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Clustering stream profiles to understand the geomorphological features and evolution of the Yangtze River by using DEMs

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Abstract: Stream morphology is an important indicator for revealing the geomorphological features and evolution of the Yangtze River. Existing studies on the morphology of the Yangtze River focus on planar features. However, the vertical features are also important. Vertical features mainly control the flow ability and erosion intensity. Furthermore, traditional studies often focus on a few stream profiles in the Yangtze River. However, stream profiles are linked together by runoff nodes, thus affecting the geomorphological evolution of the Yangtze River naturally. In this study, a clustering method of stream profiles in the Yangtze River is proposed by plotting all profiles together. Then, a stream evolution index is used to investigate the geomorphological features of the stream profile clusters to reveal the evolution of the Yangtze River. Based on the stream profile clusters, the erosion base of the Yangtze River generally changes from steep to gentle from the upper reaches to the lower reaches, and the evolution degree of the stream changes from low to high. The asymmetric distribution of knickpoints in the Hanshui River Basin supports the view that the boundary of the eastward growth of the Tibetan Plateau has reached the vicinity of the Daba Mountains.

Keywords: stream profile clusters; Yangtze River; geomorphological feature; stream evolution; digital elevation model

1 Introduction

The Yangtze River, which has a stream length of 6300 km and a drainage area of 1.8 million km^2, is the longest river in Asia and the third longest river in the world (Milliman and Meade,

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1983). This river originates from the Tanggula Mountains on the Tibetan Plateau and flows to the Pacific Ocean. During the Quaternary period, internal and external Earth surface processes related to the Yangtze River caused a rapid change in fluvial processes, shaped the different landform morphologies from the upper reaches to the lower reaches, and affected the redistribution of the river's surface material and energy (Xiang *et al*., 2007). The Yangtze River has also experienced a complex geological tectonic evolution, that crosses different geomorphological units (i.e., Tibetan Plateau, Hengduan Mountains, Yunnan-Guizhou Plateau, Sichuan Basin, and the Middle and Lower Reaches of the Yangtze River Plain). These different geomorphological units further restrict the evolution and development of the landscape and the ecosystem (Jiang *et al*., 2018; Shu, 2012; Dai *et al*., 2019; Notteboom *et al*., 2020). Thus, an extensive analysis of the geomorphological features of the Yangtze River is important for the in-depth understanding of its fluvial process from the upper reaches to the lower reaches and its formation process from a macro-topographical perspective (Lv *et al*., 2017; Wang *et al*., 2019a; Li *et al*., 2020a; Rana and Suryanarayana, 2020; Xiong *et al*., 2021).

The geomorphological features and evolutionary mechanisms of the Yangtze River have attracted considerable attention for a long time (Yang *et al*., 2007; Zhang *et al*., 2007; Lin *et al*., 2017; Li *et al*., 2018; Deng *et al*., 2019). The provenance of minerals, along with their chronological features, is one of the popularly used methods to investigate the geomorphological features and evolutionary mechanisms of the Yangtze River. To explain the idea of the provenance of minerals as a tracer, minerals are formed under a certain geological background with certain chronological features, which can be transported from upper to lower reaches. Many scholars have tried to use different minerals to investigate the geomorphological features and evolution mechanisms of the Yangtze River (Li *et al*., 2011; Yue *et al*., 2018; Wang *et al*., 2019b). Li *et al*. (2001) collected quartz samples and measured their ages via ESR and paleomagnetic analysis in the Three Gorges area of the Yangtze River. On this basis, they discussed the geomorphological evolutionary process and formation time of the Three Gorges area. However, provenance tracer methods are greatly limited by the shortage of mineral samples, and these samples are often limited to certain reaches (Ambili and Narayana, 2014; Anton *et al*., 2014). These research ideas have focused on the geomorphological evolution of the Yangtze River from the perspective of time. Moreover, the entire spatial variation in the geomorphological features and evolution mechanisms in the Yangtze River is difficult to describe by using only a few samples.

From a geomorphological perspective, the production of large-scale geographical data makes it possible to analyze the macroscopic geomorphological features of the Yangtze River (Baker *et al*., 2015; Deng *et al*., 2015; Frankl *et al*., 2015; Zhu *et al*., 2018; Gu *et al*., 2020). With the development of earth observation technology and geographical information science, remote sensing images and digital elevation model (DEM) data have been widely used to express geomorphological features and further reveal the geomorphological evolution of the Yangtze River. First, the horizontal shape of the Yangtze River can be accurately delineated from remote sensing data. Accordingly, many scholars have begun to use high-precision remote sensing images or DEM data to extract stream locations. With stream locations, the horizontal shape of the stream can be quantitatively expressed by using certain stream shape indexes, such as stream curvature, length, and density (Li *et al*., 2020b, Zhang *et al*., 2019). For instance, braided streams occur in nested basins in the source region of the

Yangtze River (Li *et al.*, 2020b). The horizontal shape of the stream was also investigated by using the entropy method to study the morphological evolution of the Yangtze River Estuary under human disturbance (Zhang *et al.*, 2019).

Horizontal shape studies have succeeded in demonstrating the basic shape and geomorphological features of the Yangtze River. However, vertical features of stream profiles should also be an important aspect of streams in addition to the horizontal shape of the Yangtze River. Geomorphological evolution should be described from the perspective of stream profiles because the vertical features mainly control flow ability and erosion intensity during fluvial processes (Li *et al.*, 2019). Stream profiles have become a popular method to study the fluvial geomorphology of different rivers (Alain, 1998; Zimmermann and Church, 2001; Zimmermann *et al.*, 2008; Martins *et al.*, 2017; Sonam and Jain, 2018; Yu *et al.*, 2020). Harmar and Clifford (2007) used the profile of main stream to study the geology, tectonic setting, and geomorphological features of a basin. Lin and Oguchi (2009) investigated the influence of stream and transverse profiles on the topography of an entire complex basin. However, these stream profile studies focused on a single main stream or a few streams in a basin. Considering that stream profiles have large differences, all geomorphological characteristics of the entire basin cannot be fully described by a single stream or a few streams.

Many streams exist in a basin and form a specific stream network. This stream network transports the matter and energy of the basin to the outlet in a 3D space. With the linkage of runoff nodes, each stream could be connected to other streams and even highly related to other streams due to an accumulation process. From this perspective, all stream profiles should be clustered together to comprehensively investigate the geomorphological features and evolution mechanisms of a river basin. In these stream profile clusters, all stream features (including the different hierarchies of streams, stream heads, runoff nodes, knickpoints, and outlets) with their certain geomorphological characteristics and formation mechanisms can be considered. Water resources in the Yangtze River System are sufficient. Apart from the main stream of the Yangtze River, the tributaries contribute to shaping the geomorphological features and revealing the evolution process in the entire basin. When analyzing the stream profile of the Yangtze River, all stream profiles should be regarded as an indivisible whole to comprehensively explore the geomorphological features and evolutionary process of the area.

