16

The Geographic, Geological and Oceanographic Setting of the Indus River

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16.1 INTRODUCTION

The 3000 km long Indus is one of the world's larger rivers that has exerted a long lasting fascination on scholars since Alexander the Great's expedition in the region in 325 BC. The discovery of an early advanced civilization in the Indus Valley (Meadows and Meadows, 1999 and references therein) further increased this interest in the history of the river. Its source lies in Tibet, close to sacred Mount Kailas and part of its upper course runs through India, but its channel and drainage basin are mostly in Pakiistan. Recent geological and geophysical information suggests that the Indus River system was initiated shortly after the collision between the Indian and Eurasian Plates prior to 45 million years ago (Clift *et al.*, 2001). The seasonal Indus drains an elevated and tectonically active upper basin that lies across western Tibet, the Himalaya, and the Karakoram. The Indus received water and sediment from a number of large tributaries. These are the Shyok, Shigar, Gilgit and Kabul from the north, and the Jhelum, Chenab, Ravi, Beas and Sutlej from the eastern plains of Punjab. It is the rains of the south-west monsoon of Asia that largely fill the Indus River although most of the run-off north of the Tarbela Dam comes from snow and ice melt. About 37 % of the Karakoram Mountains and about 17 % of the Himalaya in the upper basin carry glaciers (Tarar, 1982). The Indus, Jhelum and Chenab Rivers are the major sources of water for the Indus Basin Irrigation System (IBIS).

Seasonal and annual river flows both are highly variable (Ahmad, 1993; Asianics, 2000). Annual peak flow occurs between June and late September, during the southwest monsoon. The high flows of the summer monsoon are augmented by snowmelt in the north that also conveys a large volume of sediment from the mountains.

The 970 000 km^2 drainage basin of the Indus ranks the twelfth largest in the world. Its 30 000 km^2 delta ranks seventh in size globally. Much of the modern delta plain is rather arid, with swampy areas being restricted to the immediate neighbourhood of tidal channels and coastal plains that undergo tidal flooding. The wave power at the delta coast is about 13 $J\,s^{-1}$ per unit crest width, the fourth most powerful in the world. It rises to 950 $J\,s^{-1}$ (the highest in the world) at the offshore water depth of 10 m (Pakistan Water Gateway, 2003). Offshore, the sediment discharged by the Indus has produced the vast Indus Submarine Fan, about 5 million km^3 in volume (Naini and Kolla, 1982), second only to the Bengal Fan built by the Ganga-Brahmaputra Rivers.

One of the oldest known civilizations developed in the Indus Basin about 5000 years ago thriving on the waters provided by the Indus until weakening of the monsoon

Large Rivers: Geomorphology and Management, Edited by A. Gupta

probably drove this settlement into extinction (Possehl, 1997). The waters of the Indus River and its tributaries are heavily utilised for irrigation in this relatively arid area and the river is a lifeline for the economy and culture of the region (Fahlbusch *et al*., 2004). Around 25% of the modern drainage comprises irrigated crop land. The high population density of the Indus basin (145 people km^{-2}) results in major anthropogenic impacts. More than 90% of the original forests within the drainage basin have now been lost. Moreover, a number of dams and reservoirs in the basin have been constructed for flood control and electricity generation, which in turn have strikingly modified the channel and behaviour of the river.

16.2 THE DRAINAGE BASIN

16.2.1 Geology

The geology of the Indus drainage is largely shaped by the collision between the Indian Plate with mainland Asia, starting at around 50 million years ago. India is the last but largest of a series of continental blocks that rifted away from the southern super-continent of Gondwana, crossing the equatorial Tethys Ocean to form a collage of continental terrains that were stitched together to form the continent we see today. During the late Mesozoic the southern edge of Asia was characterized by north-dipping subduction and development of an Andean-type magmatic arc, whose roots can be seen today in the Hindu Kush and Karakoram. Around 120 million years ago a volcanic arc, similar to the modern day volcanic chains of Tonga or the Marianas in the western Pacific began to form within the Tethys Ocean south of palaeo-Eurasia. As subduction continued and destroyed the oceanic crust between this arc and mainland Asia it eventually collided with the active Asia margin at around 90 Ma. The oceanic ‘arc’ rocks, now exposed in Kohistan, were strongly deformed during their amalgamation with Eurasia. Despite this collision, north-dipping subduction of the Tethys and associated magmatic activity continued, with younger granite bodies, now exposed in Kohistan, intruding the deformed arc.

The Himalaya largely comprises the deformed northern edge of the Indian continental plate. Prior to collision India lay in equatorial latitudes and fine-grained sediments, especially limestones, dominated the shelf and slope regions. As India began to collide with Asia sedimentation changed quickly to sandstones as new mountain belts were uplifted and eroded. Along the line of collision between India and Eurasia, known as the Indus Suture Zone, a sequence of sandstones and shales document the start of mountain uplift and the birth of the Indus River. Although the northward motion of India slowed after the start of collision with Eurasia the subcontinent has continued to move northward into Asia since that time. In so doing India generated the major mountain ranges we see today. The northern edge of India was buried, deformed and heated before being brought back rapidly to the surface due to erosion, but also driven by extensional faulting triggered by the collapse of the giant mountains under their own weight. The Greater Himalaya represents the remains of the deformed northern edge of India that was intruded by granite bodies and then dramatically uplifted around 22 million years ago. As the compressional deformation migrated further south into the Indian Plate with time, new ranges have been uplifted in the Lesser Himalayas and their foothills.

Continued tectonic activity and erosion from the valleys has allowed the surrounding ranges to be uplifted to great heights. The most dramatic example of this is the peak of Nanga Parbat, located close to the Indus south of Kohistan. Nanga Parbat has been uplifting at rates of >1 cm $year^{-1}$ over recent geological times, one of the fastest such rates known anywhere in the world. Nanga Parbat also lies in a special location within the Himalayas, as east of this massif the ranges run NW–SE, while to the west they turn NE–SW. Nanga Parbat appears to mark the western edge of the colliding Indian Plate.

