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# Natural Processes and Anthropogenic Activity in the Indus River Sedimentary Environment in Pakistan: A Critical Review

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**Abstract:** The Indus River is Asia's longest river, having its origin in the Tibet Mountain northwest of Pakistan. Routed from northern Gilgit and flowing to the plains, the river passes through several provinces and is connected by numerous small and large tributaries. The river was formed tectonically due to the collusion of the Indian and Eurasian plates, which is referred to as the Indus suture Plains zone (ISPZ). The geological setting of the study area is mainly composed of igneous and metamorphic rocks. The river passed through a variety of climatic zones and areas, although the predominant climate is subtropic arid and sub arid to subequatorial. Locally and globally, anthropogenic activities such as building, dams, and water canals for irrigation purposes, mining exploration, and industries and factories all affected the physical and chemical behaviors of the sediments in various rivers. The main effect of human activities is the reworking of weathered soil smectite, a chemical weathering indicator that rises in the offshore record about 5000 years ago. This material indicates increased transport of stronger chemically weathered material, which may result from agriculture-induced erosion of older soil. However, we also see evidence for the incision of large rivers into the floodplain, which is also driving the reworking of this type of material, so the signal may be a combination of the two. Sediments undergo significant changes in form and size due to clashing with one another in the high-charge river.

**Keywords:** environmental sedimentology; sediment flux; sediment provenance; climate change impact; human role; depositional and erosional history; environmental controls; natural resources; aquatic environment; physical geography

## 1. Introduction

The Indus River is one of the most important rivers in Asia, connecting India and Pakistan (Figure 1) [1,2]. Since Alexander, the Great's expedition to the region in 325 BC, the world's biggest river has piqued academics' attention, and this is the most significant innovation of early and contemporary civilizations in the Indus valley's south Asia [3] that ever since has changed the physical geography of the area. The Indus River originates in Tibet and includes a holy peak called Kailas. The basin encompasses western Tibet, the Himalayas, and the Karakorum. While the top portion of the route passes through India, most of its characteristics (channel and drainage patterns) occur in Pakistan [4]. The river receives a massive volume of sediments as a result of water flow from various tributaries, some of which originate in the Shyok and Gilgit areas, while others originate in the Kabul area [5,6]. Sediment from the Indus River system is eroded preferentially in western Tibet and Karakorum [7,8].

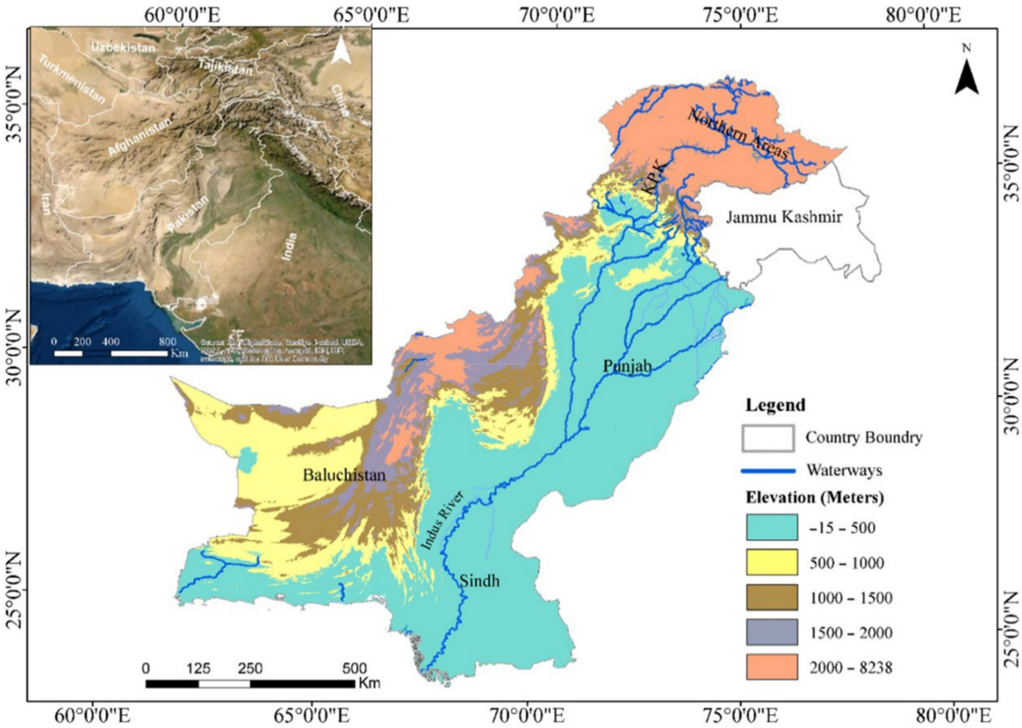


**Figure 1.** Location of the Indus River within Pakistan. Pakistan's topography borders with Afghanistan, India, and Iran are presented in the inset.

Integrated geotectonic and geophysical evidence suggests that the river system was formed prior to 45 million years ago because of plate tectonics (Indian and Eurasian plates) [9,10]. The Indus River system represents significant potential sources of information for determining the various uplifting and erosion activities associated with various periods in the history of the western Himalayas. More significantly, Tibet's development has been linked to the southwest monsoon [11]. The Indus River continues to follow the suture's strike through the Himalayas in northwest Pakistan, flowing continuously to the south portion of the Arabian Sea (Figure 1). The Bengal Fan is the primary feeder river; on the other hand, the Ganges and the Brahmaputra follow the Higher Himalaya along strike throughout most of the orogeny's length [12,13].