In this study, the clustering method of stream profiles is first proposed to describe the spatial heterogeneity of stream evolution in the multilevel basins of the Yangtze River. In addition, the clustering method focuses on the group geomorphological characteristics of all streams, and such characteristics differ from those of a single or few profiles investigated in previous studies (Harmar and Clifford, 2007; Zimmermann *et al.*, 2008; Lin and Oguchi, 2009; Martins *et al.*, 2017; Sonam and Jain, 2018). This difference occurs because the group characteristics of all streams can more comprehensively describe the formation mechanism of the basin topography. Moreover, these characteristics are not well represented by traditional methods. However, these group characteristics are important indicators for understanding the geomorphological features and evolutionary mechanisms of the Yangtze River. On the basis of the clustering method, investigating the frequency of structural uplift and identifying corresponding geomorphological features, such as planation surfaces, can help reveal the formation mechanism of the basin topography. In addition, the geomorphological characteristics of stream profile clusters are closely related to the degree of stream evolution. Thus, on the basis of the stream profile clusters, the stream evolution index is used to quantitatively describe the spatial distribution of the stream evolution degree in the Yangtze River Basin. Finally, parameters, such as precipitation, landform type, and watershed level, are introduced to analyze the coupling relationship between the evolution of the streams in the Yangtze River Basin and these factors. This study aims to understand the evolutionary mechanism of the Yangtze River from the perspective of group geomorphological characteristics, which can be found by clustering all stream profiles.

2 Study area and data

The Yangtze River originates from the Tibetan Plateau at an altitude of more than 5000 m. This river winds and twists, and it reaches the sea entrance approximately 6300 km away and flows into the Pacific Ocean (Chen *et al*., 2001a; Zheng *et al*., 2017). The Yangtze River Basin can be divided into three parts according to differences in geological conditions, climatic conditions, and geomorphological types (Figure 1). These parts are the upper, middle, and lower reaches. The upper reaches extend from the source to Yichang city, with a length of approximately 4504 km (Yang *et al*., 2007). The middle reaches are found between Yichang city and Hukou county in Jiujiang city, with a length of approximately 955 km. This part is the highly flood-prone area of the Yangtze River (Lai *et al*., 2017; Wang *et al*., 2020). The lower reaches cover the Hukou county to the Yangtze River Estuary, with a total length of 938 km (Chen *et al*., 2001b; Chen *et al*., 2000).

The Yangtze River Basin has various geomorphological types. From the source to the estuary of the stream, the entire terrain is high in the west and low in the east, thereby forming three large terrain gradients. The first terrain gradient is composed of southern Qinghai,

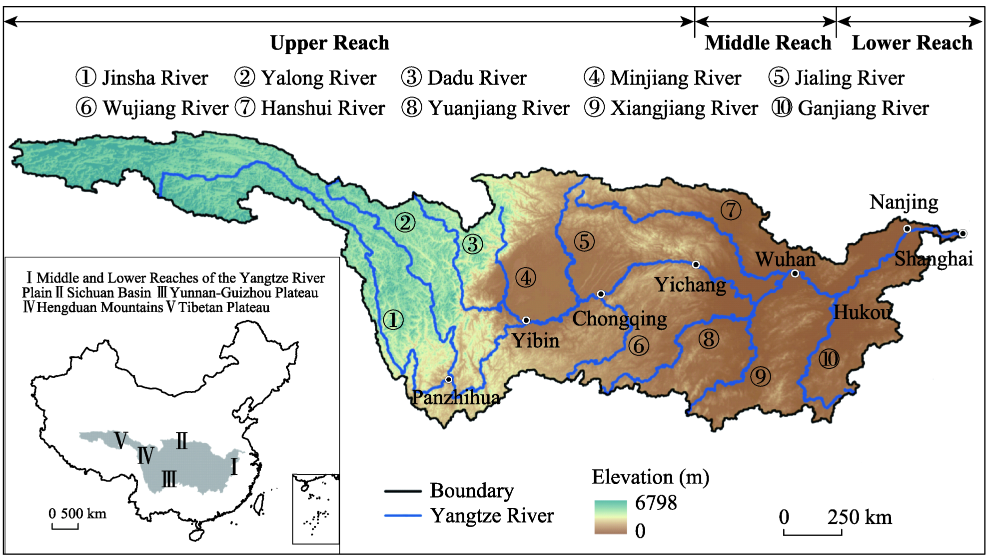

Figure 1 The Yangtze River Basin and its stream network

western Sichuan, and Hengduan Mountain region, with elevations of 1296–4976 m. The second terrain gradient consists of the Yunnan-Guizhou Plateau, Qinling-Daba Mountains, and Sichuan Basin, with elevations of 277–3689 m. The third terrain gradient is composed of the Huaiyang Mountains, Jiangnan Hills, and the Middle and Lower Reaches of the Yangtze River Plain, with elevations of less than 1374 m (He *et al*., 2013).

The Yangtze River Basin is mainly in the typical subtropical climate zone, and it has a plateau–mountain climate at its source. This basin is dominated by the monsoon system, with warm and wet summer monsoons and cold and dry winter monsoons (Qu *et al*., 2020). Differences in monsoon precipitation patterns can be observed among the upper, middle, and lower reaches (Bookhagen and Burbank, 2010). The annual precipitation decreases from more than 2000 mm in the eastern lowlands to approximately 700 mm in the Sichuan Basin and less than 400 mm in eastern Tibet (Yang *et al*., 2004).

The experimental data are shuttle radar topography mission (SRTM)–DEM data with a 90-m resolution. The SRTM is jointly measured by NASA and NIMA. This mission also acquires radar image data between 60° north latitude and 60° south latitude, thereby covering more than 80% of the earth's land surface. The International Tropical Agricultural Center has developed a digital terrain elevation model (DEM), which is the current SRTM terrain product data, on the basis of the void-filling interpolation method (Reuter *et al*., 2007).

3 Methods

3.1 Combination of stream profiles

In this study, we proposed the method of stream profile clusters to reveal the geomorphological features and evolutionary mechanisms of the Yangtze River. The stream profile clusters include the vertical plotting of all streams in the basin. We need to extract the stream network of the Yangtze River from the DEM by using the flow direction tracking algorithm to obtain the stream profile clusters (O'Callaghan and Mark, 1984; Xiong *et al*., 2017). Stream head points are extracted from the stream network on the basis of the water flow algorithm (Shahzad and Gloaguen, 2011). The elevation value corresponding to each stream network is then tracked starting from the head point along with the flow direction and continuing until the basin outlet. The elevation value of each stream network and its distance from the outlet are plotted. The X-axis is the horizontal distance between the stream network and the outlet of the basin. The Y-axis represents the elevation of the stream network (Figure 2).

