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Longitudinal profiling and elevation-relief analysis of the Indus

R. Prerna[1] · Dhananjai K. Pandey[1] · Kotha Mahender[2]

Abstract

The Indus basin—one of the largest fluvial-controlled landscapes of the world, provides a major agro-economic resource base while showcasing unique morphometry along its course. However, despite its large socio-economic relevance in South Asia, a distinct account of morphometric variations down its course still remains elusive. Here, for the first time a quantitative demarcation of the Indus basin into—upper, middle, and lower basin is proposed based on analyses of critical morphometric parameters (viz. gradient/river length ratio, elevation-relief ratio, channel width, sinuosity, and slope). Geostatistical and hydrological operations performed on digital elevation models, suggest that the highest and lowest relief sectors are tectonically more stable than the middle relief sector, inferred from a convex hypsometric curve. Elevation-relief ratio for the basin indicates tectonic stability with ~ 31% of remnant rock still in place. Cross-sectional transects also demonstrate anomalous patterns that deviate from predictive characteristics of youthful, mature, and senile stages of river development. All parameters are spatially coalesced to provide a first-ever holistic morphometric account of the Indus basin while describing fine-scale planform variations of the spectacular dynamics of this enormous river basin.

Keywords Indus · Morphometry · Elevation-relief ratio · Longitudinal-profile · Basin

Introduction

A variety of surficial and sub-surficial processes sculpt the morphology of landmasses—like fluvial, eolian, karstic, or glacial. From all these important agents of geomorphic change, fluvial processes are the most active agency dominating the continental landmass as other processes are mostly applicable to a limited proportion of the continents (Stahler and Stahler 1996; Babar 2005). Assessing the tectonic influence on landforms, and vice-versa, is conducive to understand direct links between tectonics and landforms (Schumm et al. 2000). Here, we examine the landform evolution through the Indus river system which provides one of the finest examples of fluvial landscapes with its tectonic evolution and variable morphology spread over an extensive expanse.

Morphometric analyses of river basins using geospatial techniques have been in practise—mostly to quantify the drainage-network relationships between streams and their catchment as well as to assess the interrelationship between hydrology, geology and geomorphology. Awasthi et al. (2002), Singh and Sarangi (2008), Singh (2009), Khan et al. (2014), and Garee et al. (2017) among others have worked on specific watersheds of the Indus basin to address soil conservation, sustainable water management, disaster control, and climate change projections using GIS-based hydrological modeling. Immense research in the categorization of stream and basin types has already made headway progress, albeit, most of the studies are limited to smaller catchments/ watersheds.

For Indus, as a singular system, the demarcation of the upper, middle, and lower Indus basins based on morphometry is sketchy. Channel and basin inter-relationships can be better understood with respect to various stages of development, making it crucial to first identify basin margins. Being an enormous system in itself, such categorization magnifies the intricacies of hydro-geological phenomenon which shape the morphology of a system.

In the present study, morphometry of the entire Indus river has been analyzed for the very first time, predominantly using five morphometric parameters: (a) elevation-relief ratio; (b) longitudinal profile; (c) channel width; (d) sinuosity; and (e) slope—extracted from digital elevation model (DEM) data.

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These select parameters instantaneously present the existing inter-relation between elevation/relief, gradient, planform patterns and stream behavior.

Elevation-relief ratio or hypsometry is considered close estimates to study the effects of denudation and tectonic uplift—key players of landform development. As per Strahler (1952), the form of hypsometric curve and the value of the hypsometric integral are important elements in understanding topographic form and geologic structure. *Longitudinal profiling* enables graphical representation of change in gradient with increasing river length. They provide a platform to analyze interaction between geological and geomorphic processes operating at different time scales (Sonam 2018). Sudden changes in gradient are clearly identifiable—from which categorization of a river's course into different stages of development is possible. However as a precursor, cross-sectional profiling is a must which is useful for identifying channel thalweg—the locus of lowest bed elevation or maximum flow depth within a watercourse (Dey 2014). *Channel width* is yet another interesting parameter to study the morphometry of a river system. It is calculated as a straight line distance from channel axis to either bank. When coupled with the long profile or sinuosity profile, it helps in identifying regions of high deposition (large channel width) or increased channel incision (lesser channel width). Sharp changes in channel width are often indicative of some endogenic or exogenic effects thereby helping in adding more focus to the areas under distress. Physiographic modifications caused by construction of several dams and reservoirs are clearly identifiable using channel width plots. *Sinuosity* is a measure of deviation of a channel from its central path along its course. Every flowing channel, whether fluvial, submarine or extraterrestrial, exhibits some degree of deviation from its straight-line downslope path. It is the basic nature of liquids to flow over a surface by maintaining equilibrium between its erosive power and the resistivity of the surface. Sinuosity index (SI) is a ratio of the curvilinear distance (channel length) to the shortest-path distance (valley length) (Brice 1964). Assessment of the sinuosity of Indus was essential to describe the remarkable variability in planform behavior of the Indus. *Slope* or gradient along a river's course is directly indicative of its erosional behavior. For estimating the erosive power of the channel as it progresses through various stages of development, slope makes a key morphometric player.

The Indus system plays key role in quantifying tectonically driven weathering and erosion of sediments from the Himalayas and their eventual deposition into the Arabian Sea (Clift 2002). Tectonic effects on the riverine landforms can be readily recognized by consolidated rocks, where stream channels and drainage networks have incised into existing outcrop at the earth's surface (Schumm et al. 2000). Considerable geological investigations, over several years have clearly established effects of tectonics on present-day Indus are substantial and their interpretation helps in better understanding of the system as a whole.

Based on an aggregated analysis of the aforementioned parameters, we attempt to provide a holistic morphometric description of the Indus system by (a) demarcating the margins of upper, middle, and lower Indus basin; (b) correlating the hypsometry with fluvial/tectonic stages of development; and (c) exemplifying the anthropogenic influence on the basin.

Data and methodology

Data

The drainage network and basin has been methodically calculated from DEM data i.e., CartoDEM (CartoDEM v-3 R1 2015) and SRTM i.e., Shuttle Radar Topography Mission (Jarvis et al. 2008). The mosaicked DEM of the entire Indus is predominantly at 1 arc-second resolution (30 m), excluding one tile of SRTM data at 3 arc-second resolution. Table 1 provides details of the datasets employed in this study and Fig. 1 represents the mosaicked DEM along with the river network of Indus with its tributaries. The study extent is 24–36°N and 67–82°E.

Methods

The methodology begins from the extraction of stream network from the DEMs. The drainage network attained using the Hydrology toolbox of ArcGIS® software served as input for extracting other morphometric parameters of channel width, sinuosity and slope while the drainage basin was analyzed for hypsometry. Ramesh et al. (2015) have utilized the same workflow for identification of submarine channel network from digital bathymetric models.

Due to the complexity of measuring the hypsometric integral (HI), Wood and Snell (1960) developed a more direct and equally competent measure—the elevation-relief ratio (E). This method has been empirically tested and mathematically proven to be at par with the HI (Strahler 1952) in the works of Pike and Wilson (1971) showing $E \approx HI$.

$$E \approx HI = \frac{\text{Mean elevation} - \text{Min elevation}}{\text{Max elevation} - \text{Min elevation}}$$

For calculating the hypsometry, it is essential that the drainage basin be accurately derived from an elevation model, in this case, the 1 arc-second mosaicked DEM of the Indus basin.

Long profile of the Indus was constructed for the entire length of the Indus—from source to mouth—using cross profiles constructed at every 10 km. This interval was chosen,

Table 1 Details of datasets used for extraction of drainage network

Data source	No. of tiles	Downloadable tile extent	Spatial resolution
CartoDEM	77	$1° × 1°$	1 arc-second/~ 30 m
SRTM	1	$5° × 5°$	3 arc-second/~ 90 m

after multiple simulations, as it effectively resolved every major geomorphic variation throughout the course of the river. An illustration explaining this method is given in Fig. 2.

For channel width estimation, straight line transects between either banks of the main channel were constructed at every 100 m. Here too, after close consideration, a 100-m interval was found to minutely depict the channel width variation. One of the objectives of the study is to assess anthropogenic effects on the planform of Indus. Braiding results from a surplus of sediment load exceeding the carrying capacity of a river, which leads to the deposition of sediments in the form of temporary islands/sand bars. Construction of several barrages, especially in the lower basin, could have resulted in increased braiding. Hence in this study, the width of these depositional features is included in the channel width—so that segments of the river which are highly braided can be immediately identified.

Sinuosity index (SI) for Indus was calculated by tabulating ratio of sinuous length (A) at a 10-km interval and the shortest-path distance (B) between the start and end of every reach i.e., [SI = (A) / (B)]. An interval lesser or greater than 10 km resulted in either subdued variations or extremely jagged sinuosity. The value hence selected for any morphometric analysis cannot be generic to all systems. Based on the scale of detail required to understand a particular phenomenon, measurements may permute.

Slope is measured as a ratio of elevation difference between point A (upslope) and point B (downslope) to the distance along the flow pathway i.e., $\Delta y/\Delta x$. It can be represented in terms of a ratio, percentage rise, or as an angle in degrees. For the current analysis, percentage rise with respect to the downslope course of the Indus river has been plotted. Thalweg points of the river—extracted for constructing the longitudinal profile—were employed for measuring Δy for every 10 km reach (Δx). [Percentage slope rise = (Δy Δx) × 100].

The methodology flow for morphometric analysis of the Indus system is summarized in Fig. 3.

Results

Elevation-relief ratio analysis

E can also be expressed as a percentage—an indicator of the remnant of the present volume as compared to the original volume of the basin (Ritter et al. 2002). There are numerous inferences of the value of HI or E, compared in Table 2.

Strahler (1952) studied three different watersheds, each of which belonged to a unique stage of the geomorphic cycle. The drainage basin belonging to early youth/inequilibrium stage had an integral value of 79.5%; basin from the fully mature topography had a value of 43% while the basin with old topography had an integral value of 17.6%. The low HI values of old-stage basins were mostly associated with the presence of monadnocks—isolated hill/range of hills standing above the general level of a peneplain resulting from the erosion of the surrounding terrain.

For the Indus basin, the value of E is 0.31 which implies that ~ 31% of the original rock mass is still existent. When this value is interpreted with the hypsometric curve (HC), it can be asserted that while most of the basin has attained tectonic stability, a major segment from the middle relief is still experiencing inequilibrium.

Hypsometric curves permit the comparison of forms of basins of different sizes and elevations (Strahler 1952). Also, it is related to the volume of the rock in the basin; and the amount of erosion that had occurred in a basin vs. what still remains (Hurtrez et al. 1999). The HC of the Indus basin (Fig. 4a) is complex in form, making its interpretation difficult. It shows a combination of stages as per Strahler's model (Fig. 4b). Strahler's three watershed study (previously discussed) gives a clear interpretation of the shape of the curves belonging to different stages of development. Younger basins portray a convex upward curve, mature basins follow a typical S-shaped curve (convex upward-concave downward) and older basins have a concave downward trend.

The HC of the Indus drainage basin begins with a sharply descending concave curve owing to the small proportion of high relief in its upper reaches. As the percentage area starts to rise, the HC starts to bulge convexly. Thereafter, the distinct concave downward trend is attributable to the high proportion of landmass belonging to lower elevation slabs. To quantify, 20% of the area in Indus's drainage basin lies in the highest 40% of relief, 40% of area belongs to the middle 7–60% of relief, and remaining 40% of the area lies within the lowest 7% of relief (Table 3, Fig. 5).

