Appraisal of hydro-ecology, geomorphology, and sediment behavior during low and high floods in the Lower Indus River Estuary

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ABSTRACT

The riverine ecosystem is reliant on freshwater; however, morphological changes and sediment load destabilize the natural river system which deteriorates the ecology and geomorphology of the river ecosystem. The Lower Indus River Estuary (LIRE) geomorphological response was synthesized using satellite imagery (1986–2020) and evaluated against the field measurements. The estuary sinuosity index has an increasing trend from 1.84 (1986) to 1.92 (2020) and the estuary water area is increased from 101.41 km² (1986) to 110.24 km² (2020). The sediment load investigation at Kotri barrage indicated that the median size of bed material samples during the low-flow period falls between 0.100 and 0.203 mm and the bed material after the high flow has clay and silt (0.0623 mm) ranging from 17–95% of the total weight of samples. The vegetated land loss on the banks is positively correlated with the peak runoff at Kotri barrage ($r^2=0.92$). The bank erosion was computed with high precision ($r^2=0.84$) based on an improved connection of the coefficient of erodibility and excess shear stress technique. This study will be helpful for policymakers to estimate the ecological health of LIRE, and sediment fluxes play an essential role in the mega-delta system and coastal management.

Key words: erosion and deposition patterns, hydro-geomorphologic behaviour, Lower Indus River Estuary, sediment pattern

HIGHLIGHTS

- Remote sensing trajectory analysis of channel migration in the Lower Indus River Estuary from 1986 to 2020.
- Hydro-geomorphological response based on the analysis of several channel morphometric parameters.
- Estimation of sediment load, erosion, and deposition during low and high flood periods.

NOMENCLATURE

LIRE Lower Indus River Estuary
LF, HF Low flow, high flow
USGS United States Geological Survey
MSS, TM Multispectral Scanner, Thematic Mapper
OLI/TIRS Operational Land Manager/Thermal Infrared Sensor
UTM Universal Transverse Mercator
WGS84 World Geodetic System
MEP Modified Einstein Procedure
D50 Median size of bed material
WAPDA Water and Power Development Authority
SSL Suspended sediment load
MT Million tons
TSL Total sediment load

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INTRODUCTION

Global river delta concerns have attracted a lot of attention since they are socioeconomic centres, but they are worsening day by day due to the hazards of coastal erosion, floods, rising sea levels, increase in population, and poor governance (Syvitski et al. 2005; Ijaz et al. 2020; Ve et al. 2021). The delta formation occurs at the river–sea interface when river sediment is accumulated. The delta morphology is sediment sensitive among the river input and marine outputs (Syvitski et al. 2005; Yuan et al. 2019). It varies over numerous spatiotemporal scales according to the climate changes and shifting of river channels under natural circumstances (Ve et al. 2021). The construction of dams that trap the sediment load, variable flows, and flood-based events considerably impact channel morphology (Syvitski et al. 2005). The direct and indirect hydro-geomorphic perturbations influence the riparian ecology (Yang et al. 1999). The riparian vegetation modification impacts the geomorphology by reducing the sediment load and entrapping the nutrients (Hupp et al. 2008). The vegetation cover also affects hydrology by the alterations in hydraulics roughness and water absorption. The sediment discharge changes play an important role in wetland loss (Fernández & Lutz 2010).

The evaluation of hydro-geomorphology, ecological, and economic sustainability is essential for the riverine ecosystem’s sustainability and restoration (Day et al. 1997). The hydrological compatibility was established with its floodplains through site observations and remote sensing in the Amazon River. It was observed that hydrological connectivity processes along floodplains occurred through complicated inner routings of runoff, and hydrologic connectivity depended on the floodplain geomorphology (Park & Latrubesse 2017). The effect of floods was examined on land-use changes at the catchment scale, and innovative techniques were proposed, such as complex methods to couple processes across the temporal scale, physical–biology–chemical relations, and focusing on the connectivity and patterns on spatial scales (Rogger et al. 2017). However, it is not easy to evaluate the impact of flooding on vegetation and agricultural policies when the area of the watershed increases. The channel width, land-cover changes, and land stability (Brahmaputra River) were examined using the remote sensing and GIS. The result indicates that the episodic flood events significantly impact the river migration (Yang et al. 2015a). The effect of geomorphology such as riverine migration and erosion based on the numerical model was examined (Takagi et al. 2007). It is evident from the previous studies that limited attention is paid to the co-evolution of hydro-geomorphology, sedimentary-morphology, and ecology of the regulated tidal river, and the current study seeks to fill the gap. Until now, the Lower Indus River Estuary (LIRE) sediment load has not been identified and measured.

The Indus River originated from the Himalayan range and flows through China, India, and then Pakistan, before finally discharging into the Arabian Sea. The Indus River is the 12th biggest transboundary drainage watershed and almost 80% of agriculture depends on this river (Ijaz et al. 2020). The existing dam (Terbela) at the upper reach of the Indus River has significantly reduced the sediment load at the Lower Indus River, but deforestation, land-use changes, population exposed to riverbanks, and climate-based flood events have increased the erosive action in the channels (Carling 1988). There is numerous literature available on how reservoir projects have changed the fluvial dynamics of the Indus River with a decrease in average annual runoff, and as a result, the channel geomorphology is crumbling due to sediment load variations. Thus, the river is experiencing substantial problems linked to the variation of sediment load, which is due to human activities in the basin. The existing dams cause the modification in the hydrological cycle, sediment load variations in the floodplain, and estuarine at risky levels. The hydro-sediment budget is also directly jeopardized by sand mining, and thus, sand mining and sediment load variations are undoubtedly increased by alterations of top channel width. Thus, an entire ecosystem has been considerably disrupted as a result of combined influence of the affected hydro-geomorphology (Ijaz et al. 2020). This is indicated by a reduction in organic matter, changes in geochemistry, inhibited growth of mangrove forests, and increase in estuarine salinity (Inam et al. 2007; Lückge et al. 2012).