Since the dawn of human civilization, rivers such as the Indus have altered numerous fluvial landscapes [14,15]. In the late 20th century, the Indus River played a critical role in the development of modern civilization, while simultaneously raising environmental concerns [16,17]. Urbanization and related human activities pose a significant threat to the river system [18,19]. While human activities like bridge construction and artificial levee construction are necessary for human progress and welfare, they have a detrimental effect on river shape and natural features [20–22]. Prior to the 19th century, this river basin was almost deserted [23]. Following India's separation from Pakistan, many immigrants entered the neighboring rivers and settled around the Indus River [24,25]. Since then, the people have relied on the Indus River to meet their personal requirements and to profit economically. Not only are humans contaminating the river water directly or indirectly, but they are also changing the river's shape [26,27]. However, most published articles (e.g., Inam, Clift, Giosan, Tabrez, Tahir, Rabbani and Danish [4], Yang, Brown, Yu, Wescoat Jr and Ringler [26], Usman et al. [28], Hester and Doyle [29], Al-Ghanim et al. [30] or Tsering et al. [31]) focus on human effects on the river, such as environmental pollution, with just a few studies addressing changes in the physical structure of the Indus River as a result of anthropogenic activity. Moreover, several studies that dealt with human influence on various rivers around the globe have overlooked the Indus river's significance. An additional aspect of its importance relies on the fact that Pakistan is strongly dependent on the Indus River system and its tributaries for all of its water requirements. The building of irrigation and power dams has decreased the river's flow, significantly reducing the amount of freshwater available downstream. Tarbela and Mangla Dams, located upstream of the main agricultural areas, are the sites of two large hydroelectric plants powered by the river. Since Pakistan relies on Indus River Basin irrigation system for 90% of its food resources, this basin accounts for 25% of the country's gross domestic product and Pakistan may be confronted with serious food shortages because of water scarcity. Since the early 19th century, human activities, have had a major impact on the Indus River, while on the other hand the sedimentary environment had a major impact on the Indus River's course in terms of morphological, hydrogeological, and sedimentological changes.

The main objective of the present study is to assess the sedimentary environment of the Indus River system and further highlight how anthropogenic activities have affected hydrogeology and sedimentation. In this regard, water discharge from the Indus River due to the monsoon system and glacier melting due to rising temperatures are discussed in this regional case study. These factors may have a significant impact on the Indus River's water flow across the contemporary catchment areas.

## 2. Geological Setting

### *2.1. Geotectonic Framework*

The Himalayan uplift encompasses and deforms a significant portion of the northern Indian continental plate (Figure 2). Prior to the collision, the Indian continental plate settled in equatorial latitudes with fine-grained sediments, particularly limestone successions, dominating the shelf and high-slope region [32,33]. When the Indian and Eurasian plates met, sedimentation rapidly changed to sandstones, resulting in the formation of new mountain ranges [34–36]. During this process, uplifting and erosion occurred. The sequence involves the development mostly of shales and sandstones, the beginning of mountain rising, and the ultimate birth of rivers along the line of collision separate between the Indian and Eurasian plates, which is known as the Indus suture Plains zone (ISPZ). Although the northwest migration of the Indian plate has slowed since its collision with Eurasia and the subcontinent, it was not halted but continued to travel north towards Asia [37–39]. The northern Indian plate edge was buried as it seems distorted and heated before rapidly returning to the surface due to erosion, while the remaining portion is driven by extensional faulting caused by the fall of the huge mountain volumes under excessive weight [40,41]. The major Himalayan range represents the surviving deformed northern Indian plate boundary, primarily intruded by granite rock bodies that elevated 22 million years ago. Over time, the main compressional force distorted plates and moved towards the southern area of the Indian plate [42]. In this instance, new ranges are emerging in the lower Himalayas [33]. Tectonic activity continued due to erosion in the valleys and adjacent mountains which uplifted to great heights (Figure 2). The most striking and abrupt example is the mountain "Nanga Parbat" which is adjacent to the Kohistan region (Indus south) [43,44]. Over the most recent geological periods, the range of the escalating Nanga Parbat has been >1 cm each year, which is considered one of the world's highest known rates [44,45] with the massif ranges moving towards northwest and southwest directions. Similarly, the plains of the province of the Sindh shelf evolved in the Cretaceous about 70 million years ago [46,47], during when India reconnected to the Seychelles Island [48,49]. The moderate rate of subsidence and sedimentation of the shelf and slope in the southeast of Karachi contrasts with the coastal line and marine geological setting in the west [33].