Going by the interpretation of the HC, the basin seems to be undergoing geomorphic transformation in the mid-relief 53% of its area (Sector 2). Very similar in form to the Inequilibrium stage given by Strahler (1952) this sector of the Indus basin has greater proportion of its remnant rock still remaining. It can be inferred that the elevation slab from ~ 4600 to ~ 400 m is yet to attain erosional stability and the denudational processes are continually in play. The evident convex bulge in the HC
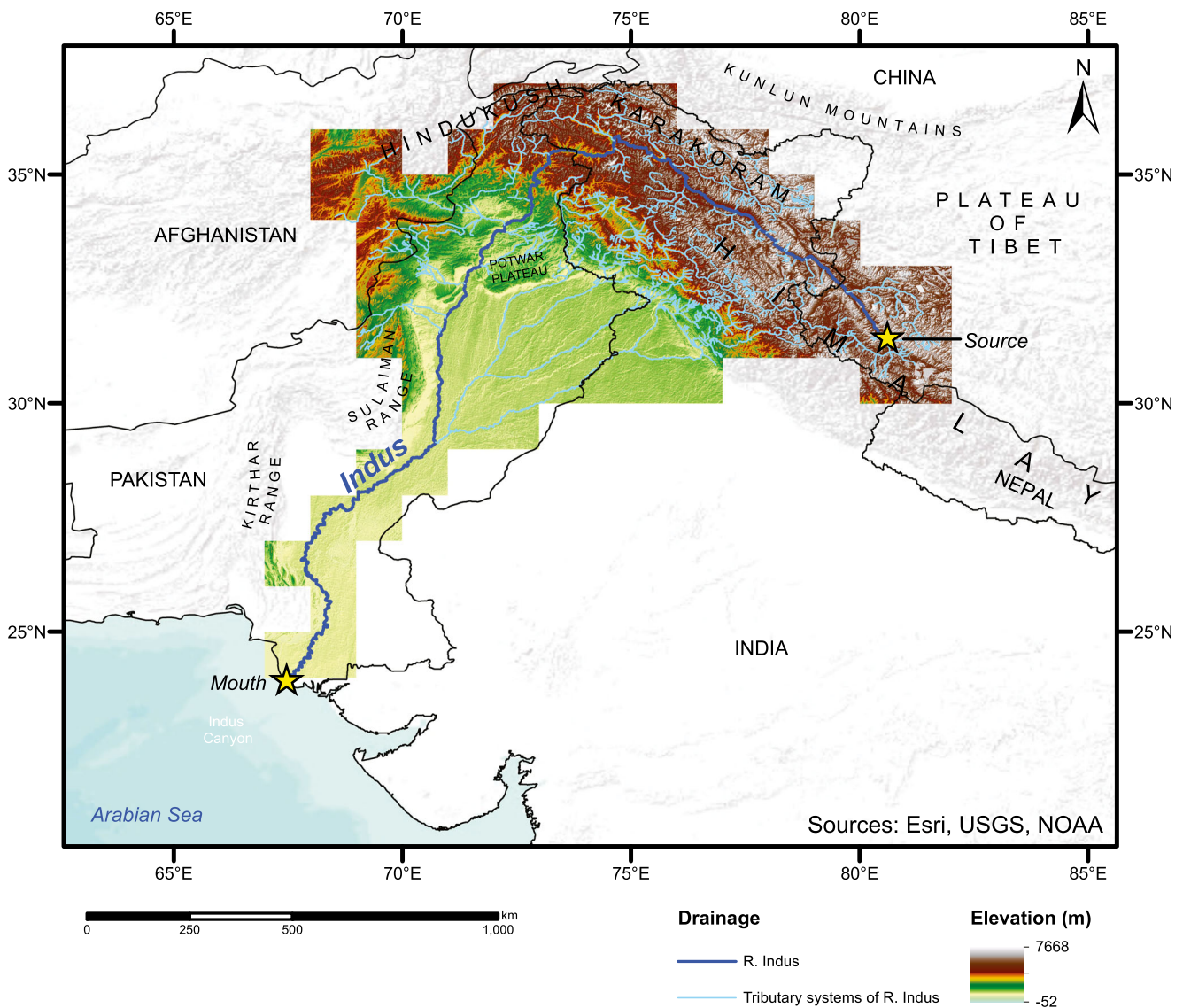
Fig. 1 Mosaicked DEM and Indus drainage network extracted from CartoDEM and SRTM data (CartoDEM v-3 R1 2015; Jarvis et al. 2008)

of the Indus river is attributable to this sector of the Indus basin.

Longitudinal profile analysis

The profile of this 3300-km long river is indeed quite interesting (Fig. 6). The Indus originates north of the Indus Suture Zone (Clift 2002) by the confluence of Gar Zangbo and Sênggê Zangbo flowing in the Gangdise Shan Range (also called the Kailash range) on the Tibetan plateau. Gar Zangbo originates near a small lake Cuo Ma'erdeng (31° 23′ 46″ N, 80° 32′ 25″ E). This location, at 4682 m asl, has been considered as the source of the Indus river in this study. The river follows a steep gradient for the first 100 km of its course before widening into a depositional lobe with anastomosing channels. Such channels mostly form under relatively low-energetic conditions near a (local) base level (Makaske

2001). Gar Zangbo unites with the E-W flowing Sênggê Zangbo at 170 km from its origin and roughly after 30 km from there—they enter the Indian Territory as Indus river.

Indus flows in a fairly SE-NW direction amidst the Ladakh and Zanskar ranges. At roughly 400 km, in Leh district, a sharp rise in slope gradient is observed in the long profile of Indus, which continues till the Leh valley where the river width increases marginally. This is typically attributed to the tectonically active Karakoram Fault (Fig. 7) which has caused substantive deformation in the region (Searle 1996; Murphy et al. 2000). Till the Leh Valley, downcutting is dominant and observable in the long/cross profiles. At ~ 570 km from its source, Indus is joined by the 138-km long Zanskar river from SW. Further 150 km downslope, Suru river unites with Indus and continue towards another major confluence of Shyok and Shigar in the Skardu valley district of Gilgit-Baltistan region, 850 km from the source. This zone of channel widening can
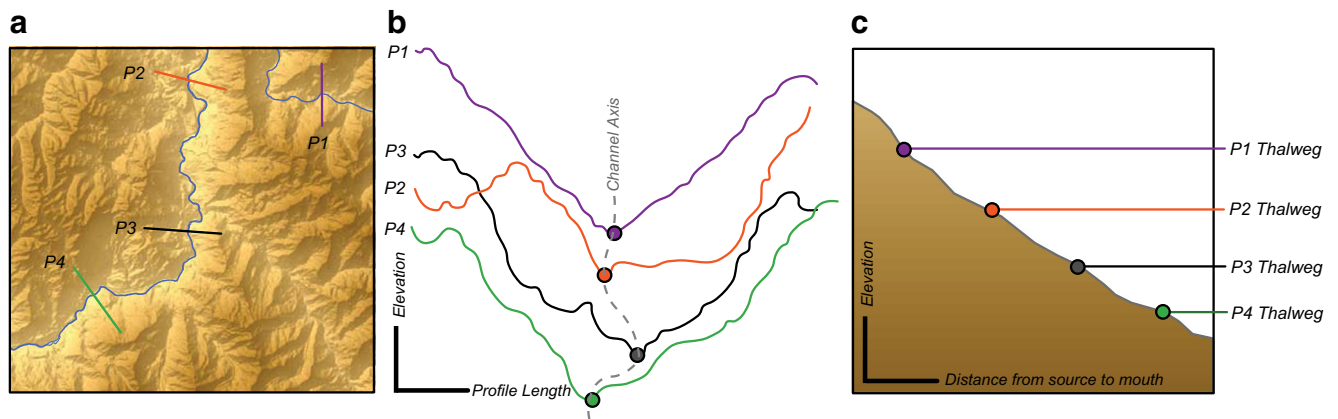
Fig. 2 **a** Four sample profiles—P1, P2, P3, and P4 along channel course shown in planform. **b** Cross-sections of P1, P2, P3, and P4 with respective thalweg points. **c** Illustrative long profile generated from elevation of thalweg points

easily be spotted on the channel width profile. Shyok river, ~ 525-km long, originates from the Rimo glacier while Nubra river sources near the Siachen glacier. The Nubra valley—confluence point of Nubra and Shyok is a major valley of the Ladakh district. After Shyok joins Indus from the east and Shigar from the north at Skardu valley, the river gains more momentum and continues to incise through the Nanga Parbat massif. Here the river forms a major gorge, also known as the Rondu canyon running for about 200 km between Sassi and Silbu (Butler et al. 1992; Kazmi and Jan 1997) at the boundary of Skardu and Astore district of Gilgit-Baltistan

region. The drainage pattern becomes anomalous because of the variable faulting activities and shear zones criss-crossing the area (Ahmed 2013). The belt is characterized by huge whirlpools, enormous water masses causing rapids, and waterfalls. The sharp declivity of the long profile with drastic decrease in channel width between Skardu valley and confluence of Indus-Gilgit represents this geomorphological zone.

The Nanga Parbat massif marks the northern outcrop termination of the Indian Plate, as a gently northward plunging antiformal structure, and its tectonic contact with the overlying Kohistan island arc forming a ductile shear zone (Butler et

Fig. 3 Schematic workflow for morphometric analyses of the Indus river and its drainage basin
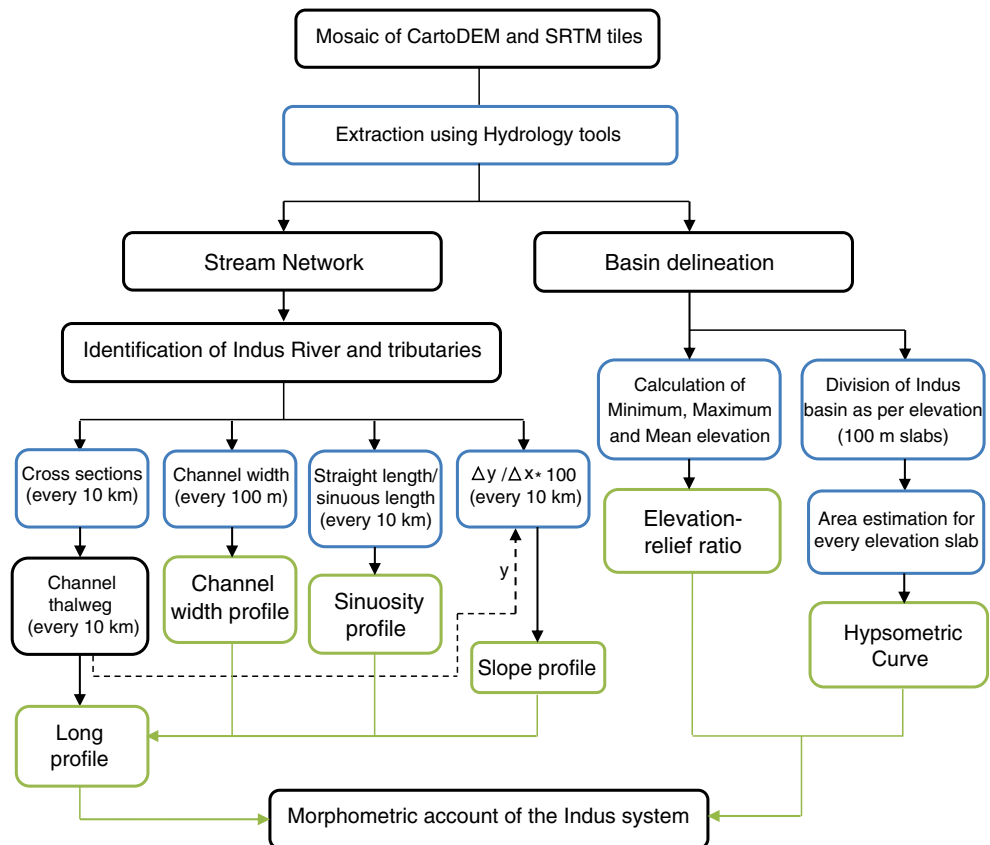
Table 2 Interpretations of HI or E values by previous workers