Previous research has focused mainly on the evaluation of sediment reduction due to dam construction and influence of water impoundments on seasonal and fluvial regimes. Conversely, the effect of climate-based flood events on sedimentology of the river reach is unexplored and need to be better studied. However, limited studies have assessed the effect of climate-
based flood events on sedimentary fluxes and hydro-geomorphology of LIRE and creeks. This research mainly joins the field observations and lab investigations to study the suspended sediment load (SSL), bed load (BL), and to comprehend erosion/deposition processes. This study examines the effective discharge value for LIRE and fills the research gap on how the flood-based events (sediment load) affect the LIRE. The objectives of the study are to (1) determine the hydro-geomorphology and sediment load variations during LF and HF periods, (2) synthesize the development of the relationship between riparian landscape and peak runoff under-regulated geomorphological effects, (3) compute effective discharge, and connect between the proportion of sand bar and braiding index (BI). To achieve the objectives, the following two hypotheses were considered: (1) erosion is higher during the HF than the LF period and (2) channel morphology is triggered by the coarser particles rather than finer particles. The findings propose a brief picture of the sediment and their transport mode along the LIRE. Because sand, silt, and clay particles play a significant role in the dynamics of the Indus River Estuary, such information will help in the adoption of integrated methods, such as hydro-ecology/geomorphology models, to enhance large-scale management of hydrosystems. Correlation analysis is used to determine the system dynamics using a coherent method that employs a combination of contemporary methodologies on a cause–effect basis. The underlying processes are interpreted using topographical, geological, and physiographic local impacts.

This paper is organized into five main sections: 1. Introduction: which explains the literature review, research gap, and objective of the current study; 2. Study Area; 3. Materials and Methods: the scientific methods adopted to assess the eco-hydrology and geomorphology of the LIRE are discussed; 4. Results and Discussion: Geomorphology, hydrology and sediment load findings of LIRE are presented; 5. Conclusion: main crux of the research and suggestions for future research are given.

**DESCRIPTION OF THE STUDY BASIN**

The LIRE started downstream from Sujawal Bridge downstream of Kotri barrage with a length of 152 km, with 838.44 km² in the Indus floodplains delta, and finally joined the Arabian sea (Figure 1) (Ijaz et al. 2020). The channel width ranged from a few metres to several kilometres and wetted width >1.7 km remains frequent during the dry season. The channel wetted area expansion occurred during the HF periods with the rare formation of new channels. The channel instability is evident during the HF periods. The 2020 flood mainly resulted in the development of sand bars with substantial sediments transported at LIRE. The average land-use area (1986–2020) comprises 12% water, 9.5% wetlands, 5.4% sand bars, 43.6% open area, and 29.5% vegetated cover. The LIRE has meandering formation, oxbow lakes, neck cut-off, lagoons, and earthen bunds. The annual basis measured discharge values vary in size, and maximum flows occurred in the summer season (Ijaz et al. 2020).

During the summer season, the snowmelt increases transporting sediments from Pajnad Rivers to LIR (Inam et al. 2007). The annual peak runoff values (1960–2020) varied from 66,475 to 996,000 cusecs in the Kotri barrage. The mean head difference between upstream and downstream is 0.97 m. The runoff, total sediment load (TSL), SSL, and material bed samples were measured. The hydraulic data surveys (secondary data source of 2018) upstream of Kotri barrage (25°26'23" N, 68° 19'0"E) were collected from PIDS. These surveys were used to calculate the average hydraulic parameters such as hydraulic flow resistance (FRS=192°R[3/5]aS[2/5])~1.03, froud flow number (FVR=0.75°V²/R)~1, bed stress (τb=γ°Rb°)~7 Nm⁻², roughness coefficient (n=1.49°R.66S0.5/V)~0.020, hydraulic radius (R=A/P)~2.2 m, froud number (Fr=V/√gdh)~0.17, and sedimentation budget using Modifying Einstein Procedures (MEP) (Guo & Julien 2004; Shah-Fairbank 2009).

**MATERIALS AND METHODS**

**Remote sensing and ArcGIS**

The runoff data during 1986–2020 was used for the selection of the Landsat multi-temporal images. The accessible information is obtained from the USGS website (http://earthexplorer.usgs.gov/), which are Landsat 1–5 MSS (1986), Landsat 4–5 TM (1992), Landsat 5 TM (2010), Landsat 8 0 L/I/TIRS (2015), and Landsat 8 0 L/I/TIRS (2020) (Table 1). The HF cloud-free tiles were processed in the UTM 42-N projection that WGS84 data reference and atmospheric corrections were not essential (Song et al. 2001). The total macro-channels are usually 10 km wide having sand bars, island, and wet and dry channels (Van Niekerk et al. 1995). The estuary centreline (based on ArcGIS) was drawn to gain the information on erosion, accretion, spatial and temporal dynamics of estuary changes. For brevity, this method is not explained here but is presented by Yang et al. (2015b) and Carling et al. (2018). Landsat images were converted into raster data sets using
ArcGIS, reclassifying the image into five categories: water, vegetative cover, open land, sand bar, and wet land by using the unsupervised classification for Landsat images (Carling et al. 2018). The positional adjustment, centreline, sinuosity index, and BI were calculated using ArcGIS 10.2 (Yang et al. 2015b). Furthermore, the flowchart of the adopted methodology is given in Supplementary Figure S1. The erosion, deposition, and river migration was computed using the equation proposed by Yang et al. (2015b).

\[ R_m = \frac{(A/L)}{N} \]  

(1)

where \( R_m \) is the rate of migration (m/yr), \( A \) is the river migrated area (m²), \( L \) is the river centreline length (m), and \( N \) is the total number of years.