3.2 Stream evolution index

Vertical erosion is an important process in stream evolution. Erosion in the vertical direction of the stream is mainly manifested in the deepening of the streambed. Stream profiles in nature can be classified into three types, concave, convex and straight ones. They all follow the rule that, with the increasing degree of erosion, the portion carried by erosion gradually increases and the section left behind decreases. The upper and lower areas of the rectangle around the cutting section of the stream can effectively express the evolution degree of the stream (Strahler, 1952). In this study, the stream evolution index is used to quantify the evolution degree of the stream on the basis of the stream profile clusters (Figure 3); the index is defined as follows:

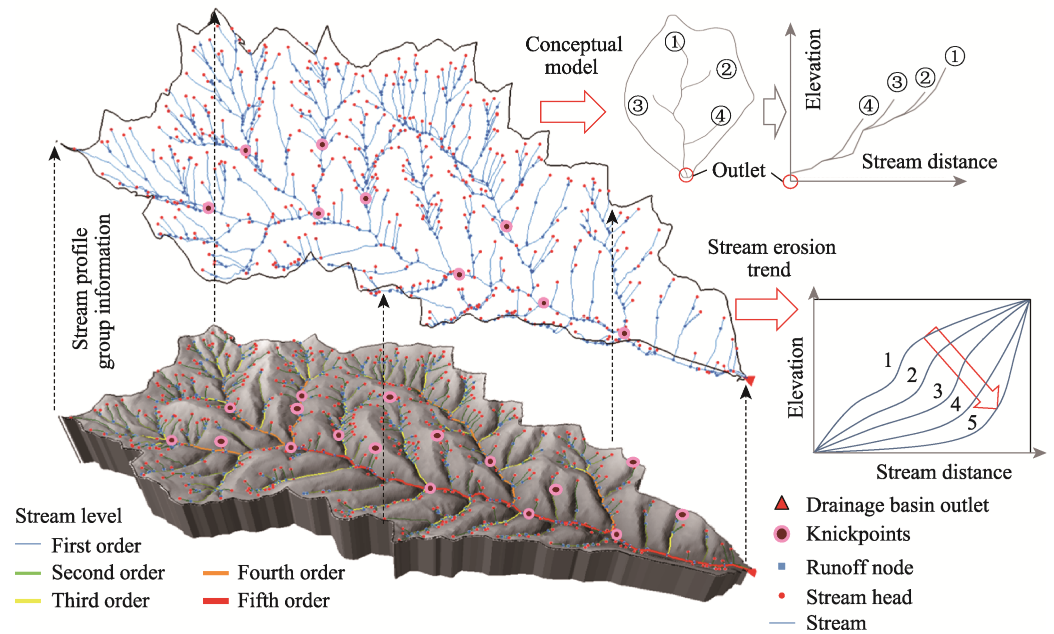

Figure 2 Conceptual model of the stream profile cluster approach

$$\text{Stream evolution index}=\frac{\int_0^l (h_x - h_{\min})dx}{l*(h_{\max} - h_{\min})},$$

where l indicates the length of a stream, h_x is the elevation of a point on the stream profile, $h_{\max}$ is the maximum elevation of the profile, and $h_{\min}$ is the minimum elevation of the stream profile.

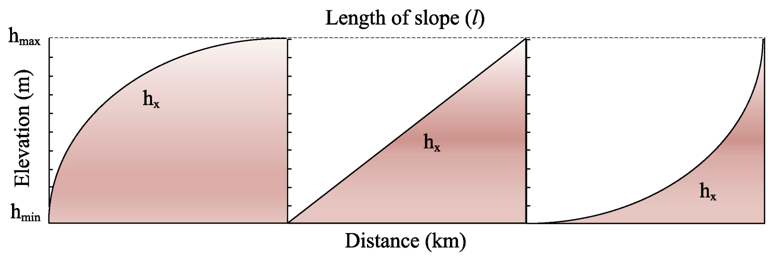

Figure 3 Schematic for calculating the stream evolution index based on three types of slopes (concave, convex and straight slopes). The upper half of the rectangle is what the stream has eroded away. The lower half of the rectangle is what the river has not yet eroded away.

We can calculate the evolution index of all streams on the basis of the stream profile clusters. Each sub-basin has many streams. A basin is the basic unit of the calculation. Based on the result of the evolution index calculation for each stream, statistical information for each basin can be derived, including the mean value, median value and standard value. The mean and median values can reflect the degree of stream erosion. The higher the mean and median values, the lower the stream evolution degree and the higher the erosion potential. The value of the standard can reflect the complexity of the natural conditions in each area. If the value of the stream evolution index standard is high, it means that there is an obvious difference in the evolution of each stream in this area. In contrast, if the value of the stream evolution index standard is low, the underlying surface properties are relatively uniform in this area. Accordingly, the entire evolution process of the basin can be quantitatively expressed. A comparison of the stream evolution indexes, which belong to different sub-basins, facilitates the understanding of the geomorphological features and evolutionary mechanisms of the Yangtze River Basin.

3.3 Sequence of the Yangtze River Basin

The Yangtze River has a vast area and complex natural environment. The Yangtze River Basin can be divided into almost 30 sub-basins by using the basin segmentation algorithm according to the spatial topological relationship of the internal stream network (Roerdink and Meijster, 2000). The evolution degree and morphological features of the sub-basins differ in space because the sub-basins are mainly affected by precipitation, landforms, and basin hierarchy (Gurnell *et al.*, 2012; Chen *et al.*, 2019; Chen and Zhang, 2020). This study uses the sub-basin as the basic study unit. On this basis, all the sub-basins in the Yangtze River are arranged in a sequence according to a spatial order from the upper reaches to the lower reaches and classified using precipitation distribution, landform type, and basin hierarchy as classification indicators. The correlation between the stream evolution index and each indicator is further explored on the basis of the sorting and classification results. The spatial heterogeneity of the geomorphological features and evolutionary mechanisms of the Yangtze River Basin are further analyzed.

4 Results

The stream profile clusters of the entire Yangtze River Basin are shown in Figure 4. All streams in the basin converge to a baseline. This line is the plotting of the erosion base in the entire basin and the boundary of the vertical undercutting of the stream. At this position, the erosion and accumulation of the stream achieve a balance. Moreover, the location and shape features of the erosion base are influenced by the geological structural background, precipitation, and basin hierarchy. The height of the erosion base plays a decisive role in the profile shape of the basin (Langbein, 1964).