| Author(s)	Value of HI or E (%)	Description
Strahler (1952)	> 60	Inequilibrium (youthful) stage
	35–60	Equilibrium (mature) stage
	< 35	Monadnock stage
Wood and Snell (1960); Pike (1963)	15–40	Isolated relief features on extensive level surface
	40–80	Broad level surface broken by occasional depressions
Willgoose and Hancock (1998)	> 50	Dominant diffusive/hill-slope processes
	~ 50	Relatively stable, developing landscape
	< 50	Dominant fluvial processes
Singh and Sarangi (2008)	> 50	Approaching youthful stage
	< 50	Approaching monadnock stage
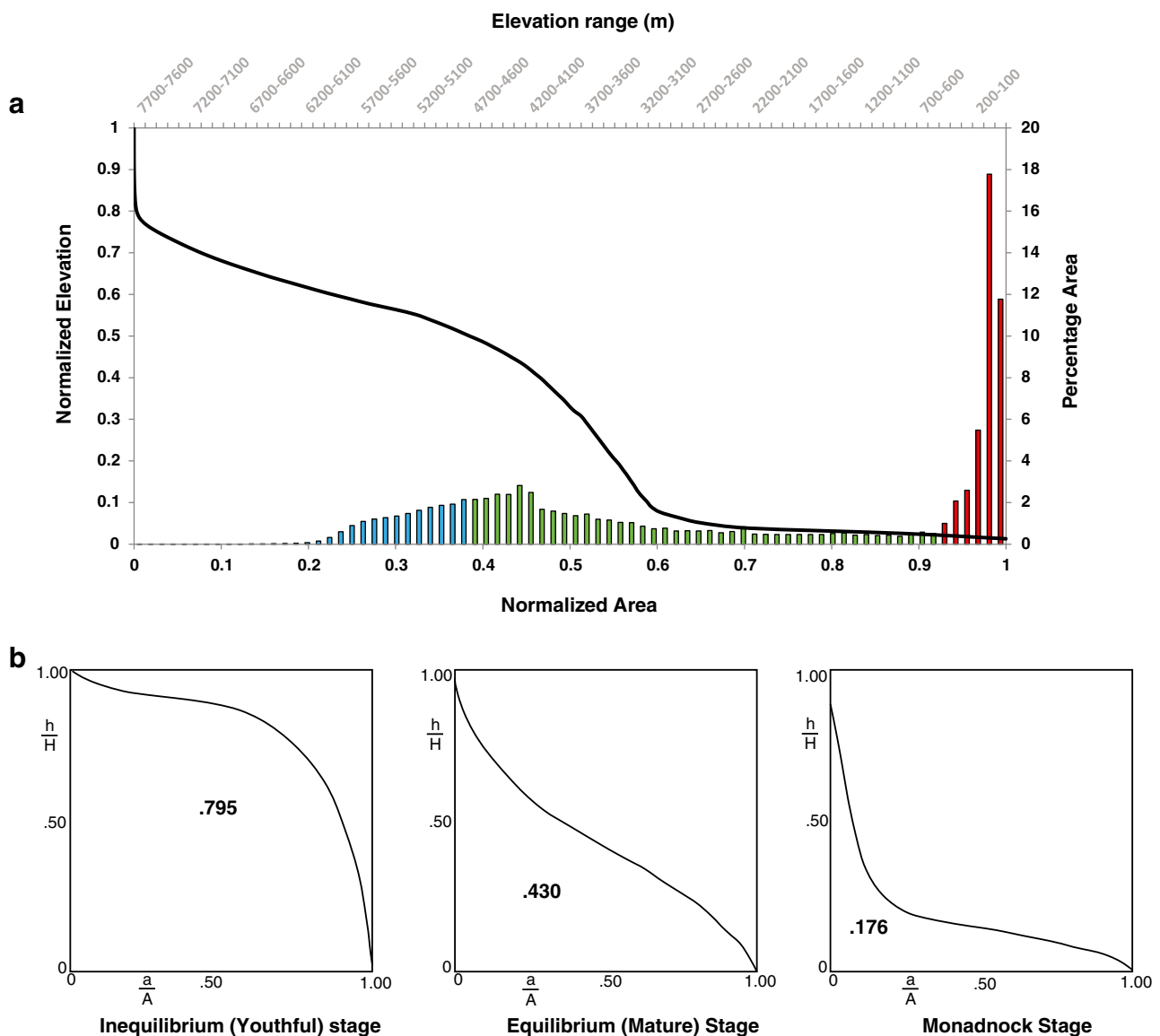
Fig. 4 **a** Hypsometric curve for the Indus basin. Normalized area (primary abscissa) is plotted against normalized elevation (primary ordinate) and the secondary axes show percentage areas within each elevation slab (of 100-m interval). **b** Shapes of hypsometric curves belonging to youthful stage, mature stage, and monadnock stage with HI of 79.5%, 43% and 17.6%, respectively (modified from Strahler 1952)

Table 3 Stages of development within the Indus basin based on hypsometric curve

Sector	Basin area (%)	Relief (%)	Elevation (Absolute)	Stage (as per Strahler 1952)
1	20	Highest 40	7700 to 4600 m	Equilibrium—mature stage
2	40	Middle 53	4600 to 400 m	Inequilibrium—youthful stage
3	40	Lowest 7	400 to − 100 m	Equilibrium—mature stage

al. 1992; Zeitler et al. 2001). It also separates the plutonic rocks of the Kohistan-Ladakh Batholiths from the crystalline shield rocks of the Indian Plate (Dipietro et al. 2000; Ahmed 2013). It is around here that the river takes a peculiar U-shaped bend, around the impervious metamorphic rocks of the Indian shield, in northern Astore district, where it is joined by its tributary—Gilgit from NW, running 245 km in a fairly W-E direction originating from the Shandur Top Lake area. Another 30 km further, a smaller tributary, Astore, joins Indus from the west. A smoother longitudinal profile can be observed from this point forward as the river exits the Deosai mountain range, flowing westward. At around 1150 km from its source point, Indus exits the Indian Territory and enters the Khyber Pakhtunkhwa Province of Pakistan (former North Western Frontier Province).

The first tributary to join Indus in Pakistan is Kandia river from NW, originating from the Hindu Kush Mountains. Just before the confluence of Kandia with Indus, steep channel gradient is observed. The river forms the world's deepest gorge (6500 m from valley floor to ridge crest) in the Patan-

Dasu region (Kazmi and Jan 1997). Kandia waterfalls near Kotgala are said to exist in this area, however, absence of literature deterred the identification of an exact location. Thereafter, the Indus river, flowing in S-SW, exits the rugged, high relief of the Greater Himalayas and progresses into the Lower Himalayans. Significant drop in slope provided the most strategic location for building the world's largest earth-filled dam—Tarbela Dam Reservoir. Constructed in 1974, this dam was built to facilitate irrigation and hydropower generation; but with an annual sediment inflow of over 200 million tonnes, cessation of power generation within a decade and declined irrigation release over the next 30 years is estimated (White 2001). This massive man-made barrier can only be assumed to have caused a major transformation to the course of the Indus river. Comparative satellite imageries at certain locations have been presented and discussed in further sections.

Beyond the Tarbela Dam, Indus is joined by Kabul river—one of the most significant right-bank tributaries of Indus. Spanning across a distance of ~ 400 km originating from the
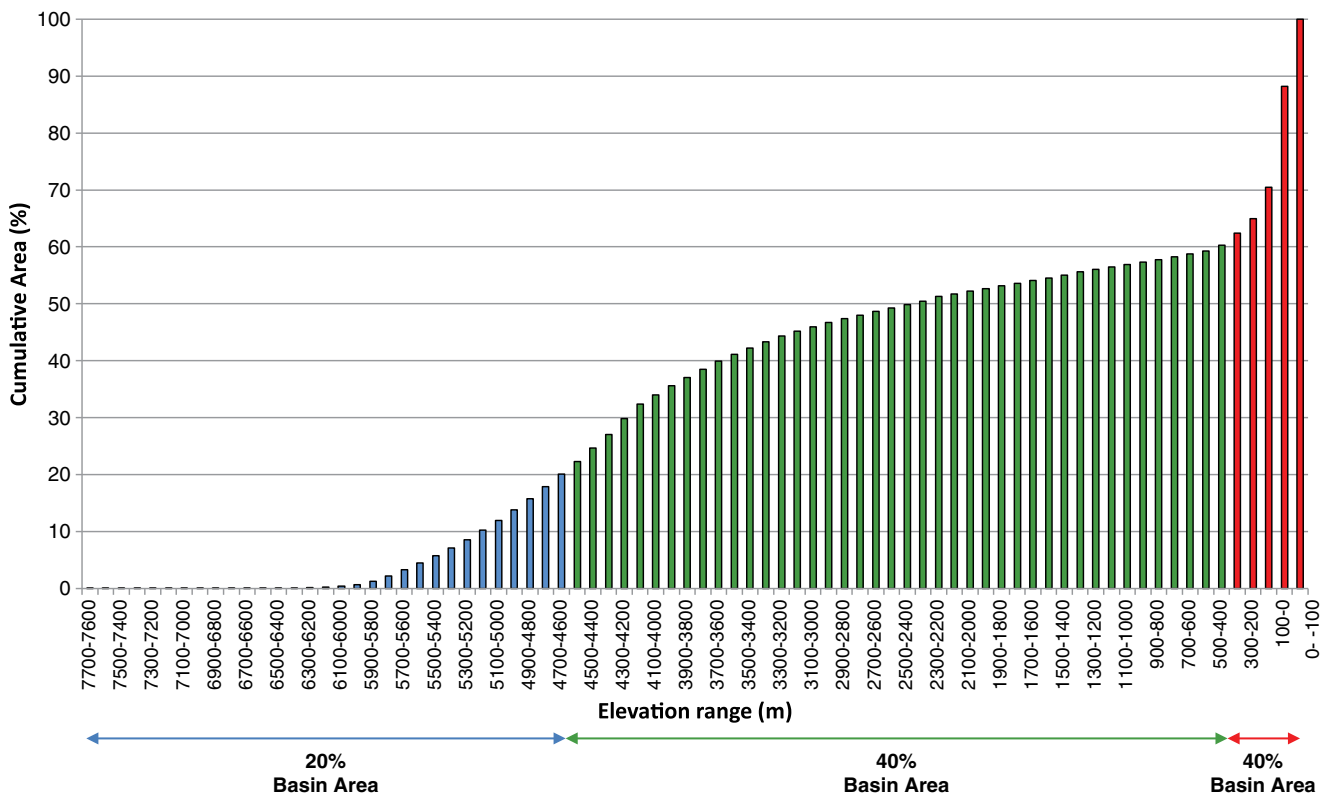