The Mann-Kendall (MK-T) and Sen’s Slope (SS-T) tests were applied in the present study after determining the non-parametric riverine flow suitability. Mann-Kendall and SS-T tests were used for the trend analysis in the average annual runoff and peak flood series in the flow system (Equations (1) and (2); Da Silva et al. 2015). The sinuosity index was calculated based on Equation (3). The multispectral image contains plenty of spatial information which is useful to quantify the features such as water, grass, and bare land. To that end, the green and near-infrared (NIR) band reflectance was applied to compute the Normalized Difference Water Index (NDWI). The single-band density slice method was used for automated channel plane

Figure 1 | The location map of the Lower Indus River Estuary in South Pakistan. The Lower Indus River Estuary (LIRE) reach has a length of 152 km from top to bottom. The LIRE reach starts from the Sujawal Bridge downstream of the Kotri barrage and then finally joins the Arabian Sea.
detection and delineation of the NIR band (Frazier & Page 2000). The density slice method is applied for the satellite image of 1986 because the LIRE extracted using NDWI does not produce satisfactory results.

\[ S = \frac{1}{n} \sum_{i=1}^{n} \text{sgn}(x_j - x_i), \quad n = \text{no. of entries} \]  
(2)

\[ \text{Sen’s Slope} = \frac{x_j - x_i}{j - i}, \quad N = C(n, 2) \]  
(3)

where \( x_i \) is a time series, \( N \) is the number of pairs of time-series elements \((x_i, x_j)\), and \( i < j \).

The LIRE top width variation is estimated by dividing the river into five different cross-sections and computing the horizontal width perpendicular to the river centreline using the ArcMap 10.3 software. The spatial changes in the top width at various cross-sections were calculated to estimate the channel bank’s stability and temporal trend. The prior studies show that estuaries can be divided into different domains (Flemming & Martin 2021), and we have divided the LIRE that is divided into river-dominated sections classified by fluvial sand, and tidal-dominated lower section classified by marine origin sand. The spatial variations extent in the river estuary geomorphology was analysed for these sections. The LIRE spatial variation quantifications represent the hotspots, and four significant classes are used for the computation of areal distribution and arrangement in hydro-geomorphological and topographic contexts.

\[ \text{Sinuosity Index} = \frac{\text{ML (Meandering length)}}{\text{VL (Valley length)}} \]  
(4)

\[ \text{NDWI} = \frac{(\text{Green} - \text{NIR})}{(\text{Green} + \text{NIR})} \]  
(5)

### Discharge selection

The periodic runoff values from 1986 to 2020 are sorted for the Kotri barrage. The threshold discharge is correlated to erosion, accretion, and sediment transportation. Thus, a strong relation between periodic runoff and vegetation land loss is expected. The observed sediment and runoff data from the Kotri barrage were used to calculate the erosion and accretion values. Gares et al. (1994) have explained the relation between riverine erosion and \( O\) runoff function. Magilligan et al. (2015) have observed a link between discharge and annul land lost, indicating that peak discharge \((O_p)\) is an appropriate
index among unit stream power and discharge hydrograph. Sear (2004) has mentioned how a riverine bank’s erosion depends on unit stream power that does not take place at low flows (Equation (5)).

\[ \dot{e} = \kappa(Qp - Qc) + a \]  

(6)

where \( K \) denotes the coefficient of a bank’s erosion and \( a \) denotes the empirically defined regression constant. Based on the preceding discussion, it is obvious that riverine land loss occurred on a threshold discharge value (Qc). Therefore, calculated Qc values are more appropriate for risk analysis (Khan et al. 2011).

**Estimation of sediment budget in LIRE**

The runoff, SSL, and BL are based on the field measurement, and locations were chosen in right pocket (RP) and left pocket (LP) at the Kotri station. The measurement of Q, SSL, bed sampling, and head reaches equilibrium experiments were conducted to estimate the sediment budget allocation in approach channel (AC), tail channel (TC), RP, and LP. For velocity measurements, standard AA-Type (Vertical Axis) Gurley current meters in good condition were used. The SSL samples were obtained in the cross-sections with ten equipped-spaced verticals. Thirty bottles of suspended sediment samples were collected with the help of a US-D-49 sampler by using an equal transit rate method. The collected samples were analysed in the laboratory for sediment concentration as well as for particle size gradation. At each discharge measurement location, material bed samples were also collected by using a BM-54 sampler (Supplementary Figure S2). The cross-sectional measurements based on mechanical sounding were collected from the PIDs department.

The samples of bed material for grain size dispersion and D50 were taken at Kotri barrage. The field observation data such as SSL and BL samples were investigated in a laboratory by the WAPDA expert team. They examined the sediment coarser than 62 \( \mu \)m by using the visual accumulation tube, and sediment finer than 62 \( \mu \)m were analysed by using the pipet method. Our expert team used the gravimetric method to determine the concentration of SSL samples. The TSL was calculated using the MEP procedures (Guo & Julien 2004), using laboratory analysis and field data of the SSL and BL samples (Vauchel et al. 2017; Zhang et al. 2017).

The computed results are listed in three parts: for particles smaller than 2 \( \mu \)m, particles between 2 and 62 \( \mu \)m, and particles larger than 62 \( \mu \)m. The 2 \( \mu \)m cut-off size is the upper size limit for medium clays. The medium to very fine clays are responsible for providing cohesion to the channel banks formed by natural or induced deposition. The bed material load, coarser than 62 \( \mu \)m, is primarily responsible for the channel bed processes. The particle size distribution of bed material load is computed for a cut-off size of 62 \( \mu \)m. Three percentile sizes, \( D_{84} \), \( D_{50} \), and \( D_{16} \), are given, as well as the gradient coefficient (\( \sigma \)) as:

\[ \sigma = \frac{1}{2} \left( \frac{D_{84}}{D_{50}} + \frac{D_{50}}{D_{16}} \right) \]  

(7)