In contrast, the plains of Sindh and the Pakistan Shelf itself were formed in Late Cretaceous times, after about 70 million years ago, as India separated from the Seychelles. The gradual subsidence and sedimentation that have characterized the shelf and slope south-east of Karachi contrasts with the coastal and marine geology to the west. In practice Karachi lies close to a modern plate boundary. The central and eastern Arabian Sea is part of the Indian Plate and has been moving north relative to Arabia along the Owen and Murray Ridges, similar to the Chaman Fault in western Pakistan, along which the Indian block is moving north relative to Afghanistan.

16.2.2 Hydrology

The regional climate is arid to semi-arid with seasonal precipitation and significant variability. Mean annual rainfall is low, ranging from <100 mm over the lower plains to about 500 mm upstream in Lahore. Rainfall is much higher in the mountains, reaching almost 2000 mm in the frontal Himalayan Ranges. About 60% of precipitation is received during the south-west monsoon (July–September). The summer temperature everywhere in the plains is high, rising above 40 °C, resulting in a high evaporation rate. The mean annual evaporation in the upper Indus plain is more than 1500 mm, a figure that rises to over 2000 mm in the lower plains. The lower Indus, especially the delta section, carries an extremely reduced discharge and sediment load which at times do not reach the delta shore face.

16.3 THE RIVER

The Indus is sourced at 5182 m elevation, on the northern slopes of Mount Kailash in the Gangdise Range of Tibet near Lake Mansarowar, close to the source of another major river, the Brahmaputra. The Indus River then flows north-west through the high plateau area of Ladakh into Kashmir (Figure 16.1). The river continues west-north-west past Skardu where it is joined by the Shyok at an elevation of 2730 m. Subsequently, the Indus partially circumvents the northern flanks of the Nanga Parbat-Haramosh Massif, where it first turns north along the Raikot Fault, then west, and finally south-west where the Gilgit River flows into the Indus from the west at an elevation of 1515 m. A number of past slope failures have wholly or partially blocked the river at times, even giving rise to catastrophic dam-failure floods downstream (Shroder, 1993). Cosmogenic dating of surfaces cut and abandoned by the river indicates that the Indus deepens its course at an extremely rapid pace between 2 and 12 mm year^{-1} in the gorge section near Nanga Parbat (Burbank *et al*., 1996). In the same area Hancock *et al*. (1998) found the Indus capable of removing blocks of rock measuring up to 70 cm during the annual peak flow. They associated rock abrasion to the fifth power of local flow velocity and suggested that abrasion happens mainly by suspended sediment. Their measurement of annual abrasion using drill holes was ≤4 mm, which is an order of magnitude higher than the rates derived from cosmogenic nucleii as

Figure 16.1 Indus River eroding Indus Molasse, Ladakh, about 1200 km upstream from the Indus Delta. (Photograph: P. Clift)

the long-term average. It is, however, evident that a very large amount of sediment, part of which is coarse, comes out of the upper Indus due to high erosive rates, periodic floods, and steep gradient of the river.

The river continues in the general south-western direction through a hilly tract as far as Durband, upstream of Tarbela, the location of a major dam of the Indus. Upstream of the Tarbela Dam, the river is deflected to the east in a loop. The Indus receives water near Tarbela through the Siran, a small and extremely seasonal stream that drains the alluvial lands of Mansehra, Abbotabad, and a part of Haripur. Downstream of Tarbela, the landscape changes and the Indus flows in a broad valley for about 50 km downstream where it reaches the Attock Gorge, cut through the compressional Trans-Indus Ranges. The gorge is 160 km upstream of Kalabagh where the plains start at an elevation of 242 m. Downstream of Kalabagh, the Indus flows for another 1600 km to the Arabian Sea. The Indus crosses the Salt Range at Kalabagh.

The upper Indus is a braided stream interrupted by gorges as it flows through the Karakoram, Kohistan, and Himalaya Ranges. The five major tributaries from the east (the Jhelum, Chenab, Ravi, Beas, and Sutlej) join the Indus River immediately downstream of Panjnad at Mithankot. These rivers drain the Lesser and Greater Himalaya and account for much of the sediment flux to the Arabian Sea. Flowing through the agricultural and densely populated Punjab, these rivers are of great importance to the agricultural productivity of the region. The Kabul River, the largest western tributary joins the Indus River near Attock, bringing material eroded from the Hindu Kush and the western Kohistan mountains. About 8 km above the Jinnah Barrage (Figure 16.2), the Soan River draining 12 400 km^2 of highly eroded Rawalpindi, Jhelum, and Attock districts, joins the Indus. It continues to be braided in its upper course in the plains until it reaches the southern Sindh region where it becomes a meandering stream. Downstream of Mithankot, a number of abandoned courses of the Indus can be recognised. Major avulsions of the river took place well above the delta, preferentially around Kashmore and Sehwan and old courses can be traced toward the Indus Delta in the lower Sindh.

16.4 EVOLUTION OF THE INDUS RIVER

Clift *et al.* (2001) showed that the Indus River was formed shortly after the collision between the Indian and the Eurasian Plates prior to 45 million years ago. The Indus is considered as one of the oldest documented rivers. The earliest Indus is older than the uplift that formed the Greater Himalaya during the Early Middle Miocene, L1