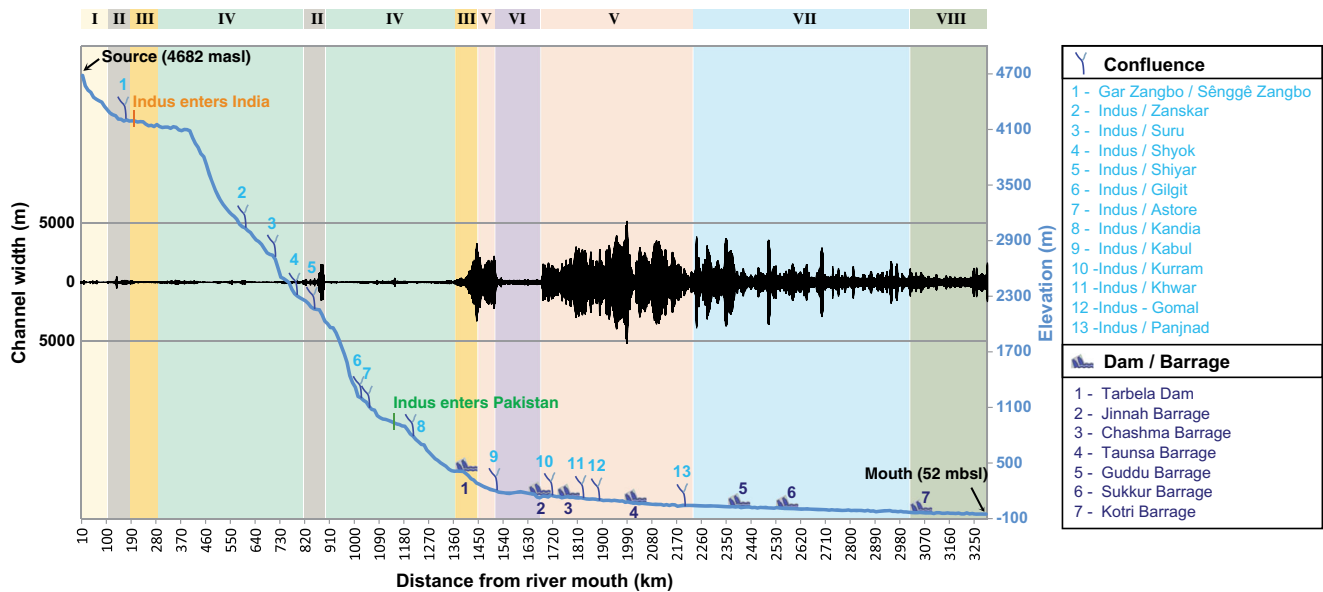**Fig. 5** Hypsometric curve for the Indus basin with corresponding percentage areas

Fig. 6 Longitudinal profile of the Indus river with major confluences/dams/barrages. Channel width is represented as distance from channel axis to either bank e.g., if the width at a given point is 500 m, the graph would show 250 m on either side from 0. Different color bands indicate the extent of each channel type (I to VIII) along the course of the river, refer Fig. 8

Panjshir province of Afghanistan, Kabul flows eastward, co-joined by two rivers from the Hindukush—Kunar and Swat, and unites with the Indus near Attock in Pakistan. Another 20 km downstream, Haro river joins Indus from the east. This confluence has been utilized as another strategic location for hydropower generation, currently operational as the Ghazi Barotha hydropower project. The Indus then continues to flow through the Kohat Potwar fold belt—a distinct geotectonic zone largely covered by Neogene Siwalik molasses (Kazmi and Jan 1997), in Pakistan's Punjab Province. The river divides the Kohat and Potwar Plateau before advancing south towards the Salt Range through the Kalabagh gorge. Its western and north-western parts consist of tectonically active ranges and valleys (Warwick 2007). It is a system of residual hills formed from glacier debris as remnants of the Ice Age (Potwar Plateau 1998), bound by Indus river on the west and Jhelum river on the east (Kazmi and Jan 1997). The middle of the plateau is associated with the structurally downwarped basin of Soan river that suggests tectonic movement in shaping the morphology. The terrain of the basin consists of interlaced ravines, set deep in the soft Shiwalik beds of which the whole area is composed (Ziring and Burki 2016). The Salt Range—a highly upheaved block of the Indian continental Shield is said to be one of the many structural-tectonic subdivisions of the Potwar Plateau (Khan et al. 1986; Gee 1989). The river in this tectonically restricted basin is characterized by near vertical channel walls with minimal scope for lateral expansion—hence characterized by narrow channel width. The Kalabagh fault, forming the western margin of the Salt Range, is known to have caused offset to the course of the

Indus and displaces the Salt Range Thrust (McDougall and Khan 1990; Kazmi and Jan 1997). From thereon, the river enters the Punjab Foreland and is mostly characteristic of broad channel widths, barring few locations which are mostly anthropogenically controlled. The Indus basin from this region till the delta is traversed by a number of basement highs like the Sargodha, Jacobabad etc., extending NW-SE for varying distances into uplifted regions (Khan and Clyde 2013). However, no significant variation in morphometry is observed. As the river flows in the Sind Sagar Doab region (doab refers to land lying between two confluent rivers), it is soon joined by another major right-bank tributary—Kurram. Sourced from the Spin Ghar Mountains of eastern Afghanistan, the rivers runs for ~ 300 km and joins the Indus near Isa Khel town of Mianwali district in Pakistan. Soon after is the Chashma Barrage—constructed in 1971 to regulate the waters of the Indus, 20 km south of Kurram-Indus confluence. Two southern-most right-bank tributaries of Indus—Khwar and Gomal, incise through the Sulaiman Range and join the Indus near Dera Ismail Khan. Maximum channel widening and braiding can be observed from here until the Taunsa Barrage (~ 2000 km from source). The total channel width inclusive of sand bars/temporary islands goes as high as 10 km after the Taunsa Barrage. Further south, Indus is joined by her left-bank tributaries—Satluj, Beas, Ravi, Chenab, and Jhelum, which unite to form Panjnad river shortly before joining Indus near Alipur town in Punjab district of Pakistan. The river thereafter follows a NE-SW orientation, through the Guddu and Sukkur Barrages up till Mohanjo Daro, from where Indus flows southward, parallel
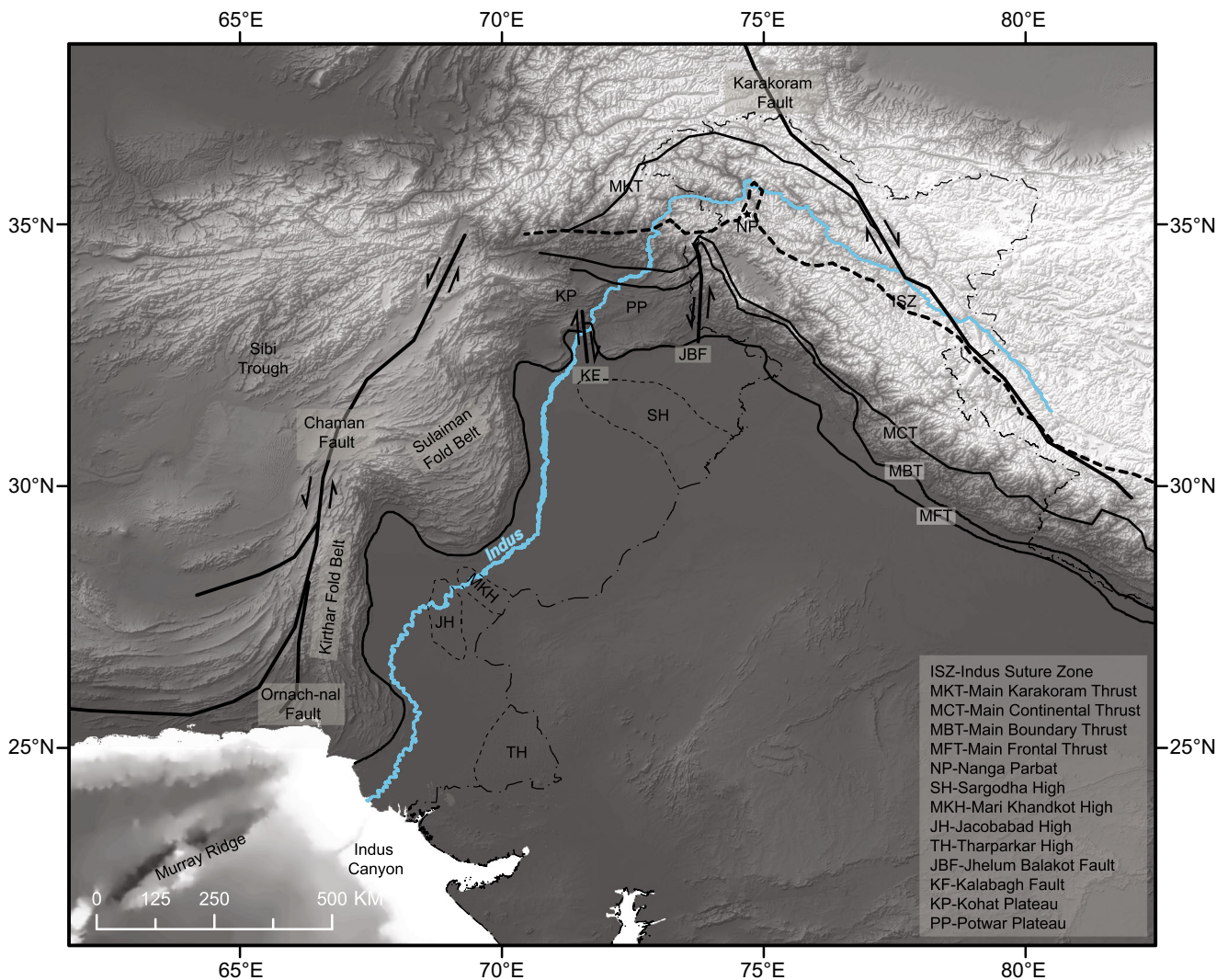
Fig. 7 Tectonic map of the Indus basin with major thrust zones/faults marked; modified from Yin (2006), Afzal et al. (2009), Chen and Khan (2010), Asim et al. (2014), and Mukherjee (2015)

to the Kirthar Range. The Kotri Barrage, last on the Indus, is 300 km away from its delta. In its final reaches, the river roughly extends to a width of 1 to 3 km, before it drains into the Arabian Sea (23° 59′ 33″ N, 67° 25′ 22″ E) near Keti Bandar. Flowing through a complete distance of 3329 km, the river exhibits a variety of planform types.

Planform classification Planform is an aerial/plane view of a feature's form. Indus ideally follows a typical transition of planform along its course, barring a few atypical forms which highlight its uniqueness. Based on the planform and cross-sectional characteristics of a channel, distinct channel types of the river have been identified and interpreted. The extent of each channel type is marked along the long profile in Fig. 6 and described in Fig. 8.