**RESULTS AND DISCUSSION**

**General hydrological observations**

The LIR which is regulated at Kotri barrage is the key freshwater source to the estuary. The estuary started from Sujawal Bridge, about 138 km long with a width varying from 200 to 1,400 m along a meandering path. The annual peak flow analysis from 1901 to 2020 shows that the highest value was observed to be 28,203 m\(^3\) sec\(^{-1}\) (2010) and the minimum value of peak flow was observed to be 1,882 m\(^3\) sec\(^{-1}\) (2000) at Kotri barrage. We have considered the flood-based events that occurred due to climate change and the decadal events at Kotri station for the temporal analysis in channel changes. It is evident that the average flows reduced to 81.02\%, and 49.98\% reduction in flood peak from 1901 to 2020. The flood events are more severe (high and very high) from 1901 to 1967, and the flood runoff values at various return periods ranging from 0 to 1,319.68 m\(^3\) sec\(^{-1}\) occurred at 79\% frequency (Supplementary Table S1). Most freshwater supplies are limited to the LIRE. The flood events values at different return periods (1, 5, 10, 50, 100, and 500 RP) were observed to be 6,582, 14,318, 18,098, 30,988, and 400,022 m\(^3\) sec\(^{-1}\), and the bankful runoff value at 2 return period (RP) was observed to be 10,219 m\(^3\) sec\(^{-1}\) as represented in the Supplementary material.

The LIR mean annual discharge and peak flood during the unregulated period from 1901 to 1955 was observed to be 98.91 BCM and 12,599.89 m\(^3\) sec\(^{-1}\). The mean annual discharge and peak flood during the partially regulated period (1956–1975), before the start of Kotri barrage and erection of Terbela reservoir was observed to be 77.41 BCM (21.9\% decreased) and
13,619.99 m$^3$ sec$^{-1}$ (2.3% increment) as shown in Table 2. However, the mean annual discharge and peak flood are observed to be 35.20 BCM (52% reduction) and 9,091.89 m$^3$ sec$^{-1}$ (31.87% reduction) in the addition of the Terbela impoundment (regulated period: 1976–2020), respectively (Ijaz et al. 2020). Moreover, a strong statistical correlation between the overall average annual peak and the average annual runoff was observed during the episodic events due to climate change. It is observed that peak flows occurred during the flooding events which increased flood peaks at Kotri station.

The MK-T and SS-T were applied to hydrological data and represented the 4.9% significance level ($\alpha = 0.049$) for trend analysis. The MK-T represents the non-significant trend in unregulated periods while decreasing sediment discharge is observed at decadal-based. In contrast, sediment discharge values increased during the flood-based or contemporary periods. It is also crystal clear that the flood events transported sufficient sediments compared with decadal-based periods. The flood frequency analysis shows that the dominant runoff value occurred at RP of 0.35 years. However, it is assumed that the decreased supplies of sediment are expected to reduce the curative capacity of floodplains and neighbouring ecological habitats.

**Spatiotemporal dynamics of the Lower Indus River Estuary**

The superimposed channel maps (1986–2020) were obtained using Landsat images and GIS, which aim to study whether flow regulation has a significant influence on estuary migration or not. The LIRE cautious examination represents the braided, new channel formation, and shifted right side at downstream. The water flows in a braiding trend, splitting and reconnecting the flows. The centreline of upper reaches is stable formation, and lower channel reaches towards the estuary have changing cross-sections (Figure 2). Erosion occurs throughout the outer bends with higher velocity and accretion in the inner bends at a lower rate. It is crystal clear that the LIR channel length is increased due to the meandering bends. For example, bifurcation at section La (Tando Muhammad Khan) was formed in 1992. A new bifurcation was formed at La (Tando M. Khan) in 2015 and its area increased in 2020. Similarly, various sections such as Lb (Khair), Lc (Kandrio), and Ld (Thatta) represent that these upstream river sections have changed their courses, cross-sections, formation of new channel bars, and rivers behave as a dynamic system (Figure 3(a)).

The LIRE sections such as L1 (Pir Jo) represent that oxbow lakes existed in 1986 and 1992 while oxbow lakes disappeared in 2010, and finally, channel bar changes in both area and shape in 2020. The L1 (Pir Jo) bend is continuously enlarging, and migration always occurs at different periods. Similarly, the meandering bend such as L2 (Ghot) is becoming enlarged and flattened on the right side as observed through satellite-based images. The neck cut-off events occurred in the L3 (Ghora) and L4 (Dandari) section in the eastward side during 1986–1992. The LIRE sections such as L5 (Kharo) and L6 (Keti) have changing cross-sections at different periods (Figure 3(b)). The noticeable morphological changes are observed with the temporal scale, but the channel top width has fewer changes because of abrupt slope in the channel, which caused the increment of flow velocity and shear stresses.

It is observed that branch channels or bars form in response to flood episodes or water levels, as anticipated, during low flow and high flow seasons. The monsoonal HF events led to the formation of branch channels and bars turn to bank erosion, but LF events did not cause any substantial alterations in the channel network, sand bars, and riverbank erosion. These findings corroborated the previous results that the monsoonal rainfall caused runoff is a major factor for riverbank erosion (Ashraf et al. 2016). Thus, riverbank erosion is not only dependent on the formation of branch channels but also associated with some other complicated conditions.

**Table 2 | Appraisal and trend analysis of hydrological behaviour concerning structural construction across the channel**

| Hydrologic regime   | Peak flood (’000 m$^3$ sec$^{-1}$) | Annual yield (BCM) | Trend analysis |
|---------------------|-----------------------------------|-------------------|---------------|
|                     | Mean | Standard deviation | Mean | Standard deviation | Kendall’s test | Sen’s slope | Trend direction |
| Regulated           | 8.90 | 6.54               | 35.03 | 28.5          | –0.26 | –0.28 | –0.17 | –0.65 | -ve | -ve |
| Partially regulated | 12.6 | 5.84               | 75.89 | 39.9          | –0.48 | –0.58 | –0.58 | –4.39 | -ve | -ve |
| Unregulated         | 12.9 | 3.50               | 98.99 | 20.8          | 0.08  | –0.99 | 0.99  | –0.37 | No  | No  |
The maximum bend occurred downstream sides at L4 (Dandari) with average width (5.4 km), and the average estuary width was observed to be 3.8 km. The oxbow lake formed due to unbalanced erosion. The cut-off bend depends on the slope, soil texture, and topography of banks. The average estuary width varies from 1.8 km (1986) to 5.3 km (2020). The relationship between the proportion of sandbar and BI of LIRE is developed. The relationship represents that the value of BI varies from 3.52 to 5.91, indicating that the number of bars and islands on the channel increased as represented in Supplementary Figure S3(a). Assessment of the proportion of estuary area dominated by bars and BI of LIRE demonstrates a positive correlation with a linear correlation coefficient of \( p = 0.0635 \) and \( R^2 (COD) \) value of 0.403. The regression analysis (LIRE) between mean flood discharge and net reach erosion is significantly correlated \( (r^2 = 0.358, p = 0.01) \) as shown in Supplementary Figure S3(b).