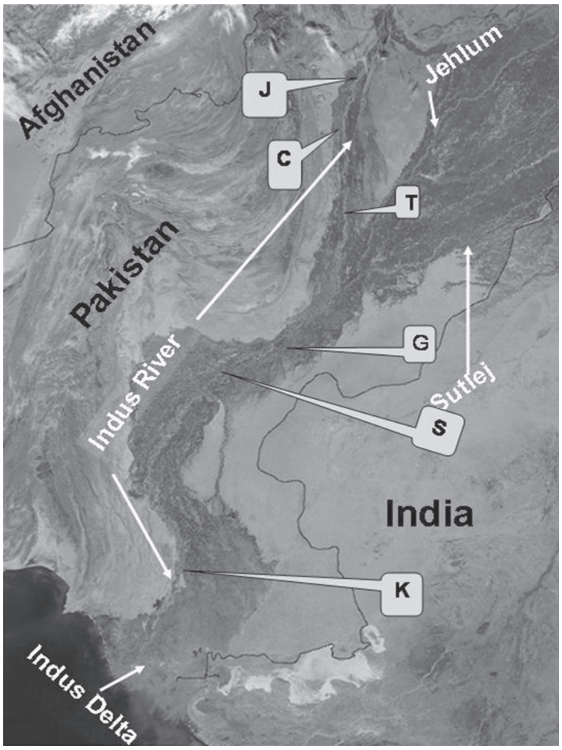

Figure 16.2 Satellite image of Pakistan, with Indus River and its drainage area. Major barrages are marked: K, Kotri; S, Sukker; G, Guddu; T, Taunsa; C, Chasma; J, Jinnah. (Image from NASA Visible Earth)

around 25–20 million years ago (Searle and Owen, 1999), and the river has followed a similar course along the Indus-Tsanpo Suture Zone in southern Tibet and Ladakh since then. According to Qayyum *et al*. (2001) two parallel west-flowing streams were in existence during the Eocene, one north and the other south of the Himalaya. These rivers jointly formed the Katawaz Delta at the western margin of the Katawaz Ocean, an embayment of the larger Tethys Ocean. The northern stream they recognized as the palaeo-Indus. The sediments of the Katawaz Delta were then axially fed into the Khojak submarine fan towards the west, now accreted and exposed in the ranges of the Makran accretional complex in Pakistan and southeast Iran.

The main stream of the Indus River has not shown much deviation from its past course in spite of tectonic events such as the uplift of the Sulaiman Range west of Punjab that displaced the main stream about 100 km towards the east since the Early Eocene. Subsequent growth of the Sulaiman Range must have pushed the course of the Indus southward by 200–300 km (Clift, 2002). Najman *et al.* (2003) interprets that 18 million years ago the palaeo-Indus first followed its modern course, cutting south through the Himalaya and into the foreland basin. According to Clift (2002), it has been flowing in approximately the same location since then. Shroder and Bishop (1999) were of the opinion that the Indus River was flowing somewhat north and well to the west of its present location during the late Cenozoic, but was captured and diverted to the south close to the Nanga Parbat massif of today as a result of extensional structures and downfaulted topography across the Kohistan Ladakh island arc terrain.

Using isotope data to trace evolving provenance Clift and Blusztajn (2005) have shown that the source of the sediment reaching the Arabian Sea changed sharply after 15 million years ago. The sudden increase in very radiogenic sediment into the Indus River was interpreted to reflect large-scale drainage capture of the Punjabi tributaries into the Indus shortly after 15 million years ago. The reason for the large-scale transfer of drainage from the Ganga to the Indus is not clear but was probably linked to regional subsidence in Pakistan caused by uplift of the Salt Ranges during the Pliocene.

In the restricted migration of the main channel, the Indus differs from several other large rivers. For example, the Nile (Said, 1981), Colorado (Elston and Young, 1991), and Amazon (Hoom *et al.*, 1995) all have present courses that differ from their past locations during the Late Miocene or later periods following regional uplift in their basins. The Indus remained pinned in the suture zone and flowing along an active strike-slip plate boundary within its foreland. The Indus therefore is located in an active tectonic region but without significant change in course through time.

Larger changes, however, are seen near its mouth. Since the last glacial maximum (about 20 000 years ago), the location of the main depositional lobe of the Indus Delta and the main channel had shifted significantly westward four times until it came to occupy its present course (Kazmi, 1984). The Indus River and its delta are prevented from moving further west by the uplifting ranges running north from Karachi.

16.5 THE INDUS DELTA

During the Holocene, the Indus has formed a vast deltaic complex in southern Sindh, most of which has been abandoned due to frequent natural channel avulsions. Much of the alluvial plain from the modern delta coast to north of Sukkur (Figure 16.2) has probably been formed during the last deglacial period and the Holocene, when the Indus

L1

River filled its own valley system that was incised during the last sea level low-stand (Kazmi, 1984). Several remnants of the pre-deltaic relief composed of Eocene limestone outcrop within the delta. A relic feature of the pre-Holocene relief is the Indus Canyon (Figure 16.3), which is erosional in its upper part on the shelf and slope, where no levees are present (von Rad and Tahir, 1997). Because of the high sea-level stand, the impact of fluvial sediment is not strong enough to maintain a supply of coarse sediment to the deep-sea. The delta extends to the east into the Great Rann of Kutch, a vast mudflat area that is invaded by storm surges during the summer monsoon. The Rann of Kutch is probably a former gulf of the Arabian Sea that has been filled by deltaic deposition (Malik *et al*., 1999; Rajendran and Rajendran, 2001 and references therein).

The lobate delta of the Indus formed under arid climate conditions under important but highly variable river discharge, a moderate tidal range, extremely high wave energy, and a strong monsoonal wind system. The relatively coarse grade of the river sediments and the fact that most sediment is delivered in phase with summer monsoon wind setup that promotes retention of sand close to the shore was proposed to have favoured rapid expansion of the subaerial delta (Wells and Coleman, 1984). However, high silt and low carbonate contents in surface sediments on the modern Indus shelf (Nair *et al*., 1982; Khan *et al.*, 1993) show that sediments from the Indus River are dominant to depths of ~60–70 m. Geophysical and core data near the Indus Canyon show only patches of a thin veneer of Holocene sediments suggesting that the outer shelf has been largely nondepositional during the Holocene (Rasul, 1992; Prins *et al.*, 1995; von Rad and Tahir, 1997). The modern coastline is dissected by numerous tidal creeks that are reworked remnants of former river channels. The intricate network of creeks once supported one of the largest mangrove systems in the world. Dispersal of sediments delivered to the Arabian Sea by the river is accomplished by tidal and wind-driven currents. Tides are semidiurnal with a tidal range at the Karachi gauge of