An important distinction, based on Rosgen (1994) and Makaske (2001), between anastomosed and braided channels

is followed in this study. An anastomosing river is a multichannel river which is fundamentally different in form, from a braided river. Schumm (1985) defined anastomosing channels as true multi-channel systems—being different from anabranched rivers which are essentially braided rivers with large exposed bars in relation to channel width. Makaske (2001) further added that anastomosing rivers have multiple channel belts, while braided rivers have a single channel belt but multiple thalwegs (Fig. 9). It was also suggested that anastomosing rivers are a composite form where individual channels belts may be braided, meandering or straight, which basically result from in-channel processes such as lateral erosion and accretion or mid-channel bar formation. Anastomosing rivers result from extra-channel processes, namely, floodplain formation by overbank deposition and avulsion, i.e., the partial diversion of flow from an existing channel onto the floodplain (Makaske 2001).

	CROSS SECTION	SINUOSITY	PLANFORM	DESCRIPTION
I		< 1.25		Vertical downcutting; low sinuosity; no lateral aggradation; typical youthful stage
II		1.25 - 1.5		Anastomosing channel; prime cause - drop in channel velocity/avulsion; sinuosity variable; typical mature stage
III		1.25 - 1.5		Vertical downcutting (non-centered); increased sinuosity than Type I; mild flood-bank deposition; youthful to mature stage
IV		> 1.5		Vertical downcutting and lateral aggradation; increased sinuosity than Type II; siginificant flood-bank deposition; typical mature stage
V		< 1.25		Braided channel; prime cause - drop in channel velocity/increased sediment load; multiple main channels; lower sinuosity than Type IV; large sand bars; typical mature stage
VI		< 1.25		Vertical downcutting; very low sinuosity; no lateral aggradation; structurally controlled; U-shaped valley
VII		> 1.5		Braided channel; single main channel; higher sinuosity than Type V; oxbow/scroll bars/sand bars; mature to senile stage
VIII		> 1.5		Single main channel; badland deposits on flood-banks; higher sinuosity than Type VI; oxbow, scroll bars; senile stage

Fig. 8 Types of channels identified along the course of Indus with their characteristics (refer Fig. 6 for location)

Fig. 9 a Anastomosis of Gar Zangbo in the Tibetan plateau—channel splits from singular to multiple to single again possibly due to drop in valley gradient causing loss of energy. **b** Sênggê Zangbo undergoes anastomosis—channel avulsion may have caused abandonment of one channel, broad channel belt indicates paleo-course. **c** Braided channel belt with multiple streams divided by depositional features. **d** Braided channel with exposed floodplains/sand bars etc. caused by lateral aggradation of the Indus river. Imagery courtesy: Google Earth™
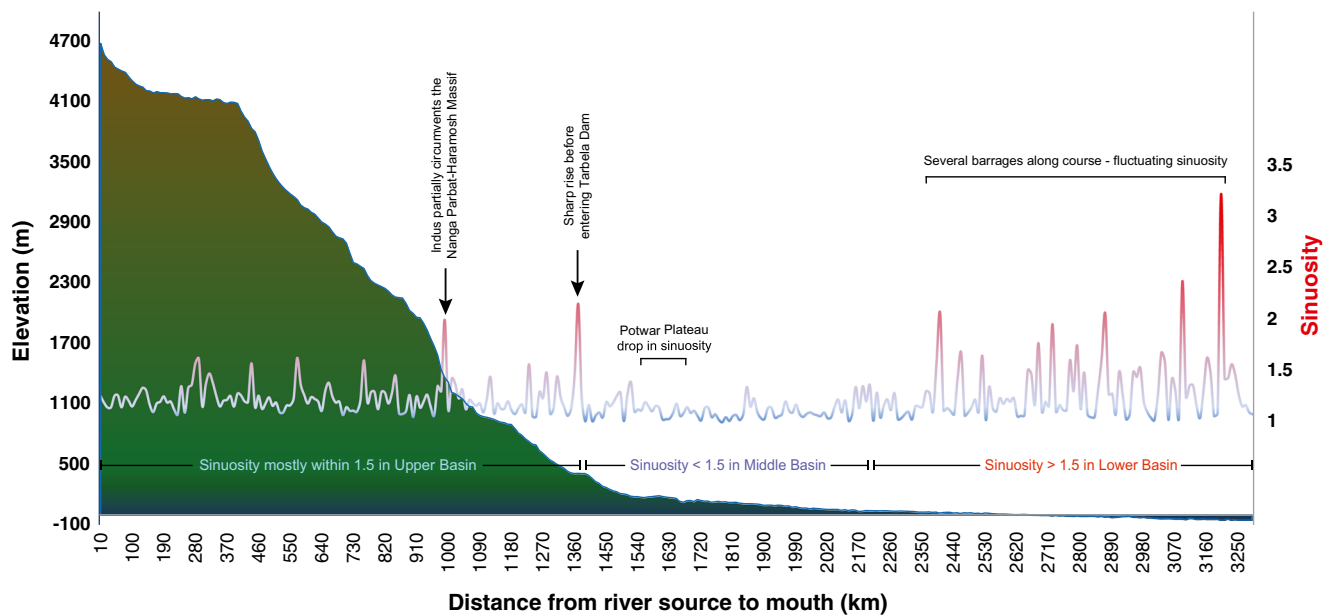
Fig. 10 Plot of sinuosity values measured for every 10 km reach and the longitudinal profile of the Indus. SI ranges from 1.007 to 3.221

Sinuosity analysis

By the value of sinuosity index (SI), streams can be classified as straight, meandering or braided. Rosgen (1994) developed a river classification system wherein, SI was used as one of the parameters to differentiate among river types. Dey (2014) has presented a simpler classification into straight (< 1.1), sinuous (1.1–1.5), and meandering (> 1.5). Makaske (2001) proposed the value of 1.3 as a distinction between straight and meandering streams. Rust (1978) defined rivers with sinuosity > 1.5 to be anastomosing for multi-channel rivers. Stream classification based on sinuosity can thereby be termed as arbitrary, yet, they do help in identifying the general channel behavior.

A sinuosity plot of the Indus river superimposed on its long profile shows a clear increase in sinuosity from source to mouth (Fig. 10). In this river system, SI ranges from 1.007 to 3.221. The first peak of sinuosity can be noticed between 900 and 1000 km—when Indus takes a sharp U-turn in the Astore district. The second peak occurs at 1360 km, just before the river enters the Tarbela Dam. The low sinuosity in the section after the Tarbela Dam is associated with the Potwar plateau region where the river has restricted scope for meandering. Both in the upper and middle basin, the geological formation of the basin strongly controls the sinuosity. However, in the lower basin, the flat terrain coupled with anthropogenic obstructions seem to cause the heightened sinuosity. At the Indus-Panjnad confluence, where five major left-bank tributaries join the mainstream Indus, sinuosity rises slightly at ~ 2170 km, thereafter, sharply rising beyond Guddu Barrage at 2350 km from source, following an undulating form of sinuosity till it drains into the Arabian Sea. It could be an interesting experiment to assess the sinuosity (without the man-made influences) with paleo planform analysis; however, due to limited data, this is currently not in the scope of work.

In this study, sinuosity value is used as a complimentary parameter to distinguish between channel types but is not entirely based on it. Seven types of channel behavior, as shown in Fig. 8 are explained below:

Type I—SI is limited to 1.25 as the channel follows a non-meandering path with greater vertical downcutting and limited lateral aggradation/widening. This pattern is noticed in the first 100 km near the source of Gar Zangbo in the Tibetan plateau from Lake Cuo Ma'erdeng.

Type II—Anastomosing river forms may contain straight, meandering, or braided channel belts within it and sinuosity may be variable. Hence, for calculation purposes, sinuosity is measured for the active channel. SI varies from 1.25 to 1.5. Gar Zangbo undergoes anastomosis after transcending from the highlands towards an unnamed valley (Fig. 9a); Indus also experiences anastomosis in the Skardu valley where Shigar joins the Indus from north.

Type III—Sinuosity range remains the same i.e., 1.25 to 1.5, but channel behavior suggests a developing transition from youthful to mature stage of development. Combined vertical downcutting and lateral expansion are noticeable with greater sinuosity than Type I. Also, cross profiles show smoother gradient. Indus exhibits this characteristic type after the confluence of Gar and Sênggê Zangbo till about 300 km from its source where there is relatively smoother channel gradient.

Type IV—Here, lateral aggradation overpowers erosive vertical downcutting and meandering is noticeably

Fig. 11 Correlation and linear regression plot showing very low positive correlation between sinuosity and slope in the Indus river system

$$y = 0.0194x + 1.2311$$
$$R^2 = 0.0004$$
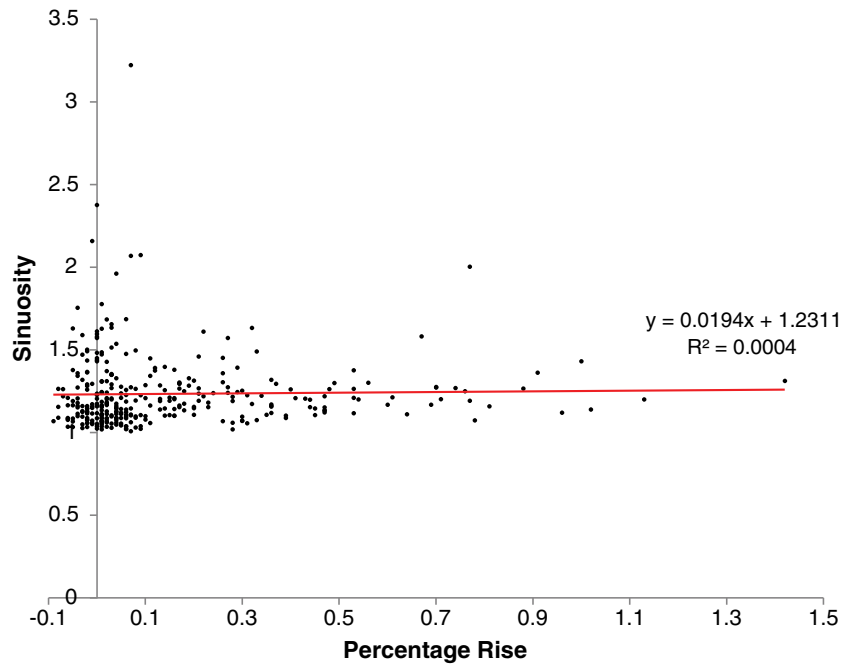
increased. Although vertical erosive powers continue to play, sedimentation of river load in the form of flood bank deposition starts to occur denoting typical mature stage channel behavior. This type continues for maximum part of the upper course of Indus—till the Tarbela Dam—barring the anastomosis observed in Type II zones.