The banks erosion computed along the digitized lines or perpendicular to outer banks shows close results; conversely, if the banks erosion is computed perpendicularly, then it gives a lower value than the computed one. Moreover, the findings of the present research show that banks erosive activity not only depends on flood episodes and their magnitudes, but the channel development and sand bar location are also essential factors, too. The monsoonal flood episodes have a greater impact on river morphology, particularly the erosive activity of outer channel banks.

The flood-based hydrologic intervals (1986, 1992, and 2010) were the most spotlighted events for the channel hydro-geomorphology, during which two (1986, 2010) flood events are the ‘very high’ and one (1992) is ‘high’, which caused channels to neck and chute cut-off (Figure 3(b)). The satellite images and land change at lower flows show that open land which

**Figure 2** | The channel centreline migration (1986–2020). (A) The bending of the Lower Indus River from Dandri to Khair. (B) Downstream bending of the Lower Indus River Estuary from Ghora to the Arabian Sea.
constitutes inactive floodplains and accreted area which occurred at active floodplains were invaded by vegetative cover. A significant correlation among riverine hydrology, riverine migration, and accumulation of sandbars was identified (Table 3). Hickin (1974) has discussed that this process enables building a channel bank, and vegetative growth on ridge and swales is

Figure 3 | The channel changing positions (a) four spots downstream of LIR and (b) five spots for LIRE. These spots represent the formation of the new channel, changing cross-sections, enlargement of meandering, oxbow lakes, and neck cut-off.
Table 3 | Linear matrix relationship of bio-physical floodplain interactions (Ijaz et al. 2020)

| Riparian landscape | Vegetation | Open land | Sand bars | Wetlands | Water area | Geomorphology | Erosion | Deposition | Migration | Average width | Hydrology | Flood Peak | Discharge |
|-------------------|------------|-----------|-----------|----------|------------|---------------|----------|-------------|-----------|---------------|-----------|------------|-----------|
| Riparian landscape | 1.00       | -0.84     |           | 0.50     | -0.66      | -0.56         | 0.51     | -0.62       |           | -0.81         | -0.78     |            |           |
| Open land         | -0.84      | 1.00      | -0.65     |          |            |               |          |             |           |               |           |            |           |
| Sand bars         |            |           | 1.00      |          |            |               |          |             |           |               |           |            |           |
| Wetlands          | -0.65      | 1.00      | 0.75      | 0.81     |            |               |          |             |           |               |           |            |           |
| Water area        | -0.66      | 0.75      | 1.00      |          |            |               |          |             |           |               |           |            |           |
| Geomorphology     |            |           |           |          |            |               |          |             |           |               |           |            |           |
| Erosion           | -0.65      | 0.76      | 0.80      | 0.83     | 1.00       |               |          |             |           |               |           |            |           |
| Deposition        | -0.55      | 0.51      | 0.83      | 1.00     | 0.83       |               |          |             |           |               |           |            |           |
| Migration         | 0.51       | -0.6      | 0.8       | 0.93     | 0.68       |               |          |             |           |               |           |            |           |
| Avg. width        |            |           |           |          |            |               |          |             |           |               |           |            |           |
| Hydrology         |            |           |           |          |            |               |          |             |           |               |           |            |           |
| Flood peak        | -0.81      | 0.68      |           |          | 0.94       | 0.81          | 1.00     | 0.99        |           |               |           |            |           |
| Discharge         | -0.78      | 0.71      |           |          | 0.94       | 0.80          | 0.99     | 1.00        |           |               |           |            |           |
distinguished from density patterns and vegetative species. The flood-event reduction also results in diminishing the vulnerability to agro-forestry in inactivated flood plains. Thus, the channel's vegetative cover increased from 170.4 km² (2002) to 364 km² (2016), which changed the physical habitats in floodplains through the declining soil infiltration rate.

Channel lateral migration and number of channels in LIRE

A phenomenal change in the channel migration area was observed. The total migration area from 1986 to 2020 reduced up to 74.56%. The migration direction depicts that the channel migrated more towards the right floodplain from 1986 to 1992, but left migration is dominant in 2000 (detailed description in Figure 4). The wetted area expansion occurred during flood events that constituted new channels, while dry channels during low flows were retained annually. The LF channels are constantly occupied throughout the year, while peak flow channels are only occupied during the monsoonal season.

The lateral changes occurred in fewer years due to erosion phenomena in macro-channels because of sediment load on opposite channels. The channel remains stable during lower flows, and abrupt changes occurred at flood events that carried large sediment. The wetted channels at lower and peak flows were identified in LIRE (1986–2020), and channels are determined based on a prior study (Carling et al. 2018). The estuary has a minimum of three and a maximum of eight channels for a given cross-section (not illustrated). The mean number of channels for lower flows is 5.25 and at higher flows it is 5.25. The higher flows have two extra channels compared with lower flows. It is concluded that three channels remain wet throughout the year, while five channels occurred during the monsoonal season.