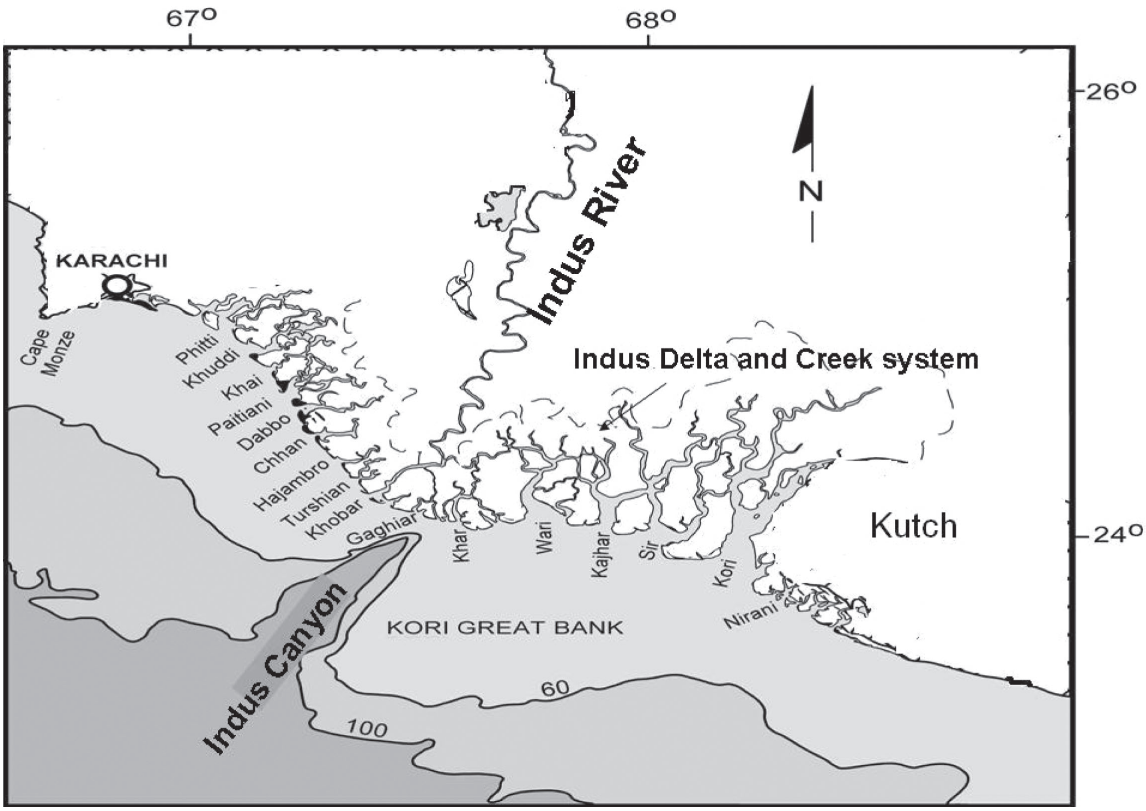

Figure 16.3 Lower Indus River with a network of major creeks and offshore bathymetric features (modified from Giosan *et al.*, 2006)

2.7 m. Measurements near Karachi show that the mean current switches from south-westerly during the summer monsoon to north-easterly during the winter monsoon (Rizvi *et al.*, 1988). The Indus Canyon is also presumed to have played a role in preventing the subaqueous delta from developing by capturing and funnelling sediment towards the Indus submarine fan (Islam, 1959; Nair *et al*., 1982; Wells and Coleman, 1984). The Indus shelf exhibits a clear compound clinoform morphology (Giosan *et al.*, 2006). Accumulation and erosion occurred primarily on the nearshore clinoform that extends along the entire delta coast from the shoreline to the 15–25 m water depth. At the active Indus mouths, the nearshore clinoform has built directly into the Indus Canyon, where sedimentation rates exceeded 50 cm year^{-1}. A second clinoform developed offshore between 30 and 90 m water depth is composed of three distinct lobes (Giosan *et al.*, 2006).

Abandoned Indus delta channels have been reworked by tides all along the coast into dendritic tidal creeks (Figure 16.3). The tidal creek network appears to be most extensive and mature east of the present Indus mouths (Khobar, Gaghiar) towards Kutch, where the coast has a dissected appearance typical of tide-dominated deltas. The wide channels of this eastern delta plain (Khar, Wari, Kajhar, Sir, and Kori) penetrate deep inland, leading to flooding of wide areas of the lower delta plain and the Rann of Kutch during the summer monsoon (Figure 16.3). The deltaic coast from Karachi to the river mouths exhibits a dense, less mature tidal channel network. A stronger wave influence along this part of the coast compared with further east is suggested by the frequent occurrence of drumstick-shaped barrier islands (Figure 16.4), typical of island systems significantly influenced by both waves and tides (Stutz and Pilkey, 2002).

16.6 SUBMARINE INDUS SYSTEM

Seaward of its delta, the Indus is transformed into a complex and spectacular distributory system which has created the world's second largest submarine fan in the Arabian Sea. The basic elements of this vast distributary system are deeply incised Indus Canyon, pronounced

