Tracking Temporal Migration of the Indus River: Morphological Changes in a Downstream Reach

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Indus River morphological changes create environmental challenges, impacting local communities and ecosystems through fertile land loss, bank erosion, and higher flood risks. Monitoring these changes is crucial for flood and water resource management and infrastructure protection. This study uses geospatial data and tools to analyze spatial and temporal morphological dynamics of a downstream Indus River reach between the Sukkur and Kotri barrages from 1995 to 2024. Satellite imagery was analyzed to study morphological changes. Significant channel adjustments in river shape and form were observed, evident through erosion, deposition, and lateral shifts over the past three decades. The maximum erosion, covering 35,540 ha, and accretion, covering 23,737 ha, were observed between 1995 and 2005, with later periods showing reduced erosion and greater stability. The total cumulative erosion was 71,575 ha, and the total cumulative accretion was 64,790 ha, which gives a net loss of 6,785 ha. The sinuosity analysis showed that the meandering tendency of the river increased over the years as the sinuosity ratio increased from 1.82 in 1995 to 1.93 in 2024. These findings reveal the features of fluvial dynamics of the Indus River and stress the importance of reducing the adverse effects of these changes as necessary for the area's sustainable development.

Keywords: River Migration, Erosion, Accretion, Sinuosity Indices, Migration Rates, Geospatial Data and Tools

Introduction:

River systems are mobile structures that evolve through time due to physical processes and human interferences [1][2]. Fluvial adjustments of river systems result from hydrological processes, sediment transport, and human activities, including the construction of dams, irrigation, deforestation, and changes in land use [3]. In this case, a change in river geometry will lead to an imbalance of the dynamic equilibrium [4], and hence, the channel form and pattern will be affected. As a result, these activities also lead to the degradation of river conditions, including hydrogeomorphology, bank erosion, and bank failure, and also affect the ecosystem and biodiversity [5]. Thus, evaluation of river morphology and sediment equilibrium is unavoidable for the rehabilitation and perpetuity of the channel ecosystem [6].

The Indus River is one of the longest rivers on the globe, and it is the lifeline of Pakistan in terms of hydrological, ecological, and economic perspectives. The stretch of the river between Sukkur and Kotri is crucial for its social and economic significance, as it links two major barrages that support the contiguous irrigation system, the Indus Basin Irrigation System (IBIS). The study reach has undergone physical changes over time due to both natural and human- induced factors. These morphological changes have significant implications for the river's form, health, ecosystem, and the user's community. Several studies have also indicated the decline in vegetation along the river banks, an increase in bank erosion rates, and sedimentation [7][8]. For instance, the bank erosion rate of the lower Indus River estuary is in direct proportion to the peak runoff events, which suggests that the river banks are vulnerable to hydrological events [9]. Therefore, it is imperative to study river morphology periodically, especially by utilizing modern river monitoring techniques such as remote sensing [10]. Such methods are suitable because they do not require ground surveys which is, which are taking [11]. Awareness of channel migration in the Indus River is important for effective water resource management, flood risk assessment, and environmental protection [12].

This study aims to analyze morphological changes in the Indus River from Sukkur to Kotri for the years 1995, 2005, 2015, and 2024 via satellite remote sensing. Using geospatial data and tools, it examines channel dynamics, including migration, erosion, and accretion, while estimating sinuosity indices. These indices provide valuable insights into river behavior in response to environmental changes.

Materials and Methods:

Study Area Description:

The Indus River is the third-longest in Asia. The river starts from the high zone of the Tibetan plateau, moves through India and Pakistan, and falls into the Arabian Sea. Sukkur barrage, constructed in 1932, regulates the Indus River and distributes water to several canals for irrigation purposes, playing a vital role in developing the agricultural industry of the Sindh province [13]. Another downstream dam is Kotri Barrage, which controls water distribution and floods of the region's water framework [14]. These barrages supply water to a vast canal network that sustains agriculture, the region's primary economic sector [15]. The region's economy heavily relies on cotton, wheat, and rice crops, which are irrigated by water from the Indus River [16]. Furthermore, the barrages serve as a flood control measure to protect people from destructive floods to property and crops [17] (Figure 1) presents the river stretch between Sukkur and Kotri Barrage.