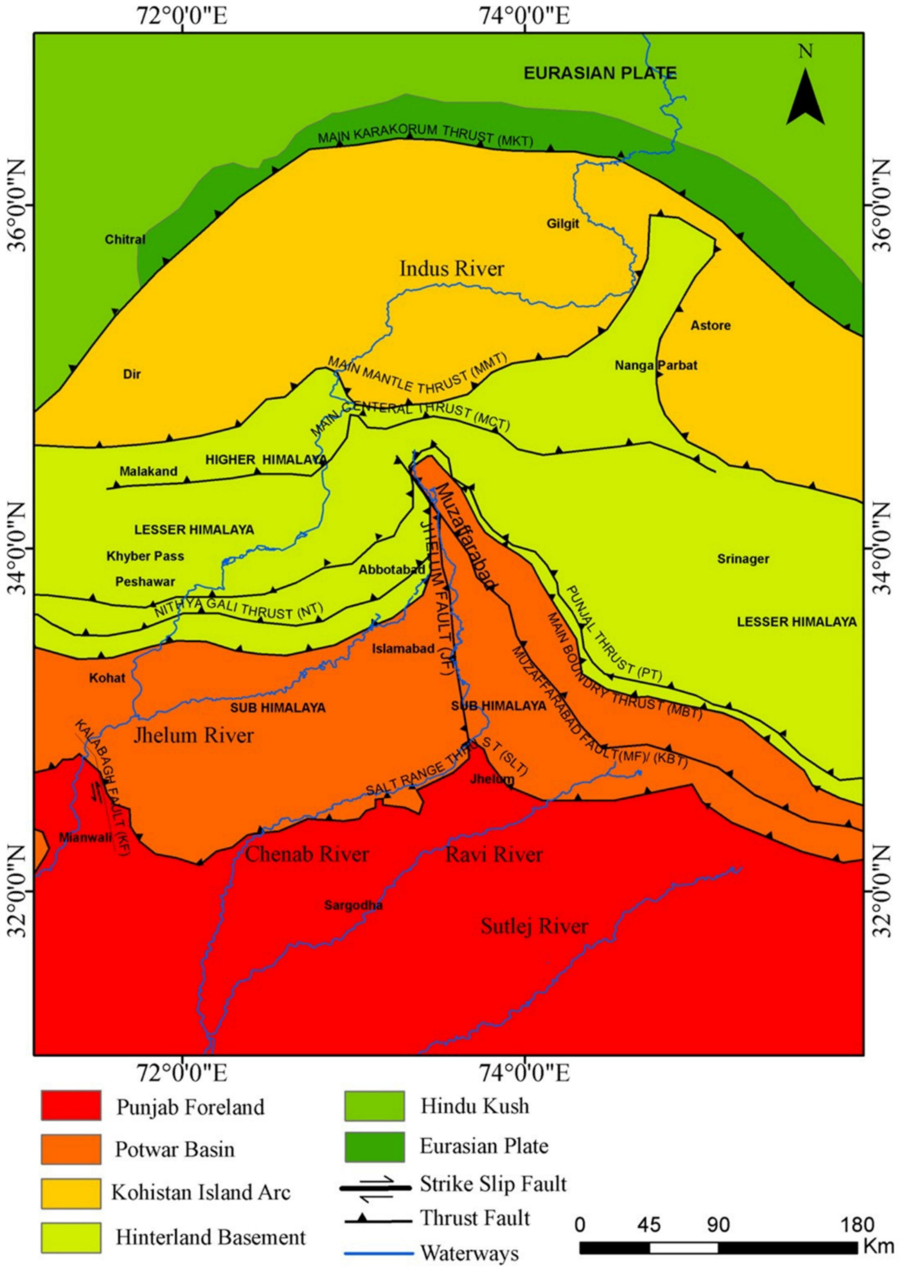


**Figure 2.** Tectonic map showing the main structural features in the northern area of Pakistan.

## 2.2. Seasonal Controls on Hydrological Variability

The Indus River that is passing different provinces of Pakistan covers different climatic zones (Figure 3). In the southwest region of Pakistan, Sindh and Punjab, climatic zonation consists of subtropical arid and subarid to subequatorial conditions [50]. In this regard, atmospheric circulation over the higher part of the basin mainly lies in the monsoonal system as typical of the (sub)tropic latitudes. This variation in climatic regime results in two distinct seasons. The ordinary weather season is between October and April, while the dry northeastern part sets over the plain and the vital portion of the basin. Based on spatiotemporal shifts in monsoon patterns observed during the entire monsoon season, the rainfall increases during summer months (Figure 4) [50–52]. In this period, the basin is subject to another climatic regime, i.e., the primary route of the trade winds began from the side of the Iranian highlands and are then transformed into dry and hot air conditions. The mean annual precipitation on the Indus basin varies from the source of the river to its mouth with mean annual values ranging between 500 and 125 mm, respectively. Although the calculated values by Kravtsova et al. [53] are quite different, they present a similar declining trend from 1270 mm in the mountain region to 100 mm per year. Indus River hydrological history characterized by the above seasonal constraints passes through three different altitudinal landscape zones [54,55]. The upper regions reach towards the river and belong to the high-altitude belt. With the increase in altitude, mostly forest land is encountered within the different landscapes, at a mean height of 4700 m. Hence, the river runs the zone of the savanna and thin forests, while most of the basin is situated in the plains of the Himalayas (Dessertified savanna) [56,57].

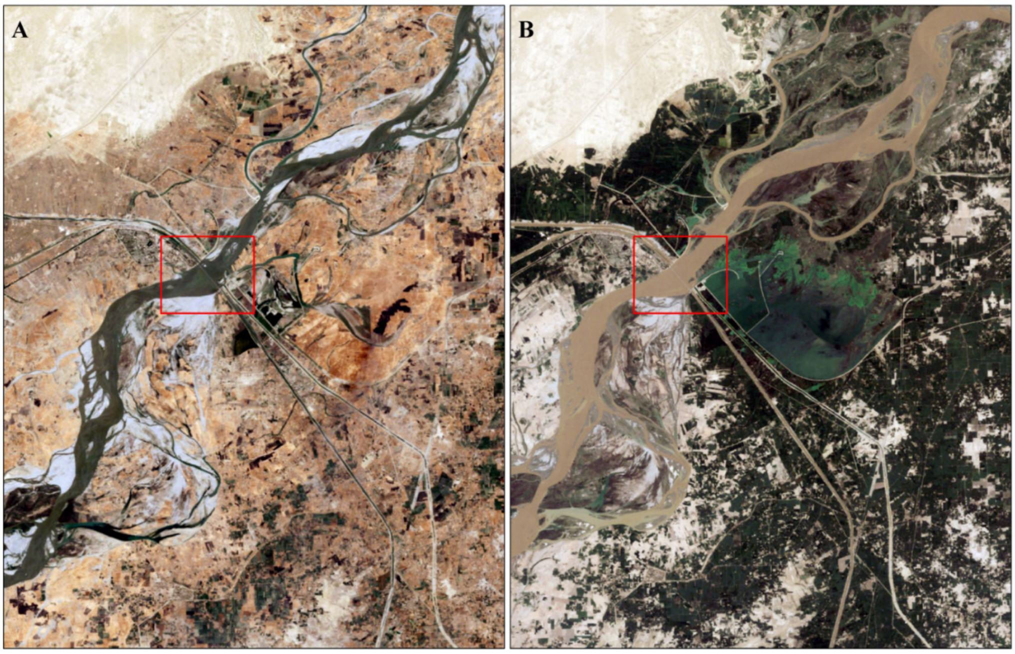


**Figure 3.** Satellite images from the Indus River near the Punjab and Sindh territories in opposite seasons: (**A**) typical shrinkage of the river discharge from May to November, when water is diverted for irrigation; (**B**) the swelling of the river from November to May due to high flow intensity (open access source from NASA Earth Observatory).

According to Giosan et al. [58], no significant changes in the river's route were noticed between 1940 and 1958. Even after the 1952 earthquake, the river's flow remained unchanged. Between 1959 and 2011, five sections of the river were identified where significant alterations occurred along its course [59,60]. Further back over 4000 years ago, the Harappa civilization flourished in the area that is now modern Pakistan and northern India's Indus River Valley, where they constructed complex cities, developed sewage systems that preceded those of ancient Rome, and participated in long-distance commerce with Mesopotamian towns [61]. By 1800 BCE, however, this sophisticated civilization had abandoned its metropolis in favor of smaller settlements in the Himalayan foothills [62,63]. Recent evidence suggests that climatic change forced the Harappas to relocate far from the Indus floodplains [59]. Beginning about 2500 BCE, a change in temperature and weather patterns over the Indus valley progressively reduced summer monsoonal rainfall, making cultivation near Harappa towns difficult or impossible [64,65]. Although the inconsistency of summer monsoons made cultivation challenging along the Indus, moisture and rain arrived more frequently in the foothills, since winter storms from the Mediterranean reaching the Himalayas brought rain and nourished little streams on the Pakistan side [50]. In comparison to the monsoon floods that the Harappas were used to in the Indus, it would have been a little amount of water, but it would have been dependable [66,67]. Rains in the foothills seem to have been sufficient to sustain the rural Harappas for the following century, but even those would ultimately dry up, possibly contributing to their collapse.

