. The northern rivers such as Subarnarekha, Baitarni, Brahmani, Mahanadi, and Godavari show a considerably higher sediment yield, which is perhaps because of extensive mineral extraction (this region is known as Indian's mineral hub) and therefore, more production of sediment.

Slope-length factor is considered as one of the most important factors in soil loss (Fistikoglu and Harmancioglu 2002; Dabral et al. 2008; Prasannakumar et al. 2012). This factor is even used as a primary factor to build sediment erosion models using Universal Soil Loss Equation (USLE) or Revised USLE (RUSLE) (Mati et al. 2000; Lu et al. 2004; Kouli et al. 2009; Prasannakumar et al.

2012). Sinha and Joshi (2012) indicate a positive correlation between the LS factor and sediment yield. However, the present study does not show any particular association (Fig. 9). The average LS value considered in this study is not a reliable measure as intra-basin LS values show huge variation.

By giving a focus on the major driving factors of hydro-sedimentary response, this study proposes a network of the peninsular catchments in India. The study shows three clusters based on the statistical analysis of 25 morphometric variables: (i) Subarnarekha, Brahmani, Baitarni, Penner Sabarmati, and Mahi, which drain moderate catchment area and relief; (ii) Godavari, Krishna, Narmada, Mahanadi, Tapi form the second cluster category which show very large catchments with considerably higher relief and; (iii) Cauvery stands alone which is more controlled by relief morphometry and steeper slope.

Although morphometric analysis in local or catchment scale is very common (Sreedevi et al. 2005; Mesa 2006; Thomas et al. 2011; Magesh and Chandrasekar 2014; Kumar et al. 2015; Pandey and Das 2016; Rawat and Mishra 2016; Dusan et al. 2017; Radwan et al. 2017; Das 2018; Das and Pardeshi 2018), the originality of this work lies behind the explanation of influence of the climate, lithology in morphometric variables. Moreover, influence of the variables which are reported as a major driving factors in other studies (Verstraeten and Poesen 2001; Molina et al. 2008; Zhang et al. 2015; Li et al. 2019) are compared in understanding the association with erosion rate in peninsular India. Though the present study establishes an elementary database about the landscape variables and their association with the hydro-geomorphology in Indian (Peninsular) catchments, a further analysis is necessary at catchment scale due to their heterogeneous hydro-climatic behavior.

6. Conclusion:

The surface water and sediment load in natural rivers are regulated by climatic and geomorphological forcing. Assessment of morphometric parameters of a catchment has ability to deliver a significant amount of information about the hydro-geomorphic response with respect to lithology, climate, and tectonic forcing. However, establishing relationship between the morphometric variables and the measured hydrological and sediment data provide a more reliable understanding. In this study, twelve major catchments were considered to understand the hydro-geomorphic evolution through morphometric analysis in Peninsular India. The morphometric data were compared with the rainfall, long-term stream flow and sediment flux data for a critical understanding of the impact of climate and geomorphology on landscape of tropical region. To determine the difference in catchment behavior, cluster analysis was performed. The major conclusions are: (i) most of the catchments in peninsular India fall between 7th to 9th order catchment, which indicate a large drainage capacity and high vulnerability to the flood occurrence; (ii) all the east flowing rivers developed a circular catchments while the west flow rivers are more elongated; (iii) the finding is enhanced by the prevalence of hypsometric integral more than 0.30 in northern catchments, which suggests intense erosion and denudation, supported by the measured sediment erosion rate (a few magnitude higher than the southern catchments); (iv) being the largest catchment in peninsular India, Godavari shows significant variation in precipitation which resemble semi-arid and humid landscapes with a great variation in lithology and therefore, shows a high amount of erosion rate; (v) Cauvery shows the maximum relief, a considerably high slope, steeper gradient, high relief ratio, LS factor and topographic ruggedness index which may lead to lesser infiltration and higher erosion (vi) the peninsular rivers in India are classified into three major categories based on geomorphic characters. The smaller catchments such as Subarnarekha, Brahmani, Baitarni, Penner, Sabarmati and Mahi. The larger catchments i.e. Godavari, Krishna, Narmada, Mahanadi, and Tapi controlled by high relief. Cauvery, the only catchment makes an independent group which is controlled by steeper slope.

Because of the large catchment characteristics of peninsular river in India, the data considered are generalized in nature, therefore, the value of this work is obviously limited. The results obtained in this study are the harmony between empirical measurements between different factors and more theoretical in origin. The generalized lithology, climate and morphometric variables create a more generalized impression about the catchment characteristics which may differ in the actual nature or in a finer scale. What this study significantly provides is a basic understanding of the hydro-geomorphic nature of lesser known tropical rivers in peninsular India. Thus, a significant amount of further work, maybe at a finer scale is required to improve the knowledge and intra-basic geomorphic variabilities in such catchments.

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Conflict of interest:

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