Geomorphological analysis and channel planform migration

The sinuosity index of LIR varies from 1.73 (1986) to 1.79 (2020), which indicates the formation of straight channels. The estuary sinuosity index (SIₑ) has an increasing trend from 1.84 (1986) to 1.92 (2020). The SIₑ temporal variation represents that the tidal-dominated segment has more sinuous (SIₑ = 1.92) than the riverine section (SIₑ = 1.79). Nevertheless, SIₑ changes have increasing and decreasing trends (Figure 5(c)). The spatiotemporal statistical trends represent a significant correlation between SIₑ and SIₑ (r = 0.66), while poor correlation was noticed with the tidal section (r = 0.14). The estuary and river length are observed to be an increasing trend. Besides, channel sinuosity rise provides a good amount of nutrients and minerals, which increase the soil fertility (Ijaz et al. 2020).

The LIR length varies from 280 to 295 km, while the estuary length increases from 142 to 151 km. The dominant erosion and accretion occur during climate-based flood events, which ultimately increase the width. The quantitative analysis illustrates that estuary channels widened towards the sea (tide section) and narrowed landward (riverine area).
The computation of top width standard deviation ($\sigma$) shows that the tidal zone is more variable than the riverine zone. Thus, top width changes at various cross-sections are due to the bank’s instability. The average estuary channel width varies from 2.1 to 5.3 km at climate-based flood events, while the riverine channel width varies from 3.2 to 5.5 km (Figure 5(d)). The water surface area of LIR and LIRE during flood-based events varies from 460 to 525 km$^2$.

**Topographic and landscape analysis**

The topographical features of the valley and estuary channels that have reacquired the digitized data with spatial changes are reproduced in Table 4. The floodplain topography ranges from the largest (7.59 m) to the smallest (2.33 m) altitude and an overall slope of 0.00403%. The correlation was aberrant ($r = 0.589$) due to the dominant sections of riverine and tidal behaved as a single reach, probably due to two different hydraulic forces (fluvial and tidal). The standard deviation of the estuary thalweg variations was more significant than the elevation points of the valley. The LIRE channel has a steeper slope (0.0109%) than the valley and thalweg depth at a single distinct spot (L4) was observed to be larger compared with other cross-sections.

**Table 4** | Topographical behaviour of the valley and estuarine channel

| LIRE cross-section | Reach elevation (m) | Valley elevation (m) | Channel thalweg depth (m) |
|--------------------|---------------------|----------------------|---------------------------|
| L1                 | 13.104              | 6.3                  | -6.66                     |
| L2                 | 52.893              | 5.9                  | -6.99                     |
| L3                 | 95.402              | 4.553                | -9.188                    |
| L4                 | 135.821             |                      | -4.411                    |
| L5                 | 146.702             |                      |                           |

As depicted in Figure 1.
When river and tidal-dominated parts were regarded as single reach, then the correlation between both slopes became aberrant ($r = 0.613$), which was due to the presence of two separate forces (tidal and fluvial). Notwithstanding, the standard deviation of LRE thalweg points is larger than valley elevation points.

The estuary land-use map at a specific section is categorized into five major classes (water, vegetative cover, open land, sand bar, and wetland) based on Landsat and field observation, but land-use has not been validated through field survey. The water area is increased from 101.41 km$^2$ (1986) to 110.24 km$^2$ (2020), and a sand bar cyclic pattern of variability was noticed. It is observed that the sand bars value decreased from 48.76 km$^2$ (1986) to 37.28 km$^2$ (2020). Fascinating trade-offs between land use and vegetative cover are observed during the study period. The land-use trend lines depict that the vegetative cover increased by 33.54%, and the open area is decreased by 50.76% (Supplementary Figure S4). The vegetative cover and land-use changes are more than open land; however, a decreasing trend in open land is quicker than the vegetation. The vegetation area from Landsat images was checked and compared with field data. The forest division in Thatta has revitalized the area between 1,647 hectares (1992–2000) and it is planned to restructure an extra agro-forest area to 10,989 hectares. Our study shows an enhancement of 142 hectares (1993–2013), while the published data recommended an estimated rise of 131.47 ha due to artificial irrigation and water management plans (1993–2010).

**Estuary banks recession**

The estuary riparian land loss on both banks (right and left) down the system’s full length was assessed to examine the relationship of bank erosion with the flood episode. The estuary annual land loss compared with maximum discharge for both banks was computed for every 150 km cross-section represented in a single cross-section (Supplementary Figure S5). Despite that required discharge value, up to 13,000 m$^3$ sec$^{-1}$ and the maximum discharge value that occurred in 2010 as a benchmark was compared with other flood events in the study reach. The 68% depicts the positive linear relationship in all sections (Equation (5)), with 51% statistical correlation ($P < 0.039$, $r^2 > 0.355$, N = 8). The 28% section has weak and non-significant relations ($P > 0.048$), whereas 60% has a positive connection with land loss at a value of 5,887 cubicms, which is considered as a bank erosion threshold runoff value. The whole positive regression analysis is bounded to the intercept of the x-axis where $Q = 5,887$ cubicms. Moreover, eight years of the study illustrated that with land loss for peak discharge <$11,900$ m$^3$ sec$^{-1}$, it is inappropriate to accept the threshold value of 5,887 m$^3$ sec$^{-1}$ for practical applications. Thus, we have investigated the land loss for the given value of discharge. The additional satellite land loss data has been plotted for eight more years (2007–2012, 2015, and 2014) to determine this method acceptability. It is evident that the 31% sample has negative and 69% has positive regression analysis. The results depict that between sections, a probability greater than 62% could be applied (10–20 km) to the next neighbouring reach. The fundamental computations indicate that increasing discharge values are associated with land loss compared with lower flows. Thus, it is clear based on the above analyses that channels change through riverine banks recession.

**ASSESSMENT OF SEDIMENT LOAD DURING LOW-FLOW AND HIGH-FLOW PERIODS**

The sediment load was assessed during LF and HF periods to check how the flood events impact the channel erosion and accretion in the study area. We have collected the pre-flood and post-flood data (2018) to check the daily erosion and accretion rate in the AC, TC, RP, and LP. From this data it may be noted that during the HF period, about 6–9% and 8–12% of Indus River flow was diverted to the canals off-taking from RP and LP, respectively. However, during the LF period, about 23–30% and 31–50% of Indus River flow was diverted to the canals off-taking from RP and LP, respectively. Thus, design or more than design discharge was diverted in almost all the canals during the monitoring period.