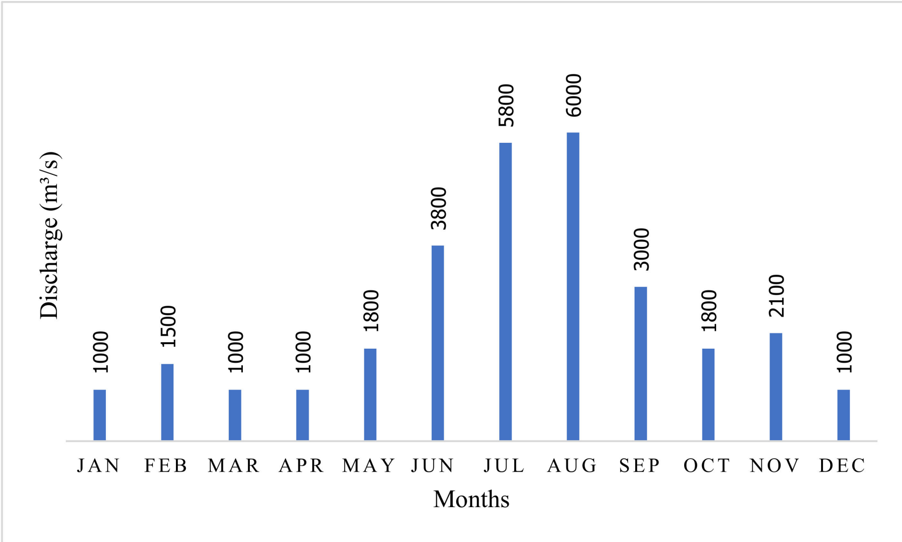


**Figure 4.** Mean monthly monsoon discharge with an entire annual monsoon duration during the time period of 1980–2017. The highest peak was observed from July to August due to glacier melting and monsoon rainfall. The flow rate during the post-monsoon period (September to December) increases compared to pre-monsoon period (January to May) because of a shift in temperature melting glaciers at the end of the monsoon season.

### *2.3. Volumes of Sediment Eroded within the Upper Indus*

Tectonically driven rock uplift and sea-level oscillations regulate sediment production and transport from mountain source to ocean basin [68]. Climate, on the other hand, has long been acknowledged as a supporting factor. The summer monsoon climate in South Asia affects the production, transport, and deposition of sediment from the western Himalayas and Karakoram to the Indus River [69,70].

These processes interact across million-year timescales, making their separation more complicated than over interglacial–glacial timescales [71]. During the Northern Hemisphere's summer, the monsoon delivers rain far inland throughout SW Asia (May–October). The reanalysis of bibliographic data [69,72] allowed the calculation of monthly mean average riverine discharges and the results are shown in Figure 4 with evident differences between monsoonal and post-monsoonal discharges. For the Indus River, the summer monsoon controls hillside sediment production, erosion, and transport [70]. Precipitation in the western Himalaya is 60–80% monsoonal, with 4–6 rainstorms providing 40% of July precipitation and dominating the river sediment movement [73,74]. Summer monsoon precipitation varies throughout the Indus watershed, from 507 mm (76%) in Chandigarh to 385 mm (64%) in Islamabad and 178 mm (82%) in Karachi [71,75]. As a result, the Indus system may experience greater changes in erosion and transport due to monsoon variability. The Indus Fan is 4.5 × 106 $km^3$ of silt spread across 1.6 × 106 $km^2$ under the continental shelf [67]. Despite its 140 km width from the present coast to the shelf edge, the shelf only covers 46,000 $km^2$ [69,76]. After the tidal backwater point, the delta plain extends 12,000 km downstream, with 43,000 $km^2$ of advancing plains to the north, mainly in Sindh, Pakistan [71,77]. The Thar Desert presently spans 140,000 $km^2$. The stem Indus and its eastern tributaries cut and dig 145,000 $km^2$ of floodplains south of the MBT [78].

## 3. Study Area

### *3.1. The Indus Fan*

For most of its life, the Indus fan resides along the Indian-Pakistani border's passive continental margin (Figure 5). The river setting is subtropical characterized by little rainfall (35 cm/year) [79]. The Holocene sediments (dark gray to green silts and muds with some interbedded sands) have a sedimentation rate of 45 cm/year, while accordingly the sedimentation rate during the Late Pleistocene is also considerable (40 cm/year) [80].