The stream profile clusters (Figure 4) demonstrate the following: the elevation drops of the streams are small in the lower reaches of the Yangtze River; the gravitational potential energy of these streams decreases; and a substantial amount of silty clay accumulates. The erosion base in the stream profile clusters is smooth. In the middle reaches of the Yangtze River, the elevation drops of the streams are large. Furthermore, the gravitational potential energy of these streams increases, and the erosion ability is strong. Mudstone, sandstone, and other sedimentary rocks are mostly distributed under the stream, and the resistance to erosion is less than that in the upper reaches. Accordingly, the erosion base in the stream profile clusters is relatively smooth in the middle reaches. In the Hengduan Mountain region of the upper reaches of the Yangtze River, the elevation drops of the streams are great, and the flow strongly shapes the ground. However, tectonic movement is frequent in this area, and the underlying bedrock is mainly metamorphic sandstone, metamorphic quartz sandstone, and other metamorphic rocks, which are difficult to erode. Therefore, the erosion base in the stream profile clusters in this part presents a stepped shape under the joint influence of tectonic movement and the underlying bedrock components.

The Yangtze River flows through three major terrain gradients of China's topography. The erosion base in the stream profile clusters drops at the edge of the terrain gradient, and the drop between the first and the second terrain gradients is large (Figure 4). All sub-basins of the Yangtze River are sorted from the upper to the lower reaches; the results are shown in Figure 5. From a morphological perspective, the elevation drops of the basins and the streambed slope gradually decrease, the erosion base changes from steep to gentle in the sequence of the stream profile clusters from the upper to the lower reaches, and stream evolution index changes from high to low. The erosion potential for the streambed is greater in the upper reaches of the Yangtze River. Sediment accumulates in the lower reaches of the Yangtze River. The streambed is gentle and stable, and the shape of the streambed is not easily changed by erosion in the short term. In addition, the upper reaches of the Yangtze River are characterized by frequent geological activities, complex tectonic stress and great differences among different streams in each sub-basin here. Therefore, the standard deviation of stream evolution index is higher in the upper reaches (Table 1). The topography of the upper reaches greatly fluctuates with a high degree of fragmentation because of the properties of the underlying surface of the Yangtze River Basin. The topography of the middle and lower reaches tends to be gentle. The Minjiang River does not obey this rule. This is because the Minjiang River lies on the eastern edge of the Tibetan Plateau and crosses the first and second terrain gradients (Luo *et al*., 2019; Gao *et al*., 2020).

Table 1 Statistics of the stream evolution index in sub-basins of the Yangtze River; basins were sorted from the upper reaches to the lower reaches

Basin name	Slope*	Mean	Median	Standard deviation
Jinsha River	$1.76*10^{-1}$	0.33	0.33	0.12
Minjiang River	$3.62*10^{-1}$	0.29	0.28	0.10
Yuanjiang River	$6.71*10^{-2}$	0.21	0.22	0.08
Hanshui River	$5.9*10^{-2}$	0.22	0.20	0.07
Ganjiang River	$3.07*10^{-2}$	0.15	0.15	0.06
Lower Reach	$1.86*10^{-2}$	0.14	0.12	0.04

Note: Slope* means the slope of the erosion base

Many knickpoints are present between the gentle and steep slopes in the stream profile clusters of these basins. The sequence of the stream profile clusters demonstrates that knickpoints mainly occur in the area with a complex structure in the upper reach and few occur in the area with a serious decline in erosion base in the lower reach (Figure 5). The upper reach knickpoints are generally caused by the structural uplift of the streambed, which releases the gravitational potential energy of the water. This condition results in serious undercutting of the lower stream of these knickpoints. The formation of these lower reach knickpoints is due to the rapid decline of the erosion base, the resumption of the undercutting of the stream from the estuary section, and the gradual intensification of headward erosion (Leviandier *et al*., 2012). The intersection between the newly formed steep reach and the newly formed gentle reach becomes the knickpoint.

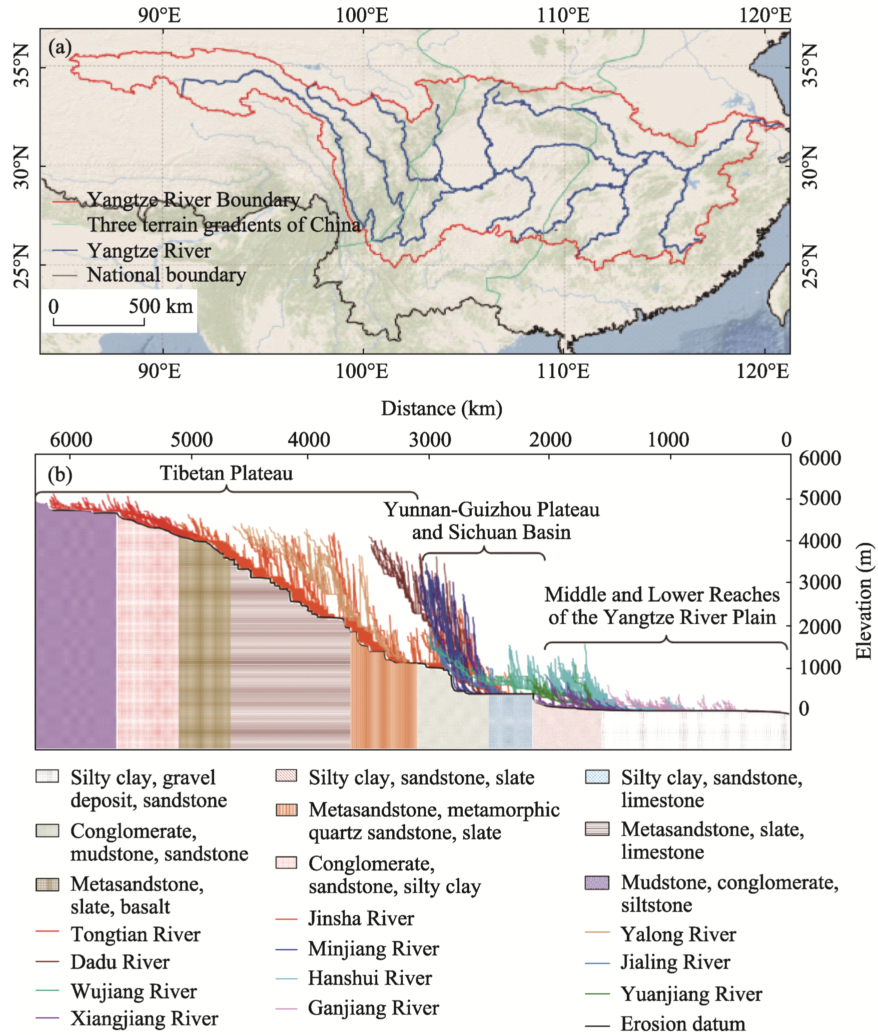

Figure 4 (a) Map of the Yangtze River Basin; (b) stream profile clusters of the Yangtze River Basin and bedrock information under the erosion base in different basins