Type V—This is a typical braided channel formation with numerous streams flowing within the channel belt

along large elongated sand bars and islands. Channel belts, as given by Makaske (2001) refer to the zone of activity of a straight/meandering/braided channel including bars and abandoned channel segments. There may or may not be a primary channel i.e., all streams within the channel belt may carry equitable load. Sinuosity is, however, restricted to 1.25 because the channel belt is so wide that is appears to have a non-meandering planform. Once the river exits from the Tarbela Dam towards the
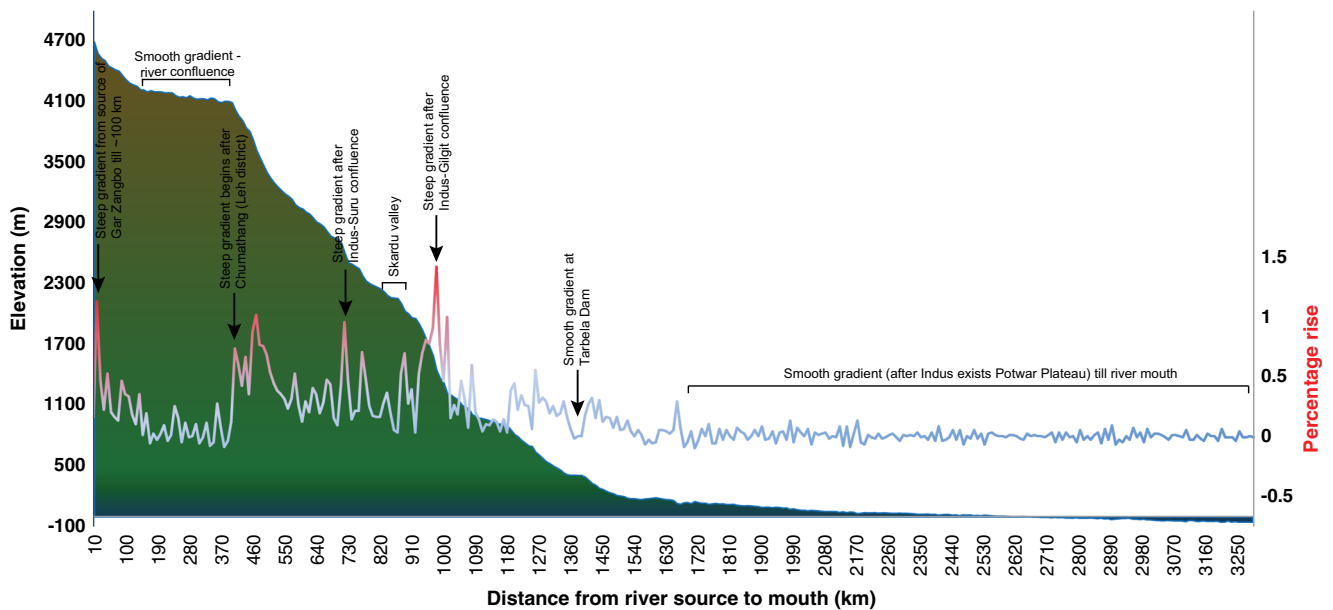

Fig. 12 Plot of percentage rise measured for every 10 km reach and the longitudinal profile of Indus river. Slope (percentage rise) varies from −0.09 to 1.42%

Fig. 13 **a** Satellite imagery of 1984, Guddu Barrage, Pakistan—shows the then active channel with ox-bow formation developing towards the lower reach; **b** Satellite imagery of 2017—shows severe lateral migration of active channel, disappearance of ox-bow and remarkable change of channel belt planform. Imagery courtesy: Google Earth™
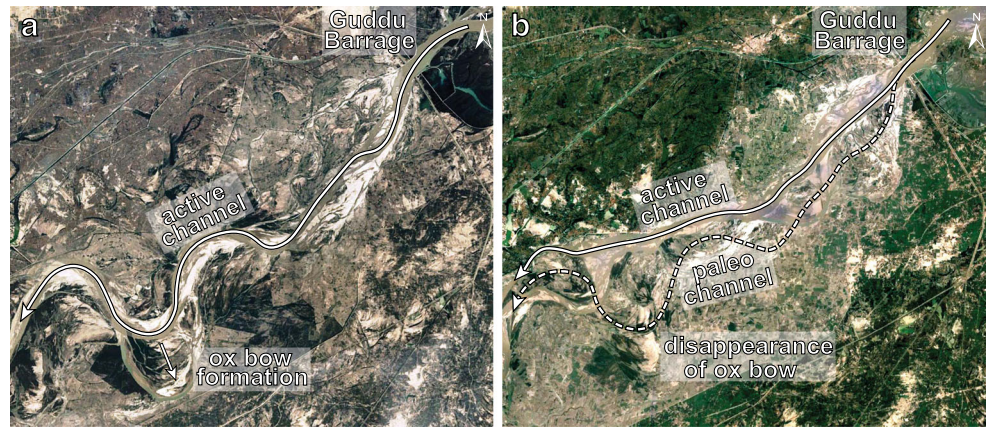
confluence of Indus and Kabul, excessive braiding can be observed. Again, whence the river exits the Potwar Plateau, Indus undergoes braiding (Fig. 9c).

Type VI—A very distinct and unique aspect of the Indus river has been described as type VI in this study, wherein, the channel flows through a structurally controlled and restricted path—carving a peculiar U-shaped valley. Although, these valley types are typical glacial land-forms, the cross-sections of the Indus within the Potwar Plateau show resemblance to U-shaped valleys. Here, channel sinuosity is rather confined to a maximum of 1.25. An otherwise typically youthful channel trait, the Indus river flows through a U-shaped valley in its middle

basin. The most distinct occurrence, causing a drastic change in the channel width profile of the river is the Potwar Plateau. Running from Indus-Kabul confluence till the Jinnah Barrage, it is here that the river's cross-sections reflect U-shaped valleys with relatively straighter walls.

Type VII—This portrays increased channel sinuosity of > 1.5 with characteristics of mature to senile transition. Ox-bow lakes, scroll bars, sand bars, cutoffs, and abandoned channels are commonly observed in this channel type. It is similar to type V with respect to braiding behavior but increased sinuosity with a distinct primary channel is what differentiates this type from the others.

Fig. 14 **a** Satellite imagery of 2001, Indus river after Tarbela Dam—shows a highly braided reach of the river with well-developed depositional features. **b** Satellite imagery of 2017—shows visible difference in channel width (marked in boxes) at several locations within and beyond the channel belt, caused either by climatic or anthropogenic influences. Imagery courtesy: Google Earth™
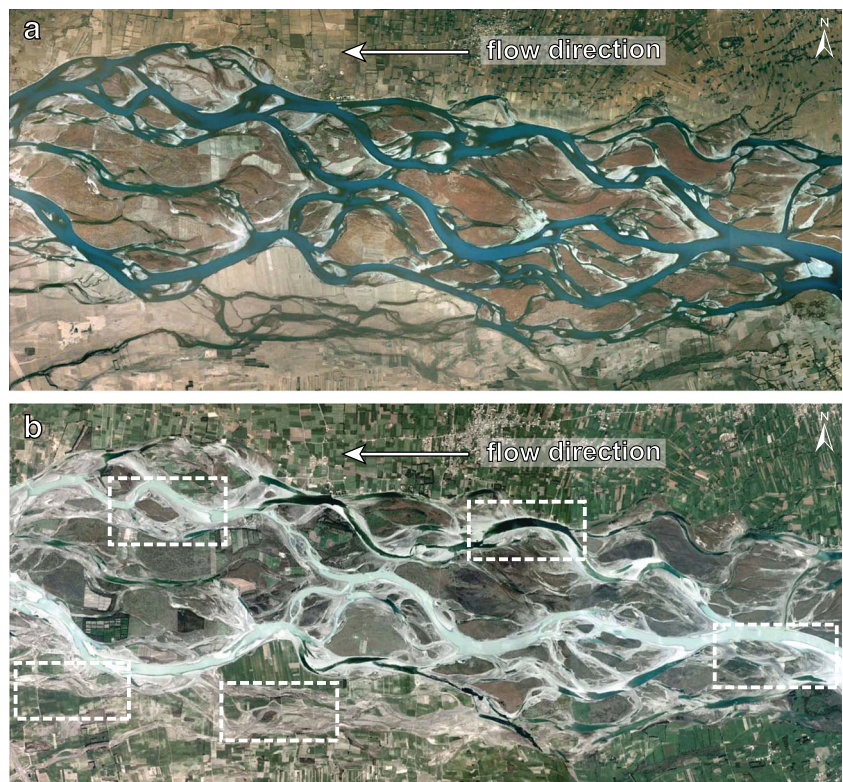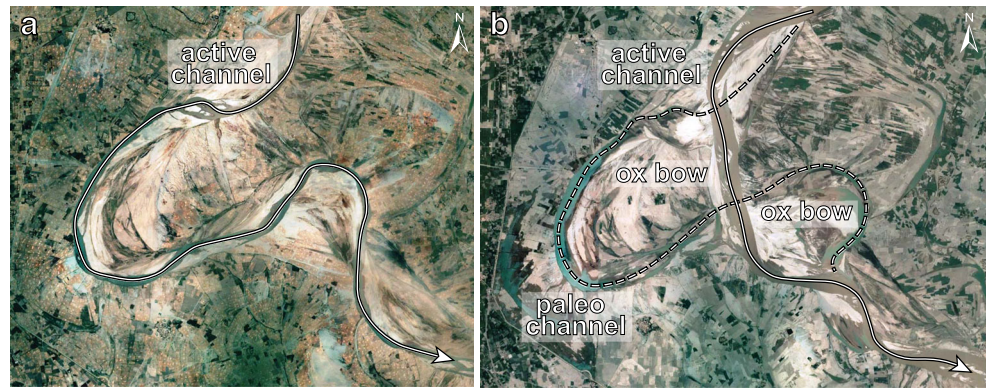
Fig. 15 **a** Satellite imagery of 2010, near Manchhar Lake, Pakistan—shows a highly sinuous channel of Indus. **b** Satellite imagery of 2017—shows two nearly developed ox-bows on either side of the active channel which has majorly undergone lateral migration. Imagery courtesy: Google Earth™


This type is observable from the exit of Indus from Potwar Plateau, up till its confluence with its major left-bank tributary, Panjnad river.

Type VIII—Sinuosity remains > 1.5 with ox-bows and scroll bars at certain locations, however, at this stage there is a singular active channel with remarkably reduced

braiding. As the river approaches senility, the system is deprived of sufficient water flow, making it possible for the river to transport only through one active channel. For the last ~ 300 km of its course (beyond Kotri Barrage), scroll bars are the only characteristic deposits noticeable along the flood banks of Indus. A singular channel, with