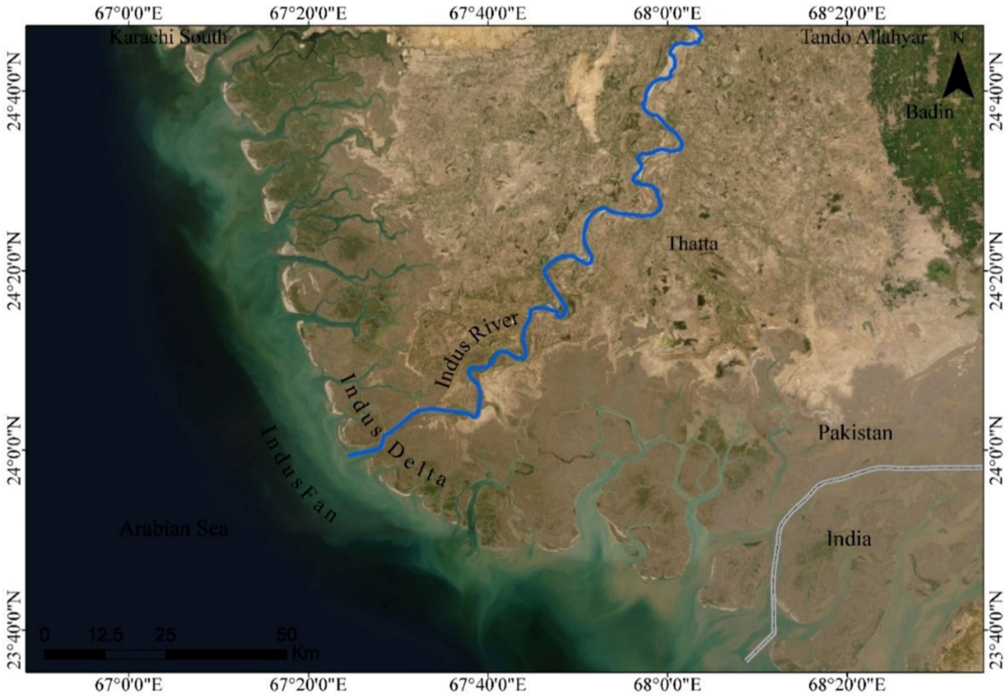


**Figure 5.** Location of several rivers and particularly the Indus River delta in Pakistan.

The huge migration into the Arabian Sea and the Indus fan period has been extensively debated [7,81]. The early Miocene caused rapid erosion of the upper Himalayas, resulting in the development of the Indus and Bengal fans [26,82]. Reconstructions of mass flux that moves into the Indus fan show an acceleration in the sedimentation rate during that time. The main perspective of the Indus fan shows an acceleration of sedimentation in the same period [83]. These mass flow estimates are based on in situ drilling, but the findings are variable between studies. In the foreland sequences, the primary cause of preferred sedimentation and erosion is the change in eustatic sea level. As accumulation is strongly related to changes in sea level over time, fluctuations in the breadth and depth of the foreland trough may thus not be an adequate indicator of mass flow across the Indus system [84].

### 3.2. Upper Indus Basin

The Upper Indus Basin (UIB) is located in the northernmost part of Pakistan, parallel to the Chinese border (Figure 5) [85,86]. The upstream catchment extends from approximately the Tarbela dam reservoir to the coved area, covering an area of ~200,600 km$^2$ [87,88]. The upper Indus basin is home to relatively some of the world's highest ranges such as Karakorum, Himalayas, and Kush Hindu Kush (KHK) with several peaks that attain a height level of >7000 m; including the second largest (K2; 8611 m) in the world [87]. Moreover, some famous glaciers occur in the (KHK). In UIB, the total cover area includes Siachen (75 km)—largest in the Karakoram and the world's second-largest glaciers outside in the Polar Regions Biafo (67.9 km), third biggest in the world Baltoro (62.1 km); Batura (59.8 km); Hisper (53.1 km) [89].

## 4. Environmental Conditions of the Sedimentary Indus River System

### 4.1. West–East Climate and Topographic Contrasts

The climate of Upper Indus Basin (UIB) is warm and dry in summer (around 30 °C) and cold and rainy in the winter (around 13 °C). The environmental conditions belong in the temperate zone, which is mostly located in the shadow of large mountains ranges [87,90]. Indeed, approximately 90% of the UIB falls in the Himalayan shadow zone (HSZ) [87], which results in the drastic reduction of the monsoon winds influence on north-westwards. The main annual precipitation of the UIB at the arid valley floor is 150–200 mm, whereas in the Gilgit region river valley at 4400 m altitude, the precipitation increases to almost 600 mm, and at 5500 m is 1500–2000 mm [91,92]. The climate of the UIB is quite similar to that of the eastern Himalayas [87]. Both the eastern and western parts of the Himalayas have different climatic conditions, with the eastern portion receiving more than 3000 mm more than the western part [93,94]. On the other hand, the western areas receive less than 300 mm per year, which directly and indirectly impact the river's discharge period. Moreover, the spatial and seasonal snow fluctuations vary significantly among areas within UIB. During the monsoon season, the eastern and central Himalayas get massive amounts of snowfall in the winter, that are mainly snow heaps that originate from westerly circulating winds due to northwest (Karakoram and UIB) and westerly circulations [95]. The Himalayan glacier implies the middle Karakorum holds back a large amount of snow, causing avalanches to move downhill to steep slopes. The topography of the UIB also shows great variability from the minimum elevation less than 1000 m in the flat area near the area of Tarbela and Mangla dam reservoirs to over 8000 m at a number of peaks [87,96]. Although, the LIB is mostly dependent on snow and glacier melting water for various sources.

### *4.2. Sedimentary Processes and Characteristics of the Indus River*

The source of eroded sediments into the Indus River from the Himalayans Mountains is due to tectonics. These marine sediments represent the longest succinct archives of continental environmental history that allow reconstructions of the previous geographical patterns, altering habitats, or erosional rates at the time of deposition [60,97]. These archives may then be utilized to evaluate the impact of climatic and tectonic forces on continental environmental conditions. With the marine record, we can determine the flow limit of clastic sedimentary rock from continental sources to the marine sink. The ocean's efficiency varies from days to weeks to >105–106 years [80], while the Asian River systems maintained a relatively constant and mass flow into the ocean for the past two million years due to sediment buffering in a flood plain [76,98–100]. However, there is presently insufficient control in place to determine how efficient this buffering mechanism may be on short time periods.

### *4.3. Traveling Path of Sediments*

Due to the intense tectonic activity, uplift of the mountain range (including the derived sediments) such as the Himalayas Koh-Hindukush, Koh-I-Safaid, Parachinar, the Waziristan agencies ranges, Sulaiman-Kirthar fold belt and Khojak Flysch sub-basins, downstream by several river systems that include Indus, Panjkora, Swat, Kabul, Kunhar, Kurram, Gambila, and Gomal Rivers. The variety of sediments which feed all the above rivers with detritus differ in their origin (igneous, sedimentary, and metamorphic rocks), source areas (even for the weathering products which present a differential flow regime from variable directions) and their age which ranges from Precambrian to the Holocene [101,102].

Following the Last Glacial Maximum (LGM), sediments were carried to the Arabian Sea by a river whose course fluctuated greatly. The deposited silt area is between 4050 and 5675 $km^3$. Most of the depositional volumes come from the upper alluvial plain (10 ka) with the Nanga Parbat syntaxes estimated to contribute 32–40% of the sediment flux (Himalaya), while the Karakoram Mountain contributes approximately 21–27% to the total sediment released (Table 1) [103]. However, in the mountains, sediment is slowed by land sliding, which is influenced by climate [102]. It is found that 5% of terraces in the monsoonal area of the lower and upper Himalayas had been degraded with major bedrock weathering of up to 46% of post-glacial sediments reaching the delta and since changes in the erosional patterns after the 8 ka delta are not reflected in composition shifting, extensive reworking from terraces and flood plains throughout the mid-late Holocene is implied.