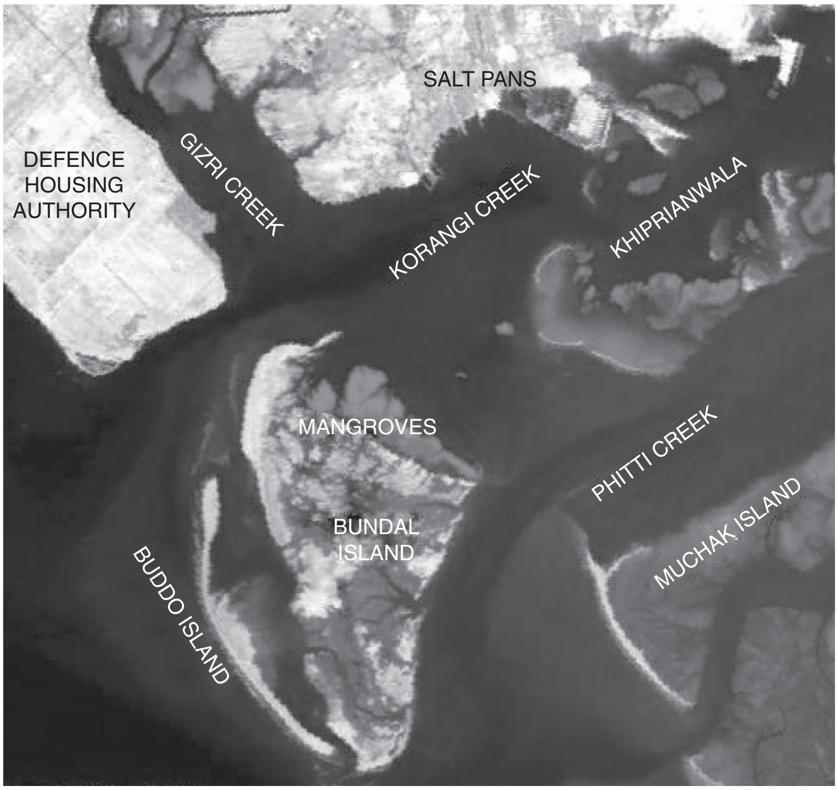

Figure 16.4 Satellite image of the barrier islands off the Indus Delta (NIO Report, 2001)

bathymetric channel-levee systems of various orders, and low-lying terminal sand lobes and sheets. The morphological features of this submarine 'fluvial' system exhibit striking similarities, both in shape and position, with morphological features of mature fluvial systems such as intricate meanders accompanied by neck and chute cut-offs, levee and crevasse-splay deposits, point bars, a full range of straight, meandering and braided channel patterns, gooseneck or convex down-valley asymmetric loops, anabranching and bifurcation channel patterns (Ayub, 1992).

The modern Indus canyon commences close to the delta coast, about 3.5 km from mouth of the Gaghir creek and in the water depths approximately 20 m and then progressively deepens seaward across the continental shelf and slope region with a maximum relief of about 1030 m in the shelf break vicinity. Along its approximately 185 km long traverse its average width is about 8 km and it shows a broad north-westward bend in the outer shelf and slope area (von Rad and Tahir, 1997).

The Indus Canyon, like many other large riverfed canyons, is considered to have been initiated and progressively developed by the extension of the channel of the Indus River over the subaerial continental shelf exposed during the Quaternary low sea levels and deposition of sediments at outer shelf/upper slope where turbidity currents and mass wasting processes eroded backward to carve the canyon during the glacial and interglacial times/periods/events.

At its mouth in the lower slope water depths of 1400 to 1500 m the canyon widens to 20 km (Coumes and Kolla, 1984) and transforms to large channel-levee systems of predominantly depositional/aggradational character, and progressively becomes transitional to erosional in the lower order distributary system further downfan. The youngest large channel extends to as far as 500 km up to the Upper Indus fan area where a radial pattern of small-order distributary channel-levee systems emanate.

The large channels are typically 300–400 m deep and 6–10 km wide near the foot of the continental slope, where they start, and decrease both in depth (100 to 120 m) and width (<2 km) in the distal part in the upper fan, between 2900 and 3300 m water depths. These are characterised by 10–30 km wide and up to 1100 m thick individual levee (overbank) deposits which attain a relief up to 800 m from the surrounding fan surface.

The average dimensions of small channels also progressively decrease downfan. The channel depths vary from 80 to 20 m, and widths become less than 2 km. The widths of individual levee deposits range from 20 km to 5 km and the height of levees from 60 m to about 5 m. In the extreme lower reaches, the small channels are devoid of levees and are entrenched below the fan surface. All the channels of higher and smaller order systems meander with variable sinuousity along their respective courses.

The turbidity currents are considered the main process of transporting the terrestrial sediments of the Indus River through this intricate and vast network of canyon-channel-levee complexes, to the farthest parts of the Indus Fan. There were at least two other complexes active earlier during the late Miocene and Pliocene times that are comparable with the modern Indus canyon-channel-levee complex of Pleistocene age, but only one canyon-large channel system was active at a time (Kenyon *et al.*, 1995). Thus numerous channel-levee complexes extensively migrated both in time and space, vertically as well as laterally, and ultimately coalesced and stacked resulting in the formation of voluminous Indus Fan deposits.

Thus, in fact the journey of the Indus River that started at the heights of about 5000 m in a geologically dynamic land region ends at the placid depths of about 4500 m in the Arabian Sea.

16.7 WATER MANAGEMENT

The water of the Indus has been used for six millennia from the Harappan period to the present through a series of different historical regimes and often in an organized fashion. The last half of the twentieth century, however, has seen the transfer to very large-scale management of the water system. Currently about 60 % of the Indus water is estimated to be used for irrigation, supplying water to more than 161 800 km^2, about 80 % of Pakistan's agricultural fields (Iftikhar, 2002). More than 150 000 km^2 of farmland is irrigated, giving rise to the highest national irrigated to rain-fed land ratio (4 : 1).

Pakistan depends on irrigation for producing 90 % of its food and other crops (World Bank, 1992; Asianics, 2000). This requires three major storage reservoirs, 19 barrages or headworks, and 43 major canals with a total conveyance length of 57 000 km. There are 89 000 watercourses with a running length of more than 1.65 million km.

The construction of the barrages and canals has, over the years, led to a systematic removal of water from the Indus (Table 16.1). According to several early estimates, construction of barrages, dams, and link canals has reduced the annual freshwater flow downstream from >150 billion m^3 to less than 45 billion m^3 (Keerio and Bhatti, 1999). The actual effect of the engineered diversions from the Indus River, however, is much more alarming, especially regarding the future conditions in the delta (Inam *et al.,* 2004). The subsurface hydrology of the basin is also affected. Between 1972 and 1997 the contribution of groundwater to irrigated agriculture nearly doubled in

Pakistan, from 32 billion m^3 year^{-1} to 62. Next year it declined to 50 billion, equivalent to 38% of the surface water diversion. Engineering structures across the river have also reduced the sediment load travelling down the Indus. The annual sediment load of the pre-engineered Indus varied between 270 and 600 million t (Milliman *et al*., 1984). It is a fraction of that at present.