Fig. 16 Indus basin divided into upper, middle, and lower basins; major dams/barrages are also marked based on morphometric analyses. Our analyses support precise zonation of different segments of the Indus river system from source to sink
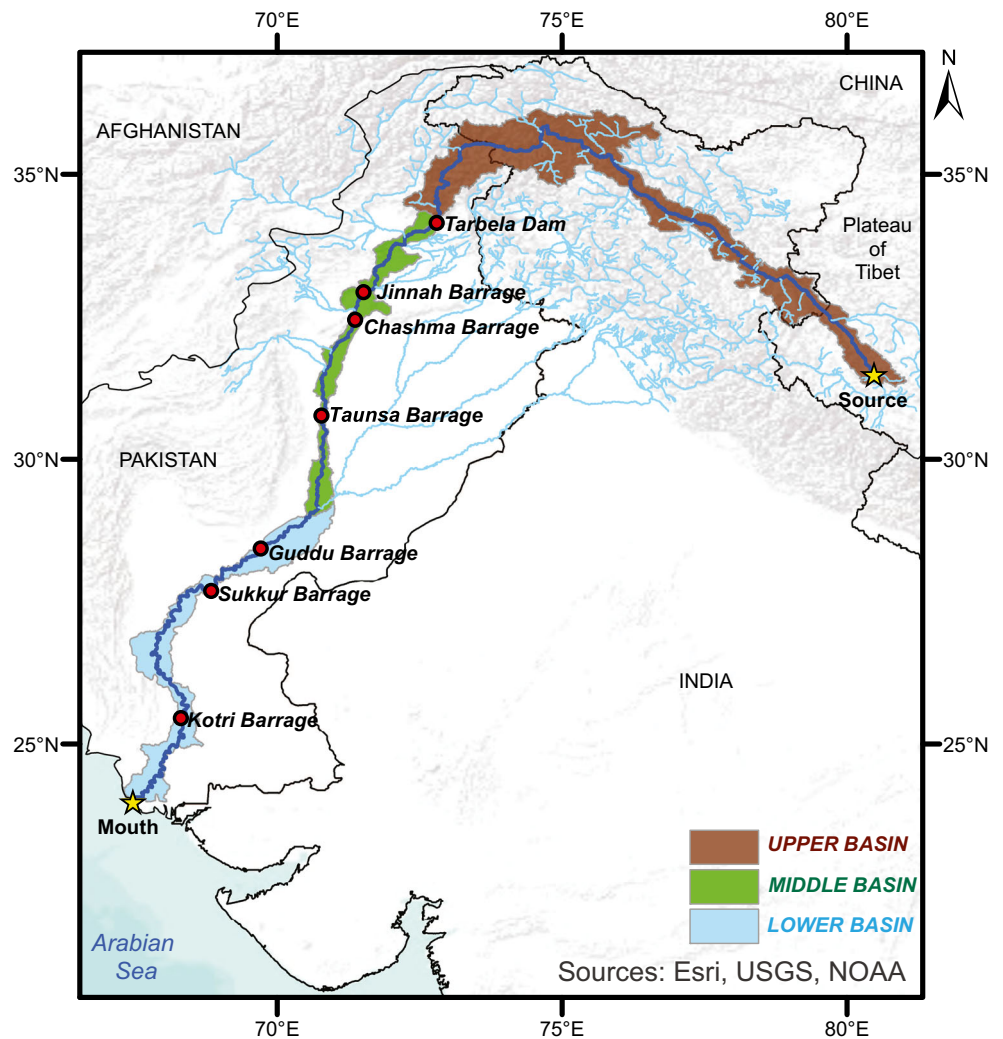
reduced braiding and negligent abandoned channels extends through this region till the Indus drains into the Arabian Sea.

Slope analysis

As defined by Flood and Damuth (1987), sinuosity is the ratio between channel length and valley length; and also a ratio between channel slope and valley slope. For example, a nonmeandering stream with sinuosity equal to 1 would also demonstrate that its channel slope and the valley slope are same (Schumm et al. 2000). However, the relationship between sinuosity and slope is not direct. Schumm and Khan (1972) attempted to test this correlation by performing a series of flume experiments. They demonstrated that threshold values of slope and (or) sediment load exist above which river patterns (in a sense—sinuosity) are significantly altered. At a very low slope and sediment load, the channels remained straight but as discharge increased, meandering channels formed; and with rising slope and sediment load, thalweg sinuosity further increased.

Contrastingly, previous literature also lends credence to the belief that channel sinuosity and valley slope cannot be used to estimate the value of one another and are rather independent variables of stream morphology. Schumm and Khan (1972) stated that flume model studies were difficult to extrapolate to natural river systems and concluded that the role of valley gradient in determining channel sinuosity does not show a strong relationship. Miller (1988) supported this by mathematically establishing the lack of significance of valley gradient in explaining sinuosity.

The morphological parameters of channel sinuosity and channel slope for the Indus river also support the idea of their mutual exclusivity. Correlation and linear regression analyses of sinuosity and slope—indicate a very low positive correlation between the two variables [correlation coefficient ($r =$ 0.02) and coefficient of determination ($R^2 = 0.0004$)] (Fig. 11).

Slope in itself is one of the most basic characteristics of a fluvial system because it helps in maintaining the efficient conditions for transporting water and sediment. The concept of a graded river as defined by Mackin (1948) is a river "in which, over a period of years, slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for the transportation of the load supplied from the drainage basin". Although, it has been felt by Miller and Miller (2007) that Mackin's definition overstates the role of slope, the concept of a graded river is highly valuable in understanding fluvial mechanics. A graphical comparison of Indus's long profile with the slope variable helps in determining the role of causative factors—driving and resisting forces of river morphology (Fig. 12).

The first 100 km of the river's course shows steep gradient which is confirmed by sharp hike in percentage rise. Thereafter, gentler profile can be observed through the confluence valley of Gar and Sênggê Zangbo. From ~ 400 km till around 1360 km near Tarbela Dam, accentuated slope is evident. It is till here that the upper Indus course is dominated by vertical downcutting and increased gradient. The sharpest jump in percentage rise at ~ 1000 km from river source occurs in the Astore district where Indus partially circumvents the northern flanks of the Nanga Parbat-Haramosh Massif (Inam et al. 2007) and joins Gilgit river. Several peaks in percentage rise associated with sharp elevation drops in the long profile—facilitate a quick understanding of the variations in channel gradient. Once the river crosses the Tarbela Dam and exits the upper Indus basin, reduced slope is observable throughout the remaining course of Indus.

Discussion and conclusion

The Indus river, by its sheer enormity and expanse, is one of the most vital river basins of the Indian subcontinent. Its immense exposure to fluvial mechanics, tectonic, and climatic undulations, with anthropogenic influences has given rise to very interesting structural variations, making the morphometry of this river a challenge to interpret. As described briefly in previous sections, the geological and tectonic influences in certain parts of the Indus basin are so vivid that they have steered the evolution of the river course and its adjoining basins. Therefore a multifaceted approach presented above is essential to quantify down-course physio-morphological variations along the Indus.

The Indus river in itself has undergone and is perhaps still undergoing substantial dynamic changes. River metamorphosis, as defined by Schumm (1969) is the complete alteration of river morphology occurring as a result of climate change or anthropogenic causes, is prominent among such changes. Disturbances—either natural or man induced alter the interaction between driving and resisting forces of landform development, such that the system is stressed beyond the limits of stability and equilibrium (Miller and Miller 2007). Disequilibrium hence caused, leads to an altered or metamorphosed form of river system that continuously thrives to attain equilibrium by coping with the new set of prevailing conditions. A river system like that of Indus, which has witnessed severe anthropogenic adjustment over historic time, along with climatic and tectonic upsurges in geologic time—is bound to undergo metamorphosis. Satellite imageries demonstrating such adjustments are shown in Figs. 13, 14, and 15. The imageries exemplify the modified planform of Indus, before and after the construction of barrages/dams or due to other anthropogenic influences. Major course alteration, ox-

bow formations, disappearing smaller channels, etc. are clear evidences of metamorphosis.

The parameters addressed in this study, indicate that the Indus river system is still undergoing river metamorphosis in its form and basinal instability. This is substantiated by the hypsometric curve and longitudinal profile which differ from the theoretical form of river development, and could be attributable to the still evolving middle basin of the Indus. Normally, these measures help in demarcation of upper-middle-lower basins or youth-mature-senile stage of river development, but the Indus drainage basin is far more complex. Very little literature is available on this demarcation for the Indus basin. Most studies have only divided it into upper and lower basins—either without a boundary or at a physical location e.g., at a barrage or dam. These demarcations seem rather arbitrary and scientifically groundless.

Basinal characterization of the Indus river

The upper, middle, lower Indus basins are identified and demarcated to support extensive research in each of these characteristically divergent basins. The basis of this demarcation is the *variation* in the longitudinal profile, planform sinuosity, channel slope and width—each of which is an indicator of stage of river development. Elevation-relief ratio and the hypsometric curve corroborate the overall tectonic/geologic state of the Indus. It is only after a consolidation of all these indicators that the demarcation of the Indus basin has been suggested.

As per the longitudinal profile, the first major physiographic knick-point on the Indus's course is the peculiar elevation drop within 400 km from its source. Precisely after Chumathang village of Leh district, the river follows a steeper gradient and continues so till the Skardu valley. The next major relief contrast is after the exit of the Indus river from Deosai mountain range in Khyber Pakhtunkhwa province of Pakistan and into the flatter plains around Peshawar and Rawalpindi. This location is that of the Tarbela Dam, which acts a reservoir for all the water draining the high-relief terrain of upper Indus basin. In the present study, this *point of contrasting relief* is proposed as the margin of upper and middle Indus basin (Fig. 16). Until this point, the basin is associated with higher relief and the channel type shows youthful to mature characteristics.

As the river progresses from Tarbela Dam towards the Jinnah and Chashma Barrages, it flows through the Potwar Plateau. This relief feature, as previously explained, causes a remarkable change in channel behavior—restricting it from following a typically mature pattern [i.e., sinuosity > 1 with depositional features]. It is only after the river opens out into plains of Sind Sagar Doab that it exhibits mature characteristics with distinct depositional lobes and braided stream flow. From

thereon till the confluence of Indus and Panjnad, type V of channel behavior prevails. Since the channel behavior is remarkably different after this confluence—it is proposed as the middle—lower Indus basin margin.

Distinct increase in sinuosity, limited braiding, and dominance of a singular channel is the characteristic behavior observed in the lower Indus basin. The channel width seems to be quite haphazard, mostly due to the construction of several major barrages. Guddu, Sukkur, and Kotri barrages greatly influence the channel planform in the lower basin. Sinuosity index values seem to be accentuated in the lower Indus basin with a declivity in channel width. In all possibility, these are attributable to the Kotri construction. As held by Khan and Akbar (2012), the overall impacts of man-made changes in the Indus River system are best observed downstream of Kotri Barrage. In the pre-Kotri period (1956–1961), there was not a single day with a zero flow downstream from this barrage which increased progressively following the commissioning of the Kotri and Guddu barrages and Mangla Dam on Jhelum. Inam et al. (2004) found zero flow days downstream from Kotri Barrage to cross 250 days/annum, since 2001 (data recorded from 1956 to 2004). Such research signifies the human interference to explain the on-going river metamorphosis of the Indus system. This demarcation based on key morphometric parameters provides a thrust to encourage research as extended scope, and could hence become a roadmap for further analyses—either from a geological, climatic, or anthropogenic perspective. Our study also has potential implications for understanding morphometric account of other major river systems in the world such as Amazon and Ganga-Brahmaputra.