The TSL in the LF period was 1,287 ppm, wherein computed bed material load of sand fraction (+62 μm) was 288 ppm and SSL of fine fraction (−62 μm) was 978 ppm. This indicates a TSL of 0.703 million tons/day, which comprised 76% fine sediment (clay and silt) and 24% sand. However, TSL on average during the HF period was about 1.274 million tons/day. The D50 of the bed material samples taken in June 2018 (before the HF period) generally falls between 0.100 and 0.205 mm (very fine and fine sand). However, the bed material after high flood also has clay and silt (<0.0625 mm) ranging between 19 and 97% of the total weight of sample. The D50 of bed material after HF, at $RD_2 + 000$ and $RD_7 + 000$, was slightly coarser than pre-flood, ranging between 0.077 and 0.254 mm. However, the D50 of bed material at $RD_9 + 000$ after high flood was finer than the pre-flood and ranged between 0.082 and 0.101 mm (Figure 6).

During the high sediment flow period, the average bed material load for the sand fraction (+62 μm) in AC, TC, and RP entrance was 257, 351, and 189 ppm, respectively. The average discharge at these sites was 50,681, 22,520, and 27,552...
cusecs, respectively. A sizeable load consisting of fine fractions (<62 μm) was carried out by river during the HF period. This averaged 1,110, 1,188, and 1,201 ppm in AC, TC, and RP, respectively. The average SSL consisted of 20% clay, 65% silt, and 15% sand during the HF period. However, the average sand fraction (+62 μm) concentration during the LF period was remarkably low. It was 33, 15, and 49 ppm in AC, TC, and at the RP entrance, respectively. The average SSL consisting of fine fraction (<62 μm) during the LF period was 740, 580, and 740 ppm at the three sites. The SSL consisted of 38% clay, 59% silt, and 3% sand during the LF period.

The 50.05% of the bed material samples collected in the field also consisted of fine sediment (silt and clay) and its percentage was on the higher side when flow in the Indus River had receded. On average, silt and clay (<62 μm) was 36.2, 58.5, and 46.3% of the total sample in AC, TC, and RP, while sand at these sites was 62.5, 40.4, and 52.7%, respectively. During the HF period, total sediment inflow to AC is 12.124 million tons and its distribution in TC and RP is 6.188 million tons (51.2%) and 6.595 million tons (53.3%), respectively. This indicates sediment erosion of 0.648 million tons in the reach from the start of AC to its bifurcation into TC and RP channels. However, there was also an erosion of 0.038 million tons of sediment in this reach during the LF period. Thus, there was net sediment erosion of 0.687 million tons during both the HF and LF periods.

Moreover, Figure 6 represents the relationship between sedimentation concentration, discharge, and sediment load, while Figure 7(a) represents the computed particle size distribution (percentile sizes) during the LF and HF periods.

During the HF period, flows leading to TC consisted of 24% sand (+62 μm) and 76% clay and silt (<62 μm). However, 0.664 million tons of sediment was deposited in TC during the HF period, and 0.175 million tons (27.8% of deposited material) of sediment was eroded from TC during the LF period. Thus, there was a net deposition of 0.478 million tons (6.9% of sediment inflows to Tail channel) of sediment in the TC.

### Erosion and deposition pattern in barrage pockets

It may be observed from the preceding that during the HF period, the average sediment concentration of sand fraction (+62 μm) in the off-taking canals is significantly lower than the sediment input in the RP. The sediment concentration of fine fraction (<62 μm) during the HF period, in almost all the off-taking canals, is slightly higher than the RP. This indicates a mixed trend, i.e., deposition of sand (+62 μm) and erosion of fine sediment (<62 μm) in the RP. However, during the LF period, the sediment concentration of sand fraction (+62 μm) at the LP entrance and off-taking channel is almost the
Figure 7 | Relationship between sedimentation concentration, discharge, and sediment load at Kotri barrage. (b) The computed particle size distribution (percentile sizes) during the LF and HF periods.
same, while fine sediment (−62 μm) concentration in all three off-taking canals is slightly more than the concentration at the entrance of RP. This indicates erosion phenomenon during the LF period. During the HF period, in right bank canals, SSL consisted of 26.5% clay, 69.5% silt, and 4% sand. However, during the LF period, SSL consisted of 38% clay, 59% silt, and 3% sand (Supplementary Table S2). During the HF period, the total sediment inflow at the start of RP is 5.784 million tons, and the total sediment withdrawn by the off-taking canals is 5.405 million tons. This indicates the deposition of 0.378 million tons of sediment in RP. However, there was sediment erosion of 0.073 million tons during the LF period. Thus, there was net sediment deposition of 0.304 million tons in the RP. Moreover, the water discharge (m³ sec⁻¹) and concurrent sediment concentration (ppm) relationship during the LF and HF periods (2018) is given in Supplementary Figure S6.

A sizeable load consisting of fine fraction (−62 μm) is also carried by the river and canals off-taking from the left bank. The average suspended sediment concentration during HF was 1,223 ppm (LP) and 1,280, 1,322, and 1,342 ppm from its off-taking canals. However, during the LF period, the average suspended sediment concentration of fine fraction (−62 μm) at these sites was 602 ppm (LP) and 817, 737, 668, and 708 ppm from its off-taking canals. This indicates that in both the high and low-flood periods, the canals off-taking from the left bank were drawing more clay and silt (−62 μm) than was entering in LP. This indicates erosion of finer sediment from the LP. The weighted average suspended sediment size in left bank canals during the HF period suspended sediment consisted of 23.9% clay, 68.9% silt, and 7.2% sand, while during the LF period, it consisted of 37.9% clay, 58.9% silt, and 3.2% sand. During the HF period, the total sediment inflow in LP is 10.484 million tons and the total sediment withdrawn by the four off-taking canals is 10.045 million tons. This indicates the deposition of 0.528 million tons of sediment in the LP during the HF period (Figure 8(a)). However, there was sediment erosion of 0.401 million tons during the LF period. Thus, there was a net sediment deposition of 0.119 million tons from LP. The prediction of estuarine bank erosion is given in Figure 8(b) with detailed discussion provided in the Supplementary material.