Table 16.1 Major dams and barrages on the Indus River

Structure	Year of construction	Maximum discharge capacity (m^3 s^{-1})
Tarbela Dam	1976	18386
Mangla Dam	1967	24630
Ghazi Barotha Hydropower project	2004	500000
Jinnah Barrage	1946	950000
Chashma Barrage	1971	1100000
Taunsa Barrage	1959	750000
Guddu Barrage	1962	1200000
Sukkur Barrage	1932	1500000
Kotri Barrage	1955	875000

Modified after Pakistan Water Gateway (2003).

Most of the lower Indus basin is flat and the natural drainage flow is gradual allowing a rise in the water table. The prevalent canal irrigation system has resulted in large-scale problems of water logging and salinity. Approximately 60% of the aquifer underlying the IBIS is of marginal to brackish quality.

To mitigate the menace of rising groundwater and the associated problem of waterlogging and salinity, a network of drainage canals was constructed within the Indus Basin to drain groundwater directly to the Arabian Sea. The drainage system has been less effective due to low gradient of the flat topography and has in fact resulted in the intrusion of sea water to about 80 km upstream (Panhwar, 1999). Sea water intrusion is much worse during the south-west monsoon (Figure 16.5).

The increase in salinity due to depleting fresh water contribution by the Indus River has reduced the suitability of the delta for the cultivation of red rice, the production of exotic fruit, and raising of livestock. The mangrove ecosystem is being degraded, and the mangroves are now virtually monospecific and comparatively stunted with losses of about 2% year^{-1}. Degradation of the mangroves is due to a combination of water flow reductions and direct human destruction and over use. The major changes in river flow below Kotri have affected the ecology in the

Figure 16.5 One of the drainage canals in the Indus deltaic area of Keti Bandar where the sea water is entering irrigated land through a defective gate

lower Sindh and the coastal areas significantly, besides adversely affecting agricultural production.

The human population in and around mangrove forests on the Sindh coast is estimated to total 1.2 million people, nearly 900 000 of whom reside in the Indus Delta (Salman, 2002). Of these, a predominantly rural population of more than 135 000 depends on mangrove resources for their livelihoods (Shah, 1999). Reductions in freshwater inflows have had tangible impacts on mangrove ecology, and on the fish populations that rely on them for breeding and habitat. At least three-quarters of the rural population of the delta depend, directly or indirectly, on fishing as their main source of income, and most of Pakistan's commercial marine fishery operates in and around the mangrove creeks on the coast of Sindh Province. A large proportion of fish and crustaceans spend at least part of their life cycle in the mangroves, or depend on food webs originating there (Meynell and Qureshi, 1993).

The effect of anthropogenic alteration in the delta is reflected in the reduced water and sediment discharge downstream of the Kotri Barrage (Figure 16.6) near the delta. Prior to the construction of major dams and barrages along the Indus River, the recorded average annual discharge of water and sediment downstream of Kotri Barrage was 107 billion m^3 and 193 million t, respectively. The major decline in the water and sediment discharges to the delta occurred after the commissioning of the Mangla Dam (1967) and the Tarbela Dam (1976). From 1998 onwards, water and sediment discharges have declined at an alarming pace below Kotri Barrage, especially when the rainfall has been low.

The effect of the engineered structures on the Indus River water discharge can be measured by the number of days with no flow below Kotri Barrage. There was not a single day with zero flow before Kotri Barrage was constructed in 1955 (Figure 16.7). Zero-flow days were observed during 1962–1967, the maximum number in a year rising to 100. This increased to 250 days in the year in the post-Kotri and post-Mangla period (1967–1975). The present situation is even more alarming due to the current trend in low rainfall in the basin of the Indus River. At present, the Indus flows downstream of the Kotri Barrage for only 2 months: August–September. A discharge of less than 1 billion m^3 was observed downstream of the Kotri Barrage for the last couple of years (Inam *et al.*, 2004). As a consequence braiding and sand bars have become common in the river south of Kotri. Sediment passing down the system tends to be deposited in the section below Kotri rather than maintaining the growth of the delta (Figure 16.8).

16.8 THE INDUS DOLPHINS

One of the most threatened dolphins in the world is the freshwater species known as the Indus River dolphin or *Bhulan*, which lives in the Indus. The dolphins of

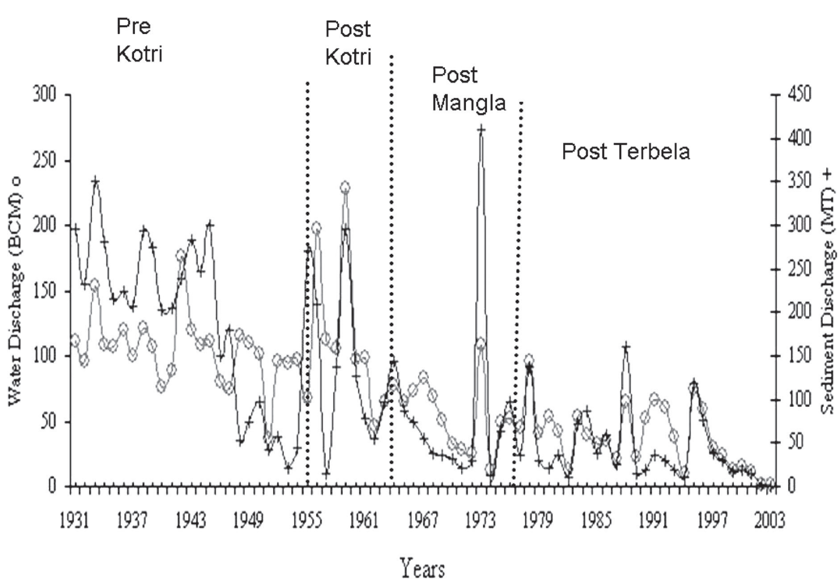

Figure 16.6 Variation in water and sediment discharge below Kotri (modified from Milliman *et al.*, 1984)