**Table 1.** Summary of the volumes eroded along the major rivers of the Karakoram, Hindu Kush and Kohistan rock landslide.

| Source | Average ($km^3$) | Maximum ($km^3$) | Minimum ($km^3$) | Average Contribution Deposited Mass (%) | Average (Gt) | Maximum (Gt) | Minimum (Gt) |
|---|---|---|---|---|---|---|---|
| River Terraces | | | | | | | |
| Karakoram | 15.40 | 240.2 | 67.7 | 2.5 | 416 | 649 | 183 |
| Kohistan and KHK Rockslides | 165.7 | 248.6 | 82.9 | 2.7 | 447 | 671 | 224 |
| Western-River Terraces | 19.0 | 28.4 | 9.5 | 0.3 | 51 | 77 | 26 |
| Flood plains | 647.5 | 925.0 | 370.0 | 10.7 | 1748 | 2498 | 999 |
| Rockslides N.P | 43.5 | 56.6 | 30.5 | 0.7 | 117 | 153 | 82 |
| Rain-shadow catchments | 76.0 | 118.5 | 33.4 | 1.3 | 205 | 320 | 90 |
| Upper-most-river basin | 12.2 | 15.8 | 8.5 | 0.2 | 33 | 43 | 23 |
| Grand total | 1507.8 | 2218.1 | 797.5 | 24.9 | 3993 | 4293 | 1587 |
| Deposited | 6065.0 | 7278.0 | 4852.0 | - | 16,376 | 19,651 | 13,100 |
| Bedrock erosion | 4557.2 | 6480.5 | 3275.4 | - | 12,304 | 17,497 | 8844 |
| % | 75.1 | 89.0 | 67.5 | - | - | - | - |

### *4.4. Source to Sink Transport of Sediment*

Erosion is caused by weathering tectonic forces and climatic changes, which transport sediments and deposit them in the open ocean. The Asian monsoon system influences Indus River and allows the exposure of the various types of the sediments under different climatic conditions. In the northwest region, the rate of erosion is mainly linked to the summer monsoon rain as well as to tectonically uplifted rocks [104,105]. Erosion and sediment transport rates increase with chemical weathering due to the climate change. Since the LGM, the sediments have been stored within the delta plain and submarine fan/shelf clinoforms system [71]. Thus, high monsoon influence reflects the high supply rate of sediments. In Table 2, we present a synopsis of the modern catchment sediment of the major five tributaries of the UIB (based on statistical Kolmogorov–Smirnov (KS) and Kuiper tests for assessing the relative similarities between the observed zircon U-Pb age). The modern river appears to be mostly supplied by the Jhelum and Sutlej rivers. However, the upper Indus basins are in general within a dry source area during the strong monsoon time [106]. The possible anthropogenic activity disruption has resulted in unusual zircon concentrations at the Indus delta [71].

**Table 2.** Modern catchment sediment analysis of five river tributaries.

| Modern Catchment Sediment | Kuiper V | $\pm 1\sigma$ | K-S D Value | $\pm 1\sigma$ |
|---|---|---|---|---|
| Upper Indus | 0.226 | 0.066 | 0.262 | 0.060 |
| Jhelum | 0.164 | 0.045 | 0.129 | 0.049 |
| Chenab | 0.067 | 0.049 | 0.068 | 0.050 |
| Ravi | 0.065 | 0.057 | 0.068 | 0.059 |
| Beas | 0.074 | 0.067 | 0.077 | 0.071 |
| Sutlej | 0.403 | 0.174 | 0.397 | 0.242 |

## **5. Anthropogenic Activity across the Indus River**

In Pakistan, dams, barrages, and bridges are still being built to address the country’s energy deficit [107–109]. Due to its maximum flow area, the Indus River provided potential advantages in terms of constructing dams and using for agriculture purposes (Figure 6) [107]. These kinds of anthropogenic activities are evident especially in the north-western areas and largely affect the sedimentary environment of Indus River, including its tributaries [4,108]. The network of the river system that stretches from the Tibetan autonomous region to China and through the Himachal Pradesh and Punjab in India, is further connected with the Indus River in Pakistan. The rivers Sutlej and Beas (that originate in India, e.g., lake Rakshasa in Tibet) adopt the route for the catchment boundaries between India and China. The active geomorphological system experienced major anthropogenic influence (to both water and sediment fluxes) by the time of civil structure constructions (hydropower bridges and roads) and extensive canal irrigation network systems [109,110]. For instance, the Bhakra and Pong dams were constructed in Sutlej and Beas rivers, respectively (Figure 6), in such a way to stream precipitation to the proposed irrigated cropland in disperse patches at the urban area as well as the grassland [111]. Both Bhakra and Pong reservoirs have multi purposes such as hydro-power generation, irrigation, and regulation of high-level flows during the monsoon seasons [76]. Certain rivers' loads have risen as a result of human activity, especially in instances of land clearing and watershed disturbance; but the loads decrease as a result of dam construction but any additional human impact will be superimposed to changes caused by the current climate change in certain river basins [112,113].

Some of the most important geomorphologic activities on both a local and a global scale related to anthropogenic interventions are as follows: (i) the new land changes in terms of deforestation with the associated mass waste, slop failure and soil erosion; (ii) agriculture and evolving tillage techniques, irrigation systems and subsurface water extraction that will contribute to an increase in soil erosion, creep, siltation and subsidence at the local level; (iii) mining and its role in river channel or hill slop changes that may cause instabilities and subsidence; (iv) transportation systems, that results in further soil erosion and riverbed scouring; (v) constructions of dams or channels, diversions and channel deepening that ultimately increase coastal erosion; (vi) global temperature rises and its various impacts on the atmospheric system and precipitation intensities, cyclonic activity, desertification and an accelerated hydrological cycle; most importantly the increasing needs for aggregate extraction [114,115].