We have compared the sediment load of the Lower Indus River with the similar study, which is conducted in the upper Indus River basin, Pakistan (Ali & De Boer 2007). The sediment results of the present study indicate that the high sediment yield occurs during the HF periods and carries coarser particles (sand) having erosive activity which causes the vegetated land loss. Thus, the evaluation of the hydro-climatological data indicates that the current speed is directly linked with the sediment yield. The previous study of SSL in the upper Indus River shows that 80–85% of the annual sediment load is transported during July and August. The sediment load at Astore River indicates that sediment yield is higher in May due to the higher precipitation and snowmelt, and lower sediment yield was observed in August due to the lower influence of glacial melting (Ali & De Boer 2007). Although both studies indicate that sediment yield is higher during the monsoonal season and sediment yield has a lower influence during the winter season, but previous studies did not explain the role of sediment load on river morphology. Therefore, the present study was conducted to estimate the riverine erosion and deposition trends.
Numerous inconsistencies such as futuristic paths of such a complex system affected by the unprecedented automotive and ecological conditions. The LIR hydro-geomorphology and ecology behaviour is altered by human-induced activities. The trade-offs between channel hydrology, river geomorphology, and landscape ecology would be useful for policymakers to determine the entire system's ecological health and enable specialists to work on providing a framework for the study of system dynamics (Flemming & Martin 2021). The statistical-based MK-T of the annual runoff and flood peaks for the last 100 years represents that the LIR hydrological regime has significantly weakened due to the upstream constructed Terbela dam. Moreover, the riparian landscape of LIRE seems to be more vulnerable to hydro-geomorphology changes. The consistent high flood peaks during the monsoonal season have changed the inundation structure and influenced the vegetative cover. The flood episodes of the marine sand reach of the Indus estuary with its enormous flood delta comes as no surprise.

CONCLUSIONS AND THE WAY FORWARD

This study inaugurates a new line of research to analyse the spatiotemporal variations in river morphology, hydro-geomorphology behaviour, and sediment analysis in the low and high-flow periods to examine the grain size variation, banks erosion, and deposition. The most noteworthy findings of this study are as follows:

- From Landsat satellite images and GIS points of view, the LIRE showed channel shifting, meandering, oxbow lake, neck cut-off, and cross-sectional variations in recent years. The average estuary channel width varies from 2.1 to 5.3 km at climate-based flood events, while the riverine channel width varies from 5.2 to 5.5 km. The LIRE means that the estuarine system has more sinuosity index than the upstream reach, and the length increased from 1986 to 2020. It is noted that banks erosion activity does not exist at a peak runoff value of $<5,887$ m$^3$ sec$^{-1}$.

- The LIR hydro-geomorphology and ecology behaviour is altered by human-induced activities. The trade-offs between channel hydrology, river geomorphology, and landscape ecology would be useful for policymakers to determine the entire estuary system's ecological health and enable specialists to work on providing a framework for the study of system dynamics (Flemming & Martin 2021). The statistical-based MK-T of the annual runoff and flood peaks for the last 100 years represents that the LIR hydrological regime has significantly weakened due to the upstream constructed Terbela dam. Moreover, the riparian landscape of LIRE seems to be more vulnerable to hydro-geomorphology changes. The consistent high flood flows during the monsoonal season have changed the inundation structure and influenced the vegetative cover. The flood epoch of the marine sand reach of the Indus estuary with its enormous flood delta comes as no surprise.

- For a certain year, the sediment discharge data was carried out to trace the flood-based HF and LF events' impacts on erosion and deposition fluxes. The TSL during the HF period was about 1.274 million tons/day, and D50 of the bed material samples falls between 0.100 and 0.205 mm (very fine and fine sand). The bed material after high flood also has clay and silt ($<0.0625$ mm) ranging between 19 and 97% of the total weight of sample. The D50 of bed material after the high flood, at $RD 2 + 000$ and $RD 7 + 000$, was slightly coarser than pre-flood, ranging between 0.077 and 0.254 mm. However, the D50 of bed material at $RD 9 + 000$ after high flood was finer than the pre-flood and ranged between 0.082 and 0.101 mm. The highest erosion was observed to be 19.9 m downstream of the Sujawal Bridge (about 2,400 m) along the right bank. Thus, LIRE morphology alteration is more vulnerable during high-flood periods because of coarser sediment carrying capacity. The quick intertidal deposition primarily occurred near the distribution mouths because of the surplus supply of sediment and human-made projects of land reclamation.

- Numerous inconsistencies such as futuristic paths of such a complex system affected by the unprecedented flood episodes and sediment loads (carrying more coarser particles during flooding events) affected the channel morphology, notably, channel width variations can be found in the LIRE. The findings of the present study are consistent; hence, various model techniques can be adopted to lessen uncertainties. It is crystal clear that LIRE channel movement leads to physical hazards in vulnerable regions and will tend to decimate the ecosystem and socioeconomic pattern of southern Pakistan, unless adequate measures are put in place. Thus, our study will help decision-makers, ecologists, and water resources managers to understand the LIRE fluvial processes. The sediment fluxes were a piece of essential information in the mega-delta system and coastal management (Diefenderfer et al. 2021). Future studies should be carried out to predict bank erosions computed through modeling approaches, which would be helpful to build a risk assessment framework of land loss.
ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (Grants # 41671455, 51879239); the major consulting project of the Chinese Academy of Engineering (Grant# 2020-ZD-18-5); and the Think Tank Research Projects of Zhengzhou Collaborative Innovation with major funding (Zhengzhou University) (Grant# 2019ZZXT01).

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 19 September 2021; accepted in revised form 19 December 2021. Available online 6 January 2022