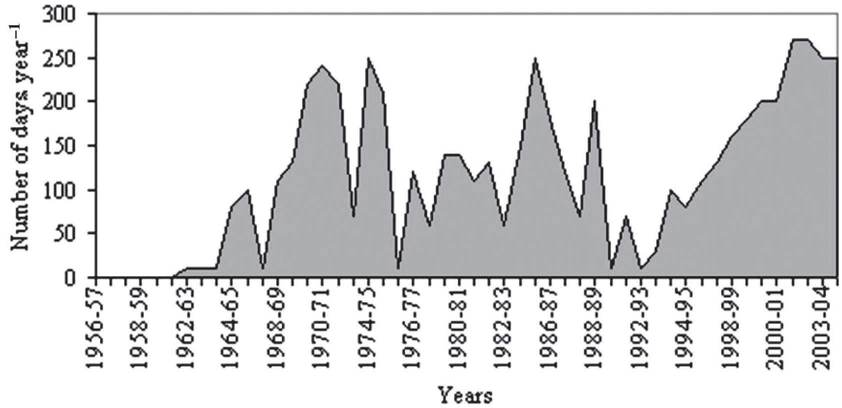

Figure 16.7 Numbers of days per season with zero flow downstream of Kotri Barrage (modified from Asianics, 2000)

Figure 16.8 Isolated water ponds downstream of the Kotri Barrage can be seen during most of the year. The flow of water downstream of the Kotri Barrage results in the catastrophic resuspension of fine sediments deposited on the dried river bed

the Indus and the Ganga rivers are unusual among the five most endangered species as these are functionally blind. Impassable irrigation barrages on the Indus River have trapped the dolphins into small populations. More than 600 dolphins are trapped between Guddu and Sukkur barrages, and progressively moving upstream, about 250 recorded between Taunsa and Guddu and less than 100 between Chashma to Taunsa. In the lower Indus, a 500 km long river sector between Sukkur and Kotri barrages has less than 20 dolphins. The low numbers probably are due to extraction of water from the river for irrigation, leaving a very low dry-season discharge through the area.

16.9 ENVIRONMENTAL CHANGES

Over time, the rich flora and fauna attracted settlements directly to the banks of the Indus and also along the numerous canals and distributary channels off it. During the eighteenth and nineteenth centuries, large volumes of water and sediment were discharged round the year through the delta. Two river ports, Keti Bandar and Shah Bandar, used to handle all imports and exports between Sindh and Bombay. The coastal agricultural areas near Keti Bandar, Kharo-Chan, and Shah Bandar produced rice which was the main export crop. Seaborne cargo traffic in transit to the upper Sindh was transported by boats. In general, the area was prosperous and the socioeconomic condition of the residents was very good. During the south-west monsoon, the boat traffic remained suspended as the vessels could not enter the delta due to the storminess of the wet monsoon. The drastic reduction of the water and discharge down the Indus following the construction of Kotri Barrage in 1955 resulted in the loss of several hundred square kilometres of fertile land. The once prosperous port area of Keti Bandar was reduced to a fishing village and the population was forced to change their age old profession of farming to fishing and also to migrate to other parts of the delta in search of fresh water and shelter from saline intrusions. The anthropogenic impact of upstream water and sediment blockage resulted in the shrinkage of the active delta and also stunted the growth of the mangrove forest (Figure 16.9).

16.10 HUMAN-INDUCED CHANGES IN THE INDUS DELTA

The lack of environmental awareness led to any release of water to the Indus Delta being considered as wastage. The

Figure 16.9 The mangrove forest along the Indus Delta is rapidly diminishing due to the scarcity of fresh water and decline in the sediment contribution from the Indus River

Table 16.2 Rapidly declining water and sediment discharges downstream of the Kotri Barrage

Period	Average annual water discharge ($10^9\,m^3$)	Average annual sediment discharge ($10^9\,t$)
1931–1954	107	193
1955–1962	126	149
1963–1967	72	85
1968–1976	47	82
1977–1997	45	51
1993–2003	10	13

Source: Irrigation Department, Government of Pakistan (unpublished).

Table 16.3 Post-dam construction variations in sediment and water discharge downstream of the Kotri Barrage

Period	Average annual water discharge ($10^9\,m^3$)	Average annual sediment discharge ($10^9\,t$)
Pre-Kotri Barrage	110	184
Post Kotri Barrage	68	85
Post Mangla	47	82
Post Terbela	37	43

Source: Irrigation Department, Government of Pakistan (unpublished).

Indus Delta itself was perceived as a wasteland of mudflats, creeks, and mangroves (Asianics, 2000). The effect of anthropogenic changes in the fluvial regime by the construction of the dams and barrages on the Indus River can be seen in the historic records of sediment and water discharge to the Indus Delta. The average annual water and sediment discharges during 1931–1954 were $107 \times 10^9\,m^3$ and $193 \times 10^9\,t$, respectively. This discharge rate, over the years dropped to $10 \times 10^9\,m^3$ and $13 \times 10^9\,t$ during the 1993 to 2003 period (Table 16.2). Prior to the construction of the Kotri Barrage the average annual water and sediment contribution of Indus River to its delta was about $110 \times 10^9\,m^3$ and $184 \times 10^9\,t$, respectively (Table 16.3). Kotri Barrage and subsequently, Mangla and Terbela Dams, restricted the passage of freshwater and sediments to the deltaic area, causing significant ecosystem changes progressively compounded by increased freshwater removal (Table 16.3). For most part of the year, no flow travels down the river between Sajawal (about 90 km below Kotri Barrage) and the river mouth at Khobar Creek (Inam *et al.*, 2004). Fresh water now reaches the deltaic area infrequently during the south-west monsoon.

Sixteen major creeks make up the original Indus Delta but, following the reduction of flow downstream from the Kotri Barrage, only the area between Hajamro and Kharak Creeks now receives water from the Indus with one main outlet (Khobar Creek) to the sea. Compared with the other creeks of the Indus Delta, the bottom sediments of the Khobar Creek are significantly coarser and more compact. In general, the mean grain size suggests that the flow of the river is not capable of carrying coarse sediment downstream to the river mouth. The sediment that the Indus has carried to the delta is confined within the channel of the Khobar Creek until a flood event flushes out the unconsolidated sediment to the Arabian Sea (Inam *et al.*, 2004). No marine component, such as shell fragments, was found. The coarser sediments at the mouth of the channels are reworked by wave and tidal processes and the gentle slope favours sediment deposition. Such an environment facilitates the winnowing of the fines while the coarser sediment is deposited as lag material.