The Jinsha River Basin is located in the north-south tectonic belt of the Hengduan Mountains, with the Sanjiang Fold System in the west. The neotectonics has an intense effect in this area. The tectonic movement is characterized by folds and uplift overall. During its evolutionary history, this area was divided into blocks of different sizes and shaped by regional major faults. There are differences in the relative movement between blocks, and intermittent uplift exists in the blocks. According to plate theory, the Jinsha River Basin is located at the boundary of Sichuan and Yunnan provinces and at the edge of the Tibetan Plateau. It is influenced by the forward compression of the Indian Ocean plate and the shearing of the Eurasian plate, as well as the eastward pushing of the Pacific plate and the Philippines plate. This area is the junction of multiple external tectonic stress fields, and the tectonic stress state is complex (Hou *et al.*, 2004). Therefore, many stream terraces appear in the stream profile clusters, the knickpoints are densely distributed here. The underlying surface is mostly composed of limestone, slate and metasandstone, which are difficult to be eroded.

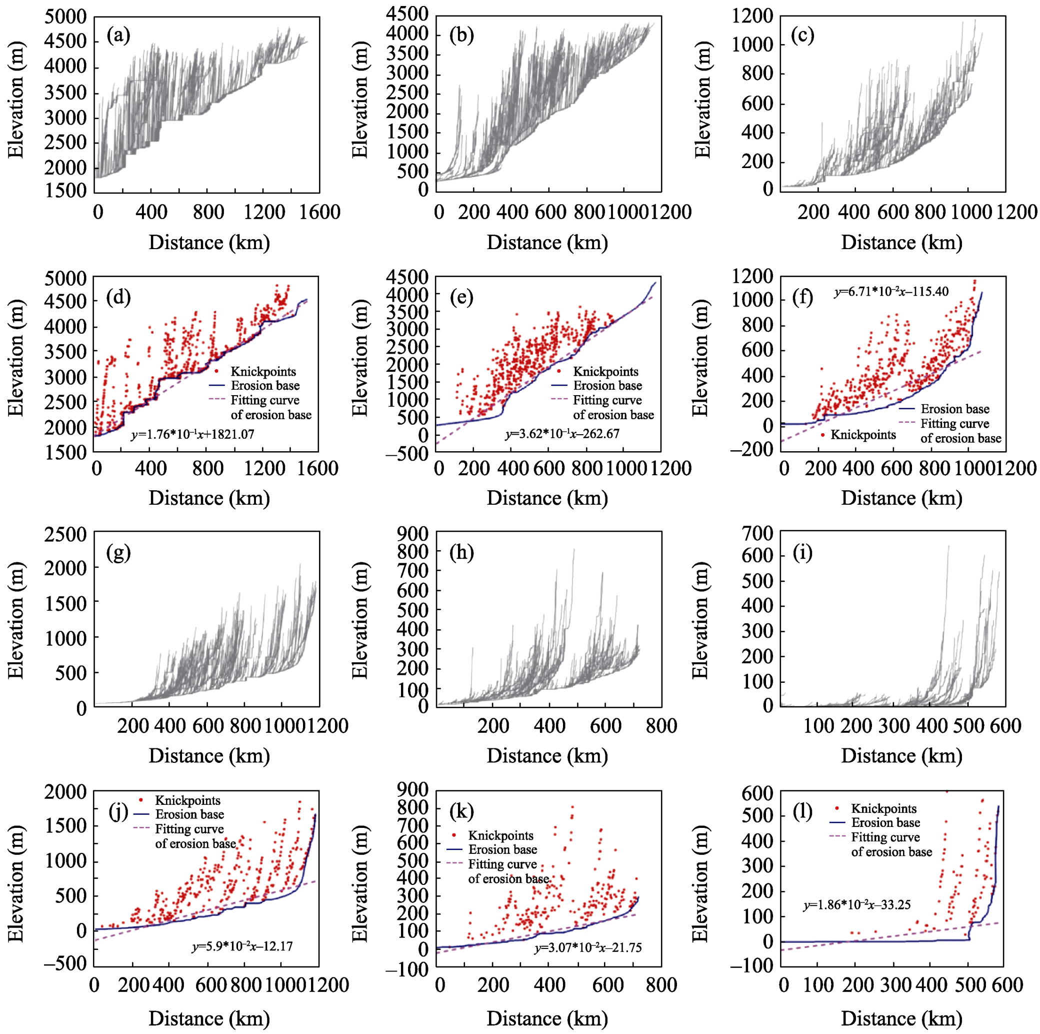

Figure 5 Sequence of the stream profile clusters in the Yangtze River. Stream profile clusters of the (a) Jinsha River Basin, (b) Minjiang River Basin, (c) Yuanjiang River Basin, (g) Hanshui River Basin, (h) Ganjiang River Basin, and (i) Lower Reaches of the Yangtze River Basin. Stream knickpoints and erosion base derived from stream profile clusters of the (d) Jinsha River Basin, (e) Minjiang River Basin, (f) Yuanjiang River Basin, (j) Hanshui River Basin, (k) Ganjiang River Basin, and (l) Lower Reaches of the Yangtze River Basin.