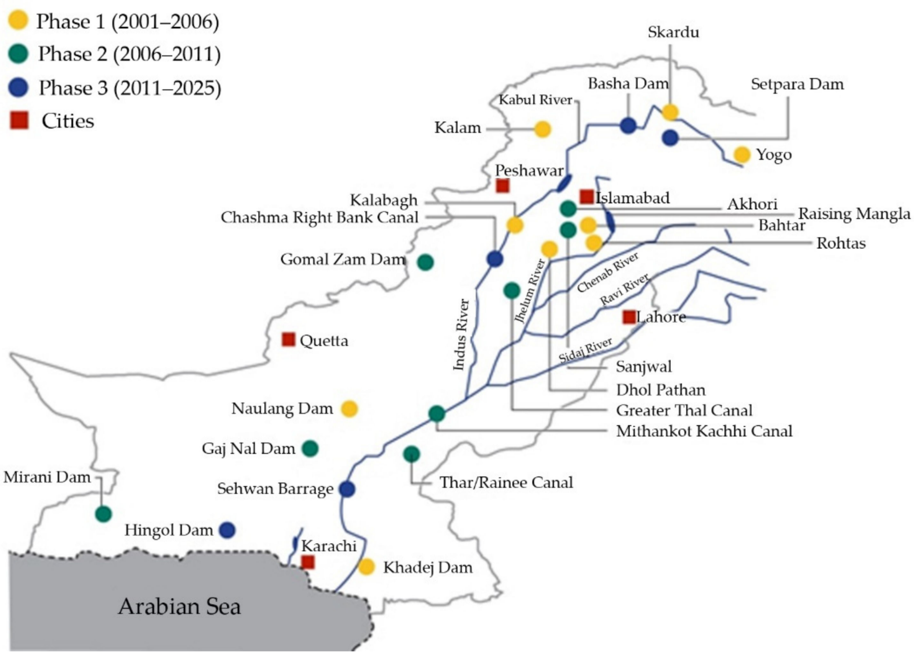


**Figure 6.** Location of dams constructed on different rivers in Pakistan.

## 5.1. Key Drivers

The river system evolution provides the evidence of two key drivers of changes in the behavior on sediments load for catchment of disturbance, which are directly or indirectly connected to human activities: (1) in terms of management land and deforestation, grazing, cultivation, irrigation and intensive monoculture, and (2) on the other hand urbanization, building constructions, sewerage and runoff as well solid waste disposal [99,102]. The industrial activity mainly lies in the sector of mining exploration, industries, and factories. Major human activity in field of civil engineering may also include roads and/or rivers engineering, canal railway lines, highways, and reservoirs (dams) construction. All of the above could be characterized as the most highlighted anthropogenic activity along different areas of the Indus River [116,117].

#### 5.1.1. Dam Construction

Construction of dams reduces sediment load in many rivers worldwide [118]. In the study area, the construction of many barrages and irrigation channels, as well as two major dams, named Mangla and Tarbela, were built on the main Indus River near Darband (Figure 6) [119]. All these geomorphic activities which began in the 1940s were carried out for various purposes such as irrigation and water supply, flood control, and hydropower generation. The impact of these developments on the Indus River's annual discharge and sediment load is also important. In the case of the lower Indus River, annual runoff is at present-day less than 20% of what it was prior to the development of extensive irrigation systems, and the current annual sediment load is also less than 20% of what it was previously [67,117].

#### 5.1.2. Land Clearance and Catchment Disturbance

Many rivers highly characterized by a high rate of sedimentation load caused by several factors like deforestation, intensification of agriculture, mining, land clearance, and related activities located in various areas along the Indus River system, result in increased sediment loads, as opposed to rivers where the sediment load has decreased as a result of dam construction (Figure 7A,B) [117,120]. Furthermore, while dam construction is a relatively recent phenomenon, whose impact can be documented by sediment load records dating back 40 or 50 years, there is an enhanced sensitivity of sediment loads to current environmental changes locally and globally [121,122]. We highlight the changes in the sediment loads of the world's rivers due to geochemical cycling, as well as the links to local and regional impacts and problems, such as the retreat of the delta shoreline due to reduced sediment supply and the distraction of coral reefs because of increased sediment inputs to the coastal seas [118,120].

#### 5.1.3. Coal Mining Influence on Central Indus Basin

Mining is another human activity that has been created along the Indus River's northern and southern banks (Figure 7B) [109,123]. According to the experts, the human input of coal mining operations contaminates natural water and soil. The microbiological control, depositional environment, basin morphology, mineralogy, and hydrological conditions of the area all influenced by its function [124]. Mining water has been discovered to be a major source of toxicity due to increased concentrations of Mn, Se, Cd, and Hg elements, raising concerns about the central Indus basin's ecological status [87,125]. Rainwater has the potential to transport these potentially toxic elements (PTEs) to lower agricultural lands and, eventually, to the Central Indus Basin's main water channel and the River Jhelum [126]. The concerned organization (i.e., Ministry of Agriculture) should make proper regulation of mine tailings mandatory, as they are a potential source of toxic trace elements in the Central Indus Basin's local ecosystem. For the conservation and protection of ecological resources, regular monitoring of PTEs in water quality is recommended around active and abandoned mining sites [87,127].

**Figure 7.** (**A**) Desu hydropower project along the Indus River, (**B**) Pothwar coal mining in the upper Indus Basin.

*5.2. Physical versus Chemical Changes in Indus River Sediments*

The chemistry of the Indus River sediments attempts to constrain the provenance of the erosion and weathering that may have resulted in the characteristics of these sediments [8,128]. The grain size also determines the chemistry of the sediments [129,130]. The lithology of the study area and the weathering of silicate and carbonate rocks from the different provenances heavily influence the geochemical importance of the Indus River water analysis. Anthropogenic activities do not appear to have a significant impact on the water or sediment chemistry in these areas. Therefore, the Indus sediments indicate the important role of mechanical weathering and erosion response to the Himalayan uplift and orogeny. Isotope stability in Delta sediments during the mid-Holocene may indicate increased reworking of floodplains beginning with agriculture linked with the Indus Valley civilization [83,131]. An increase in smectite in the submarine Canyon was also observed by Li, Clift, Murray, Exnicios, Ireland and Böning [75] that may be related to enhanced reworking due to agriculture. This chemical weathering indicator reveals greater transport of stronger chemically weathered material and some of this may be caused by the erosion of old soils broken up by agriculture; although we also have evidence for the incision of the big rivers into the floodplain which is also driving reworking of this type of material, and therefore the signal may be a combination of both processes [71,75,132]. Overall, such reworking of weathered soils could be considered the primary impact of anthropogenic processes in this setting.