Currently the Indus River hardly contributes any sediment to the delta or the Arabian Sea. The active delta is reduced to only 1200 km^2 in area from the 6200 km^2 observed before the construction of the series of dams and barrages on the Indus (Asianics, 2000). Consequently, sea water has intruded upstream in the delta, extending up to 75 km locally in the coastal areas of Thatta, Hyderabad, and Badin districts. According to Sindh's irrigation and Power Department (IPD) seawater intrusion has resulted in tidal infringement over about 4850 km^2 in delta. The near absence of riverine freshwater downstream of Kotri coupled with the strong seawater intrusion has destroyed large areas of prime agricultural land, including submersion of several villages on the coast (Figure 16.10). This in turn has caused desertification and displacement of a several hundred thousand local residents living there for

Figure 16.10 The Indus River flowing by the coastal village 'Sajanwari' in the Indus Delta. Seawater intrusion has destroyed one of the most fertile agricultural areas in the delta

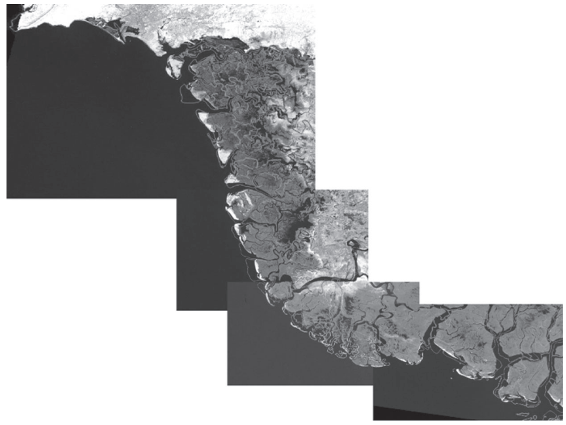

Figure 16.11 Satellite image of the Indus Delta in 2000 showing how the coast has changed since 1950. The coast in 1950 is shown as a red line, with yellow depicting sand bars developed near the mouth (unpublished, Stefan Constatinescu, University of Bucharest, Romania). (Image from NASA Visible Earth)

many generations. Furthermore, the Indus Delta is subject to the highest average wave energy of any major delta in the world (Wells and Coleman, 1984), mainly due to the intense monsoon winds that produce high energy waves. An extreme level of wave energy and little or no sediment contribution from the Indus River together are transforming the Indus Delta into a wave-dominated delta and sandy beaches and dunes are developing along the former deltaic coastline.

Comparison of recent satellite images with the topographic and bathymetric maps of the region published in 1950 provides evidence for widespread retreat of the coast and widening and deepening of tidal inlets (Figure 16.11). The subaerial morphology of the delta suggests wave and tide influences west of the active river channel, whereas it is tide-dominated to the east of the river mouth. Deltaic evolution in natural conditions between 1855 and 1954 was characterized by active sediment accumulation in two major depocentres: the nearshore zone along the entire delta coast and the western shelf between ~25 and 40 m water depth. Until 1954, the shoreline advanced or was stable along most of the delta coast. The progradation rate at the active mouth surpassed 100 m year^{-1}. The clinoform at the mouth has directly built into the head of a major submarine canyon that dissects the shelf. Deposition patterns on the shelf suggest that the Indus Delta has produced a compound clinoform on the western shelf, probably as a result of extremely active sediment transport under an energetic mixed wave-tide regime. Development of a nearshore clinoform simultaneously with an entirely submerged clinoform challenges the current sedimentation and facies models that emphasize single clinoform development as a delta progrades across the shelf. After the reduction in discharge in the late 1950s, the deltaic shoreline along most of the western coast started to recede at rates of ~50 m year^{-1}. Surprisingly, the eastern tide-dominated coast remained stable or even prograded. This differential shoreline behaviour suggests an active role for sediment transfer processes in the reworking of abandoned deltaic coasts (Giosan *et al.*, 2006). Active accretion of the coast is limited to the south-central part of the delta lobe where the river used to discharge until its recent westward shift to the Khobar Creek. Near the salt flats of the Rann of Kutch to the east, the coastline appears to be stable and has even advanced seaward since 1950. The tidal channels, however, are much wider closer to the sea than before, indicating active erosion. Loss of the coastal land is most acute between the Khobar Creek and Karachi (Giosan *et al.*, 2006).

16.11 CONCLUSION

Most of the upper drainage basin of the Indus River lies within the Karakoram with smaller parts within the Kohistan, Hindu Kush, and High Himalaya Mountains. The Indus has occupied a relatively stable course throughout its history due to its location within the Indus-Tsanpo Collision Suture and also because of the strike-slip alignment towards Afghanistan to the west. It has deposited a considerable amount of alluvium in the Himalayan foreland basin, and has built the huge alluvial plains of Punjab and Sindh. Over six millennia, the Indus River has been the source of water that supported the economy of the region, nurturing old and modern civilizations. The flux from the river has enabled an extremely large irrigation system to be developed within its drainage basin. However, these engineering structures also had adverse impacts on the once fertile and richly vegetated deltaic area of the Indus.

The life of the delta is dependent on the availability of freshwater and sediment. The severe reduction of both as a result of dams, barrages and associated structures upstream has resulted in the pronounced erosion in parts of the delta and consequently in the reduction of the mangroves. The faunal and floral assemblages in the delta have shifted from estuarine to hypersaline types. Coastal erosion is increasing also due to unplanned coastal development in the area. The well-being of the delta requires a realistic assessment of the minimum volume of river water and sediment needed round the year to prevent the near-disappearance of the Indus Delta. The management of the delta should become part of an integrated coastal zone management in a holistic fashion. Not only the coastal environment should be managed integrally but environmental studies also need to be extended to the entire Indus ecosystem from the mountains to the Arabian Sea.

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