Therefore, the erosion base presents the characteristics of ladder shape for a long time (Figures 5a and 5d). The Minjiang River Basin is located in the eastern margin of the Tibetan Plateau, which is at the junction of the Minshan Uplift Belt, Longmenshan Structural Belt and Songpan-Ganzi Fold Belt. The Minjiang River originates from the hinterland of the plateau on the west side of the Minshan Uplift Belt. The main stream flows through the Longmenshan Structural Belt from north to south, intersects with three major tributaries, the Heishui River, Zagunao River and Yuxi River, and finally joins the Sichuan Basin. The Minjiang River spans the first and second topographic steps in China, and the height difference within the basin is great, reaching 3560 m. The uplift of the Tibetan Plateau provides topographic conditions for the evolution of modern glaciers in the upper reaches of the Minjiang River. The carrying capacity of runoff is poor and the stream fall is relatively small. In the middle and lower reaches of the Minjiang River, due to the long-term deep cutting of the Minjiang River, the stream erosion is strong and the elevation drops of streams are large (Kirby *et al.*, 2000). Therefore, the overall stream profile clusters of the Minjiang River have a large drop, among which the elevation drops in the middle and lower reaches are higher than those of the upstream profiles (Figures 5b and 5e). The Yuanjiang River originates from the Yunnan-Guizhou Plateau. The upper reaches of the Yuanjiang River are composed of many alpine gorges. In the middle reaches of the Yuanjiang River, the slopes of the streams are gentle. Hilly mountains are mixed with the distribution of canyons in this reach. The canyons from Qiancheng to Hongjiang, Huangshi Cave to Copper Bay have lengths of tens of kilometers. The evolution of streams here is limited by the topography of the gorge, so in the middle reaches of the Yuanjiang River, the length of streams is short and the elevation drops are small. The Yuanjiang River Basin is geographically located in a region with good structural stability, which spans two tectonic units: the Yangtze Platform and the South China Fold Belt. There is no obvious tectonic uplift of the erosion base, and streams tend to be balanced gradually due to self-adjustment (Zhan *et al.*, 2015). The erosion base in stream profile clusters is a smooth curve (Figures 5c and 5f). The Hanshui River originates near the Qinling-Daba Mountains, and there are many canyons and basins along the coast. The middle reaches of the Yangtze River flow from Danjiangkou to Zhongxiang county, through the Southeast Hills, and finally flow into the Middle and Lower Reaches of the Yangtze River Plain. From the perspective of plate theory, the Hanshui River is located near the Dabashan Tectonic Belt and the southern margin of the Qinling Fold Belt. The Dabashan Tectonic Belt was formed by the collision between the Qinling microplate and the Yangtze plate in the Late Triassic. Located at the eastern edge of the Tibetan Plateau, it is affected by a tectonic stress stretching from west to east (Wang *et al.*, 2007). Therefore, in response to the eastward growth of the Tibetan Plateau, the height difference of the Hanshui River from upstream to its outlet decreases gradually, and the number of the knickpoints decreases gradually, and the group morphology of the stream profile clusters shows that the stream elevation drops decrease gradually from the upstream to the downstream (Figures 5g and 5j). The Ganjiang River Basin has a mountainous and hilly landform pattern, and there is an important regional fault in the basin called Ganjiang River Fault Zone. The main fault of the Ganjiang River Fault Zone is concealed at the bottom of the Ganjiang River. In addition, there are a few secondary faults perpendicular to the direction of the Ganjiang River in the middle reaches of the river. Tributaries in this reach flow into the nearby basin along the valleys formed by the faults (Xu *et al.*, 1987). Therefore, in the middle reaches of the Ganjiang River Basin, the stream network is relatively scarce and the elevation drops are low (Figures 5h and 5k). The middle and lower reaches of the Yangtze River are located on the Yangtze platform. The geological unit is stable and there are few geological activities. Therefore, the stream course as a whole is very gentle, the elevation drops are small, and the distribution of knickpoints is few (Chun *et al.*, 2003). In addition, the knickpoints are concentrated near the stream head points. This is because this reach of the Yangtze River flows from hilly mountains to plains. In the mountainous area, the underlying surface is mostly composed of conglomerate, sandstone and silty clay. In comparison, the plain area, where the underlying surface is mostly composed of sandstone, river deposits and other materials, is prone to be eroded. Runoff flows from the mountains to the plain, and at the junctions, the streambed cuts down rapidly, forming locally distributed knickpoints. In the plain region, the stream slows down and the stream is dominated by accumulation, so that the basin boundary formed by the head points of the stream is almost completely parallel to the erosion base (Figures 5i and 5l).

Overall, the number of tributaries is large, and the stream profile clusters are intensive in the upper reaches of the Yangtze River. In the lower reaches of the basin, the number of tributaries is small, and the stream profile clusters of the basin are sparse. This pattern shows that the tributaries of the upper reaches of the Yangtze River gather the energy contained in the flow into the main stream during the process of confluence. Accordingly, the energy contained in the main stream gradually increases, the control effect on the entire basin is strengthened, and the ability to shape the surface is enhanced.

5 Discussion

5.1 Geomorphological variation in the stream profile clusters

This study connects all the stream heads in the stream profile clusters. The resulting curve is the plotting of the basin boundary line. Figure 6 demonstrates the basin boundary and erosion base of the Tongtian River Basin at the source of the Yangtze River. The Tongtian River Basin is a typical Paleogene-Neogene basin on the Tibetan Plateau. A large area of Paleogene and Neogene clastic rocks and carbonate sediments is exposed in the basin. The Tongtian River Basin is the product of the Paleocene Indian continent's collision with Eurasia; it has experienced multiple tectonic movements and planation effects (Coleman and Hodges, 1995). Since the Paleogene and Neogene, the Tongtian River Basin has been characterized by fluvio-lacustrine deposits (Wu *et al*., 2011). The tectonic movement is mainly a horizontal strike–slip fault, and a rare local tectonic uplift is found in the basin (Huang, 1986; Yu *et al*., 2018). The terrain within the basin is smooth (Zheng *et al*., 2017). In addition, the underlying bedrock stratum of the basin has continuity. Thus, the erosion base is smooth in this area. The layer-by-layer sedimentary depositional process causes the lacustrine sediment to cover the underlying strata. The basin boundary line (green line in Figure 6) and the erosion base (blue line in Figure 6) are basically parallel. This finding supports the viewpoint that landforms often inherit features of sedimentary landforms (Xiong *et al*., 2014; Xiong *et al*., 2016). The positional relationship between the basin boundary line and the erosion base can be ascertained from the stream profile clusters and opens a new perspective to evaluate the intensity of tectonic movements.

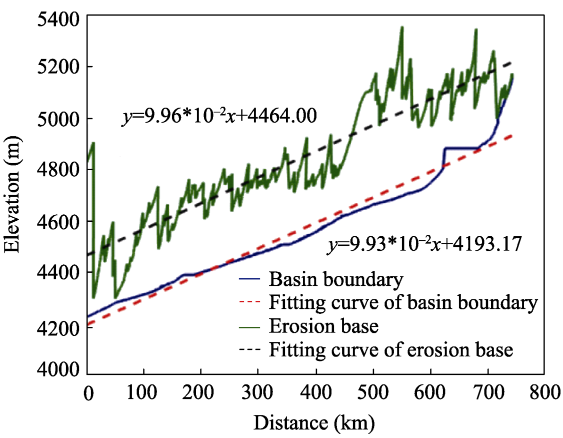

Figure 6 The diagram of the basin boundary line and erosion base line of the Tongtian River Basin

In the upper reaches of the Yangtze River, the erosion base in some basins are tortuous. In the middle and lower reaches, the erosion base is smooth because the geological activities in the upper reaches of the Yangtze River are relatively more frequent than those in the middle and lower reaches. For example, the Jinsha, Yalong, and Dadu river basins near the Hengduan Mountains have complex geological structures and are controlled by the Yunnan-Tibet and Kunlun geosynclinal fold systems in the Tethyan Himalayan tectonic domain (Huang *et al*., 1977). The tectonic uplift and compression are intense. Moreover, many stream terraces can be found in the nearby basin, and they are plotted onto the stream profile clusters, thereby forming a stepped stream profile (Figure 7a).