## 6. Influence of Natural and Anthropogenic Factors on Hydrogeology

Chemical water–rock interactions have a significant impact on groundwater composition because of the role played by the geosphere [133,134]. The rock type and the manner of weathering of the particulate minerals seem to be the major influences on hydrogeology in bedrock wells [135]. In Pakistan along the Indus river, the chemical composition of the groundwater in fissures and cracks is influenced by the bedrock composition, as is the chemical composition of the groundwater in Quaternary deposits [136,137]. In the absence of human intervention, water quality changes are caused by natural processes such as bedrock evapotranspiration and wind-deposited dust [138]. Water's physical and chemical composition may vary due to natural processes including soil erosion and runoff, as well as hydrological variables that cause runoff and biological activities in aquatic environments [139–142]. The Indus River's natural environment may include both dissolved and undissolved elements as a result of natural processes [125], thus this information should be taken into consideration. As lakes, rivers, streams, and groundwater are natural water sources that sustain life, they must have high-quality water [139]. Due to processes like erosion, leaching, and weathering, there are a number of contaminants present in the Indus river waters; these contaminants can only be reduced in concentration by standard water and wastewater treatment processes, so their presence in a specific water source may restrict its use [143–145]. Droughts and floods may dilute or concentrate dissolved chemicals, changing the water quality [146,147]. When the Indus River flow rates are low, temperature increases, dissolved material concentrations rise, and dissolved oxygen concentrations fall [143]. These changes have the greatest impact on water quality. Natural weathering and rainwater may leach phosphorus from rocks and minerals in the Earth's crust, contaminating surface and ground water and therefore public water systems, with fluorospar, cyolite and fluorapatite [148,149]. For instance, in Pakistan regions of with fluorine-rich volcanic rocks, Rafique et al. [150] found very high fluoride concentrations in surface water.

Heavy rainfalls transport more sediment enriched with nutrients than do light rains, although soil moisture and permeability also have a role in sediment migration [151,152]. The capacity for run-off sediment transport is determined by the relationship between dominant soil flow shear and critical rainfall stress. In coastal regions of Pakistan, large quantities of groundwater usually imply saltwater intrusion [153,154]. Increased quantities of dissolved components in groundwater, especially SO4, Cl, and Na, have been demonstrated by Naseem et al. [155] to indicate the presence of relict saltwater trapped in bedrock fissures and cracks and salty pore water in marine clay and silt deposits. For example, the Tualatin River in Oregon, the United States, has significant background amounts of phosphorus [156]; for arsenic, go to India and Bangladesh [157].

Some agricultural methods in Pakistan may increase environmental pollution, such as overgrazing grasslands, and overusing pesticides, ploughing over irrigated fields and fertilizer application [158,159]. Loss of top soil from fields is the most frequent cause of agricultural water contamination in Pakistan [160,161]. Rainwater mobilizes sediment particles and washes them into adjacent bodies of water, altering the quality of the water [162], since washed into water bodies are contaminants that adhere to soil particles, such as fertilizers, pesticides, and heavy metals. Through algal growth and oxygen depletion, these contaminants put aquatic life at danger. Increases in suspended sediment concentrations and loading rates increase turbidity, a metric for the light scattering effects of water-borne suspended particulate material [163,164]. Aside from these factors, the particle size distribution, refractive index, and water color are also important. Spring and fall have greater concentrations of suspended solids in streams than summer [165]. Agricultural pests in Pakistan are eradicated with the use of insecticides, herbicides, and fungicides. Run-off from fields or air deposition may carry these contaminants into the water, or they can be applied directly to the water. The usage of land for agriculture may lead to a variety of pollutants getting into the water, which contaminate it [166–169]. Pesticides are a class of dangerous chemicals that may be harmful to human health if used improperly [170–172]. Agricultural chemicals pollute water resources through nonpoint and point sources including field leaching, runoff, dumping, and washing. Pesticides pollute surface and groundwater. Abiotic and biotic degradation rates influence water solubility.

Urbanization is a rapidly growing land use [173,174]. Expanding impermeable surfaces like croplands and forests improve air quality and reduce greenhouse gases [175,176]. Impervious surfaces promote nonpoint (diffuse) polluted runoff harming aquatic habitats. Industrialization, sewage discharge, and other household activities damage Pakistani cities more than the rural regions [177–179]. Human activities such as industrial and household wastewater discharge, agricultural chemical usage, and land use and cover changes all impact surface water quality [180,181]. Change in land use and land cover impacts river flow and quality in Pakistan [174,182–184]. Human-induced changes in landscape pattern have significant effects on river conditions.

## 7. Conclusions

The Indus River is one of the largest rivers in south Asia with the maximum flow area in Pakistan. The main origin of this river is from the neighboring country India and it is a connective transboundary river between Pakistan and the Indian border. The Himalayan range is uplifted during the Indian-Asian collision. This activity resulted in the Indus River, which is known as the Indus Suture Plains Zone (ISPZ). The main route of the flow and sedimentation is to the end of the Arabian Sea (Indus fan). The flow starts from the rise in the western Tibet, northwest through the Ladakha and the Gilgit regions of Kashmir and flows southwest through Pakistan before it discharges into the Karachi (Arabian Sea). The early Holocene period was rapid sediment flux to the south Asia deltas. Indus River passes several climatic zones from subtropical arid to sub arid. The subequatorial atmospheric circulation system mainly lies in the higher part of the basin, while the monsoon is typically observed in tropic and sub tropic latitude. The dry months (October and April) in the northeastern part sets over the plain and piedmont portion of the Indus basin. The highest monsoon rainfall takes place in the summer session (May to September), while the annual rainfall drops from 500 to 125 mm from the river source to its delta. The densest anthropogenic activity takes place at the major northern part of Pakistan due to the increased needs for water storage for hydropower energy. These anthropogenic activities cause changes in the environment of the Indus River, causing increased sediment loads due to land clearance for agriculture or other facets such as land disturbance, logging activity in the forests, land mining activity and major civil engineering activity. Mining sediment significantly alters downstream sediment flux that possibly increases the effect of subsidence in the river of the deltas as well as causing scouring around engineering structures. Furthermore, coal mining influences the depositional environment, basin morphology, mineralogy, and hydrological conditions of the area.

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