Apart from its geographic and economic strengths, the Indus also holds great geo-political significance. The Indus Water Treaty, 1960, is by far considered to be one of the finest examples of international water sharing. The treaty, signed between India and Pakistan provides for a peaceful platform to allow optimum yet equitable usage of the river's waters for irrigation, transport, power generation, etc. (FAO 2011). Ranked as the twelfth largest drainage basin, seventh largest delta, and second largest submarine fan globally (Inam et al. 2007), the impact of this fluvial system in shaping the landscape is phenomenal. A river of such vitality, hence, calls for effective monitoring and management for safeguarding the interest of millions of lives running on its support.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Afzal J, Williams M, Aldridge RJ (2009) Revised stratigraphy of the lower Cenozoic succession of the Greater Indus Basin in Pakistan. J Micropalaeontol 28(1):7–23. https://doi.org/10.1144/jm.28.1.7

Ahmed MF (2013) A regional study of landslide hazards and related features in the Upper Indus River Basin, northern Pakistan. Doctoral Dissertations. Paper 2109

Asim S, Qureshi S, Asif S, Abbasi S, Solangi S, Mirza M (2014) Structural and stratigraphical correlation of seismic profiles between Drigri Anticline and Bahawalpur High in Central Indus Basin of Pakistan. Int J Geosci 5:1231–1240. https://doi.org/10.4236/ijg.2014.511102

Awasthi KD, Sitaula BK, Singh BR, Bajacharaya RM (2002) Land-use change in two Nepalese watersheds: GIS and geomorphic analysis. Land Degrad Dev 13:495–513. https://doi.org/10.1002/ldr.538

Babar Md (2005) Hydrogeomorphology of Landforms. Chap. 8 in Hydrogeomorphology: fundamentals, applications and techniques. New India: New Delhi Publishing Agency, pp 142—171

Brice JC (1964) Measurement and description of channel pattern: meandering and sinuosity. Topic in Channel patterns and terraces of the Loup Rivers in Nebraska. Geol Surv Prof Pap 422-D:D1–D25

Butler RWH, George M, Harris NBW, Jones C, Prior DJ, Treloar PJ, Wheeler J (1992) Geology of the northern part of the Nanga Parbat massif, northern Pakistan, and its implications for Himalayan tectonics. J Geol Soc 149:557–567. https://doi.org/10.1144/gsjgs.149.4.0557

CartoDEM v-3 R1 (2015) NRSC Open EO Data Archive (NOEDA). National Remote Sensing Centre, Hyderabad http://bhuvan.nrsc.gov.in/data/download/index.php

Chen L, Khan S (2010) InSAR observation of the strike-slip faults in the northwest Himalayan frontal thrust system. Geosphere 6(5):731–736. https://doi.org/10.1130/GES00518.1

Clift PD (2002) A brief history of the Indus River. Chap. In The tectonic and climatic evolution of the Arabian Sea region. Geol Soc Lond Spec Publ 195:237–258. https://doi.org/10.1144/GSL.SP.2002.195.01.13

Dey S (2014) Fluvial processes: meandering and braiding. Chap. 9. In Fluvial hydrodynamics, hydrodynamic and sediment transport phenomena. GeoPlanet: Earth and Planetary Sciences 529–562. https://doi.org/10.1007/978-3-642-19062-9_9

Dipietro JA, Hussain A, Ahmad I, Khan AM (2000) The main mantle thrust in Pakistan: its character and extent. Geol Soc Lond Spec Publ 170(1):375–393. https://doi.org/10.1144/GSL.SP.2000.170.01.20

FAO (2011) Indus River Basin. In: Frenken K (ed) Irrigation in Southern and Eastern Asia in figures. AQUASTAT Survey – 2011, FAO Water Report 37:129—142

Flood RD, Damuth JE (1987) Quantitative characteristics of sinuous distributary channels on the Amazon deep-sea fan. Geol Soc Am Bull 98:728–738. https://doi.org/10.1130/0016-7606(1987)98<728:QCOSDC>2.0.CO;2

Garee K, Chen X, Bao A, Wang Y, Meng F (2017) Hydrological modeling of the upper Indus Basin: a case study from a high-altitude glacierized catchment Hunza. Water 9(17):1–20. https://doi.org/10.3390/w9010017

Gee ER (1989) Overview of the geology and structure of the salt range, with observations on related areas of northern Pakistan. Special paper of the GSA 232:95–112. https://doi.org/10.1130/SPE232-p95

Hurtrez JE, Lucazean F, Lave J, Avouac JP (1999) Investigation of the relationship between basin morphology, tectonic uplift and denudation from the study of an active fold belt in Siwalik Hills (Central Nepal). J Geophys Res 104(B6):12779–12796. https://doi.org/10.1029/1998JB900098

Inam A, Khan ATM, Amjad S, Danish M, Tabrez AR (2004) Natural and man-made stresses on the stability of Indus deltaic ecoregion. Extended Abstract at the Fifth International Conference on Asian Marine Geology, Bangkok, Thailand (IGCP475/APN)

Inam A, Clift PD, Giosan L, Tabrez AR, Tahir M, Rabbani MM, Danish M (2007) The geographic, geological and oceanographic setting of the Indus river. Chap. 16. In A. Gupta (ed) Large rivers: geomorphology and management. UK: Wiley, pp 333—346

Jarvis A, Reuter HI, Nelson A, Guevara E (2008) Hole-filled SRTM for the globe Version 4. Available from the CGIAR-CSI SRTM 90 m database. http://srtm.csi.cgiar.org

Kazmi AH, Jan MQ (1997) Geology and tectonics of Pakistan Graphic Publishers. ISBN: 9698375007, 9789698375003

Khan MZ, Akbar G (2012) In the Indus Delta it is no more the mighty Indus. Chap. 6. In Boon P, Raven B (eds) River conservation and management. UK: Wiley, pp 69–78

Khan IH, Clyde WC (2013) Lower Paleogene tectonostratigraphy of Balochistan: evidence for time-transgressive Late Paleocene-Early Eocene uplift. Geosciences 3(3):466–501. https://doi.org/10.3390/geosciences3030466

Khan MA, Ahmed R, Raza HA, Kemal A (1986) Geology of petroleum in Kohat-Potwar depression, Pakistan. AAPG Bull 70(4):393–414

Khan AD, Ghoraba S, Arnold JF, Luzio MD (2014) Hydrological modeling of upper Indus Basin and assessment of deltaic ecology. IJMER 4(1):73–85

Mackin JH (1948) Concept of a graded river. GSA Bull 59(5):463–512

Makaske B (2001) Anastomosing rivers: a review of their classification, origin and sedimentary products. Earth Sci Rev 53:149–196. https://doi.org/10.1016/S0012-8252(00)00038-6

McDougall JW, Khan SH (1990) Strike-slip faulting in a foreland fold-thrust belt: the Kalabagh fault and western salt range, Pakistan. Tectonics 9(5):1061–1075. https://doi.org/10.1029/TC009i005p01061

Miller TK (1988) An analysis of the relation between stream channel sinuosity and stream channel gradient. Comput Environ Urban Syst 12:197–207

Miller JR, Miller SMO (2007) River metamorphosis. Chap. 7. In Contaminated Rivers: a geomorphological – geochemical approach to site assessment and remediation. Springer, pp 235–270

Mukherjee S (2015) A review on out-of-sequence deformation in the Himalayas. Geol Soc London Spec Publ 412:67–109. https://doi.org/10.1144/SP412.13

Murphy MA, Yin A, Kapp P, Harrison TM, Lin D, Guo J (2000) Southward propagation of the Karakoram fault system, southwest Tibet: timing and magnitude of slip. Geology 28(5):451–454. https://doi.org/10.1130/0091-7613(2000)28<451:SPOTKF>2.0.CO;2

Pike RJ (1963) Landform regions of southern New England—a quantitative delimitation. In Pike RJ, Wilson SE (eds). 1971. Elevation-relief ratio, hypsometric integral, and geomorphic area-altitude analysis. GSA Bulletin 82:1079—1084

Pike RJ, Wilson SE (1971) Elevation-relief ratio, hypsometric integral, and geomorphic area-altitude analysis. GSA Bulletin 82:1079–1084

Potwar Plateau (1998) In: The Encyclopaedia Britannica Online. https://www.britannica.com/place/Potwar-Plateau

Ramesh P, Pandey DK, Mishra R (2015) Approximation of flow patterns for submarine channel systems in the Arabian Sea using a GIS approach. IJARSG 4(1):1142–1160. https://doi.org/10.23953/cloud.ijarsg.103

Ritter DF, Kochel RC, Miller JR (2002) Process geomorphology. In Singh O, Sarangi A (eds). 2008. Hypsometric analysis of the lesser Himalayan watersheds using geographical information system. Indian Journal of Soil Conservation 36(3):148–154

Rosgen DL (1994) A classification of natural rivers. Catena 22:169–199. https://doi.org/10.1016/0341-8162(94)90001-9

Rust BR (1978) A classification of alluvial channel systems. In: Miall AD (ed) Fluvial sedimentology. CSPG Memoir 5:187–198

Schumm SA (1969) River metamorphosis. J Hydraul Div 95(1):255–274

Schumm SA (1985) Patterns of alluvial rivers. Annu Rev Earth Planet Sci 135:5–27. https://doi.org/10.1146/annurev.ea.13.050185.000253

Schumm SA, Khan HR (1972) Experimental study of channel patterns. GSA Bulletin 83. 1755—1770. doi: https://doi.org/10.1130/0016-7606(1972)83[1755:ESOCP]2.0.CO;2

Schumm SA, Dumont JF, Holbrook JM (2000) Active tectonics and alluvial rivers. Cambridge University Press, UK, p 37

Searle MP (1996) Geological evidence against large-scale pre-Holocene offsets along the Karakoram fault: implications for the limited extrusion of the Tibetan plateau. Tectonics 15(1):171–186. https://doi.org/10.1029/95TC01693

Singh O (2009) Hypsometry and erosion proneness: a case study in the lesser Himalayan watersheds. J Soil Water Conserv 8(2):53–59

Singh O, Sarangi A (2008) Hypsometric analysis of the lesser Himalayan watersheds using geographical information system. Indian Journal of Soil Conservation 36(3):148–154

Sonam JV (2018) Geomorphic effectiveness of a long profile shape and the role of inherent geological controls in the Himalayan hinterland area of the Ganga River basin, India. Geomorphology 304:15–29. https://doi.org/10.1016/j.geomorph.2017.12.022

Stahler A, Stahler AN (1996) Fluvial Processes and Landforms. Chap. 17. In Physical geography: science and systems of the human environment, 2nd edition. New Delhi: Wiley, pp 471–500

Strahler AN (1952) Hypsometric (area-altitude) analysis of erosional topography. GSA Bull 63:1117–1142. https://doi.org/10.1130/0016-7606(1952)63[1117:HAAOET]2.0.CO;2

Warwick PD (2007) Overview of the geography, geology, and structure of the Potwar regional framework assessment project study area, northern Pakistan. Chap. A in Regional studies of the Potwar plateau area, northern Pakistan. U S Geol Surv Bull 2078:A1—A9

White R (2001) Evacuation of sediments from reservoirs. In Appendix 2: Numerical model case study. UK: Thomas Telford Publishing, pp 163—169

Willgoose G, Hancock G (1998) Revisiting the hypsometric curve as an indicator of form and process in transport-limited catchment. Earth Surf Process Landf 23(7):611–623. https://doi.org/10.1002/(SICI)1096-9837(199807)23:7<611::AID-ESP872>3.0.CO;2-Y

Wood WF, Snell JB (1960) A quantitative system for classifying landforms. In Pike RJ, Wilson SE (eds). 1971. Elevation-relief ratio, hypsometric integral, and geomorphic area-altitude analysis. GSA Bull 82:1079–1084}

Yin AN (2006) Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation. Earth Sci Rev 76:1–131. https://doi.org/10.1016/j.earscirev.2005.05.004

Zeitler PK, Koons PO, Bishop MP, Chamberlain CP, Craw D, Edwards MA, Syed H, Jan QM, Khan MA, Khattak MUK, Kidd WSF, Mackie RL, Meltzer AS, Parl SK, Pecher A, Poage MA, Sarker G, Schneider DA, Seeber L, Shroder JF (2001) Crustal reworking at Nanga Parbat, Pakistan: metamorphic consequences of thermal-mechanical coupling facilitated by erosion. Tectonics 20(5):712–728. https://doi.org/10.1029/2000TC001243

Ziring L, Burki SJ (2016) Pakistan. Article in Encyclopædia Britannica. https://www.britannica.com/place/Pakistan