The Dadu River Basin spans three major structural units: the Ganzi Fold Belt, the Sichuan–Yunnan–North–South Tectonic Zone, and the Sichuan Basin. Under the effect of the neotectonic movement, numerous stream terraces have been formed. An uplift is indicated by the erosion base. After the tectonic uplift, the signal of uplift is received at the stream head in the lower stream. Moreover, the intensity of headward erosion is strengthened. Accordingly, the elevation drops of streams located in the lower reaches containing these knickpoints is larger than that of streams in the upper reaches containing these knickpoints (Figure 7b). Similar to the entire western Sichuan, the Dadu River Basin became a peneplain with an altitude of only 1000 m after denudation and planation in the Paleogene and Neogene. Since the Pleistocene, the planation plane has disintegrated due to Neotectonics, thereby forming a multilevel-layered terrain. A plateau can be found in the upper reaches. The middle reaches present a planation surface corresponding to a relatively horizontal plane existing in the plotting of the erosion base (Suhail *et al*., 2020). All streams are constrained by this planation surface (Figure 7b). The lower reaches consist of low mountains and hills.

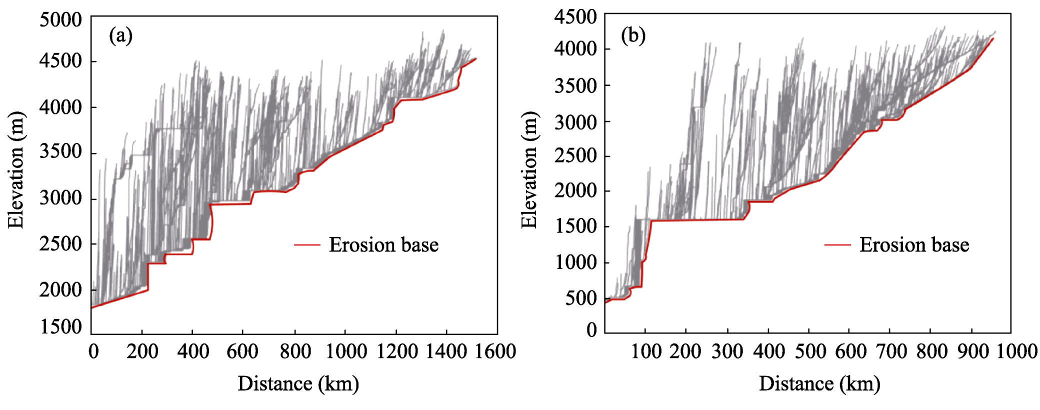

Figure 7 Stream profile clusters of the (a) Jinsha River Basin and (b) Dadu River Basin

The demarcation of the eastward expansion boundary of the Tibetan Plateau has two main viewpoints. Some scholars hold the opinion the tectonic deformation related to the eastward expansion of the Tibetan Plateau currently occurs near the West Qinling Mountains (Enkelmann *et al*., 2006; Tian *et al*., 2012; Yang *et al*., 2017), whereas others suppose that the extension has stretched to the Daba Mountain region in the east (Song *et al*., 2018; Wang, 2018). The study of stream profile clusters in the sub-basin of the Yangtze River (Hanshui River Basin) can bring a new understanding to this debate. Figure 8 shows the knickpoints distribution in the largest basin (Hanshui River Basin) in the Daba Mountain region. The Hanshui River is an east–west trend stream. The number of knickpoints in the upper reaches

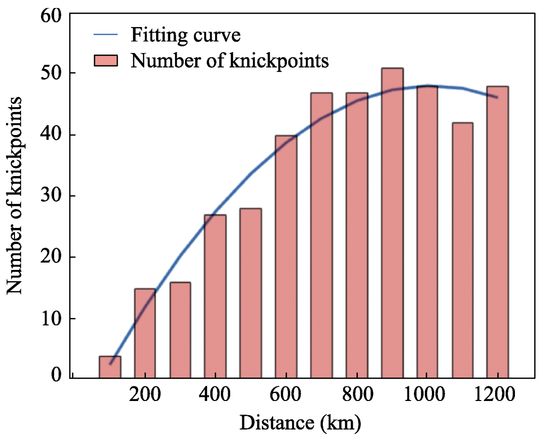

Figure 8 Knickpoints distribution derived from stream profile clusters of the Hanshui River Basin

(west) of the Hanshui River is far greater than that in the lower reaches (east). The asymmetry of the distribution of these knickpoints indicates that the formation of the knickpoints in the basin near the Daba Mountains was controlled by an east–west strike tectonic stress; the bedrock in the upper reach of the stream was rapidly uplifted under the influence of neotectonic movement in the late Cenozoic (Shi *et al*., 2020). This finding strongly corroborates the latter views that the extension of the Tibetan Plateau to the east has expanded to the western part of the Daba Mountains.

5.2 Correlation analysis based on different factors

From the perspective of basin hierarchy, the change in the stream evolution index follows a certain rule (Figure 9). From the primary stream (tributary) to the tertiary stream (main stream), the mean and median stream evolution index continues downward, and the overall stream evolution degree of the basin continues to increase. The plotting of the erosion base gradually becomes smooth because the high-hierarchy of the main stream has the most energy and can shape the surface, thereby gradually smoothening the streambed.

The stream evolution indexes of the basins with various hierarchies in the Yangtze River are shown in Table 2. In summary, the stream evolution degree of the high-hierarchy (main

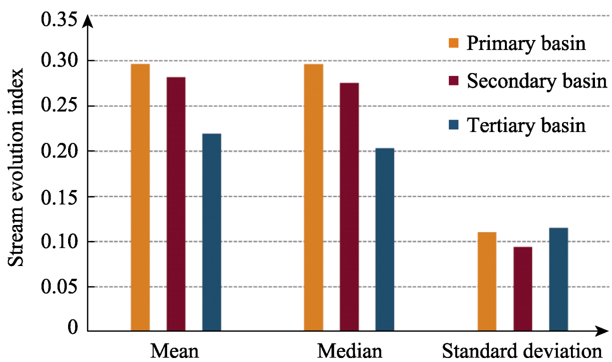

Figure 9 Stream evolution index constrained by basin hierarchies

Table 2 Stream evolution index statistics under the constraints of stream network hierarchies

Basin hierarchy	Mean	Median	Standard deviation
Primary basin	0.2966	0.2964	0.1105
Secondary basin	0.2817	0.2755	0.0941
Tertiary basin	0.2194	0.2033	0.1152

stream) basin is greater than that of the low-hierarchy (tributary) basin. From the primary basin (tributary) to the tertiary basin (main stream), the stream evolution index gradually decreases, and the stream evolution degree of the stream slowly intensifies. The degree of data dispersion in the secondary basin is low, indicating that the stream evolution degrees of streams in the secondary basin are the most similar compared with those of the other basin hierarchies.

From the perspective of precipitation, the mean and median stream evolution index keeps moving downward, and the stream evolution degree of the stream increases with the continuous increase in precipitation (Figure 10). The stream evolution indexes of different dry and wet areas in the Yangtze River are shown in Table 3. In summary, the mean and median of the stream evolution index in each area from the semi-arid to the humid constantly decrease with the continuous increase in precipitation intensity. The median decreases, and the stream evolution degree constantly increases. Furthermore, the dispersion degree of the stream evolution index in each region increases. The data on dispersion degree of the semi-arid area is much lower than that of other areas. This phenomenon occurs because the semi-arid area is close to the source area of the Yangtze River, the underlying surface properties are relatively uniform, and the impact of precipitation on the evolution of the stream is considerable. The evolution of the stream in the humid area is significantly disturbed by other factors.

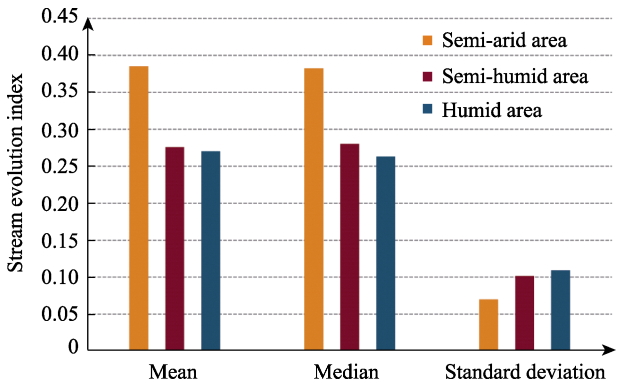

Figure 10 Stream evolution index constrained by precipitation

Table 3 Stream evolution index statistics under the constraints of precipitation

Precipitation	Mean	Median	Standard deviation
Semi-arid area	0.3852	0.3826	0.0701
Semi-humid area	0.2762	0.2805	0.1018
Humid area	0.2702	0.2634	0.1092

From the perspective of geomorphological types, the erosion base is gentle in the plain area. So the plain area has a low potential to be eroded, compared with other geomorphological types. Moreover, the shape of the stream profile clusters of mountains and hills are similar (Figure 11). The stream evolution index of the different geomorphological types of the Yangtze River is shown in Table 4. The hilly landform area has a high stream evolution index and a low degree of erosion. In the mountainous terrain, the stream has sufficient water energy and strong erosion ability due to the large elevation drops of the streams.

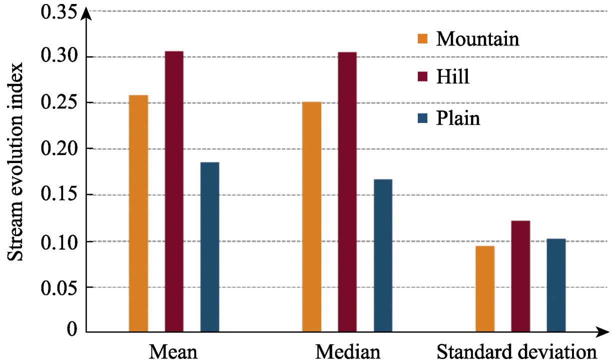

Figure 11 Stream evolution index constrained by geomorphological types

Table 4 Stream evolution index statistics under the constraints of landform types

Landform type	Mean	Median	Standard deviation
Mountain	0.2587	0.2514	0.0947
Hill	0.3066	0.3052	0.1223
Plain	0.1857	0.1673	0.1026

Accordingly, the streams in mountainous area are more mature than those in hilly areas. The dispersion degree of the stream evolution index in the hilly areas is the highest, followed by the plain and mountainous areas.

6 Conclusions

This paper proposed a novel approach for studying the geomorphological features and evolution of the Yangtze River based on the stream profile clusters. Compared with the traditional approach for studying the Yangtze River based on a single profile, all the streams are taken into consideration as a whole. Therefore, group characteristics, which cannot be ascertained from single profile, can be derived to express the evolutionary mechanism of the Yangtze River, including the morphology of erosion base, the distribution of knickpoints, and the location relationship between basin boundary and erosion base.

In the upper reaches of the Yangtze River, the frequency of tectonic movement was relatively higher than that in the middle and lower reaches. The erosion base in the lower reaches is smoother. On the whole, the erosion base of the Yangtze River generally changes from steep to gentle from the upper reaches to the lower reaches, and the slope of the erosion base ranges from 3.62×10^{-1} to 1.86×10^{-2}. Moreover, the stream evolution degree changes from low to high. The mean stream evolution index is higher in the upper reaches, reaching 0.33, while this value is 0.12 in the lower reaches. The Minjiang River seems not obey this rule. This is because the Minjiang River lies on the eastern edge of the Tibetan Plateau and finally joins the Sichuan Basin. The elevation drops of streams in the Minjiang River Basin are very large. In addition, the standard deviation of the stream evolution index is higher in the upper reaches. The upper reaches of the Yangtze River are characterized by frequent geological activity and complex tectonic stress. The underlying surface is complex here.

The Tongtian River Basin is characterized by fluvio-lacustrine deposits. The erosion base is smooth, and stream terraces are rarely found here. Sediments carried by runoff covered the ancient landforms. Due to the transportation of modern streams, fluvio-lacustrine deposits were prone to be eroded and carried downstream. At the bottom of the stream is ancient bedrock. In the Tongtian River, the erosion base, representing the ancient landforms, can be expressed by the equation $y = 9.93 \times 10^{-2}X + 4193.17$. The boundary line, representing the modern landforms, can be expressed by the equation $y = 9.96 \times 10^{-2}X + 4464.00$. The basin boundary and the erosion base are basically parallel. The location relationship between the basin boundary and erosion base derived from stream profile clusters can be an important indicator for distinguishing whether fluvial deposition is the main shaping force of basin geomorphology.

The Hanshui River is an east–west trend stream. From the stream profile clusters, 68.3% of the knickpoints are found in the upper reaches, while only 31.7% of the knickpoints are found in the lower reaches. The number of knickpoints in the upper reaches (west) of the Hanshui River is far greater than that in the lower reaches (east). The asymmetry in the distribution of these knickpoints indicates that the Hanshui River is controlled by the east–west strike tectonic stress. This finding strongly corroborates the views that the extension of the Tibetan Plateau to the east has expanded to the western part of the Daba Mountains.

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