Satellite Image Acquisition:

The first process in the methodology was the collection of satellite imagery for the years 1995 (Landsat 5), 2005 (Landsat 7), 2015 (Landsat 8) and 2024 (Landsat 8) at a high spatial resolution. Satellite imagery was obtained from the USGS Earth Explorer https://earthexplorer.usgs.gov/, which offers multispectral data appropriate for land cover classification and water body extraction [18]. The images were chosen with respect to their availability and the cloud cover of the area to get the best quality for analysis. The methodology chart is presented in (Figure 2).

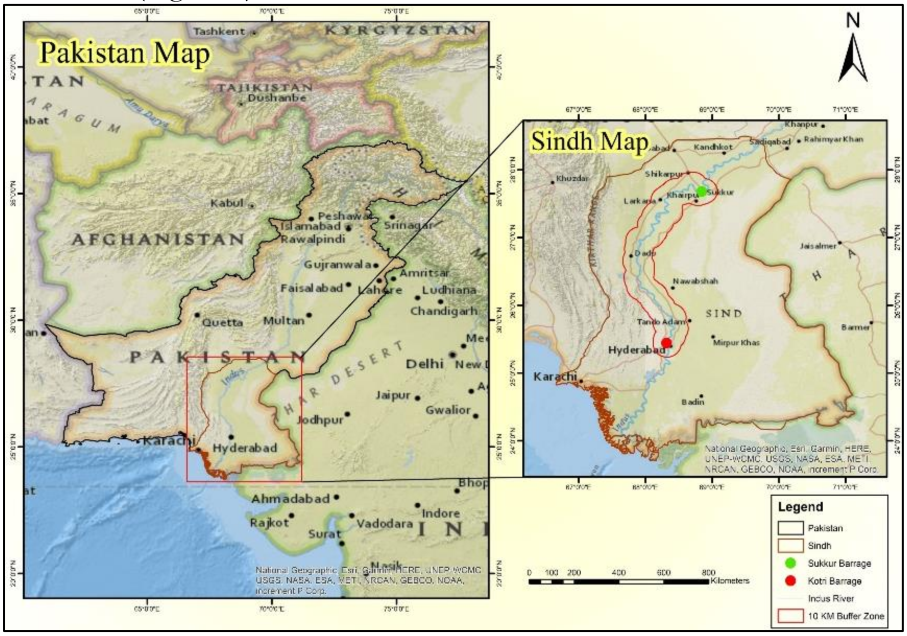

Figure 1. Study Area Map

Image Classification and Image Preparation:

The K- means clustering classification technique was used to classify the image into 5 classes based on spectral similarity, and the water class was used as a key focus to improve the accuracy of identifying water bodies [19]. Additionally, classification results were converted to polygons, and the river body was then manually selected and extracted from other land cover polygons for further analysis, which enabled the clear separation of the water body from other land covers (LC) without relying on water indices like NDWI. K- means clustering was used as a primary method, future studies could benefit from comparison with spectral indices like NDWI or MNDWI.

Channel Migration Analysis:

To assess channel migration, the river polygon extracted from the vector file was placed in a pair of two in one frame to reveal the channel movement. The intersect tool in GIS was applied to measure the area of the unchanged regions between the two-time intervals. This step was crucial in approximating the areas of erosion and accretion in the river channel [20]. Equation (1) is used to calculate erosion and accretion:

$$E = At_1 - At_2 \; A = At_2 - At_1 \quad (1)$$

Where:

E= Erosion

A=Accretion

At_1= Area of the river channel at time t_1

At_2= Area of the river channel at time t_2

Sinuosity Calculation:

The sinuosity of the river channel was computed for each period to determine the level of meandering [21]. Further, to better visualize sinuosity, the river was divided into five segments to calculate sinuosity. The sinuosity was calculated using Equation (2):

$$Sinuosity = \frac{LR}{LD} \quad (2)$$

Where:

LR = Length of the river channel

LD = Straight-line distance between the endpoints of the river channel.

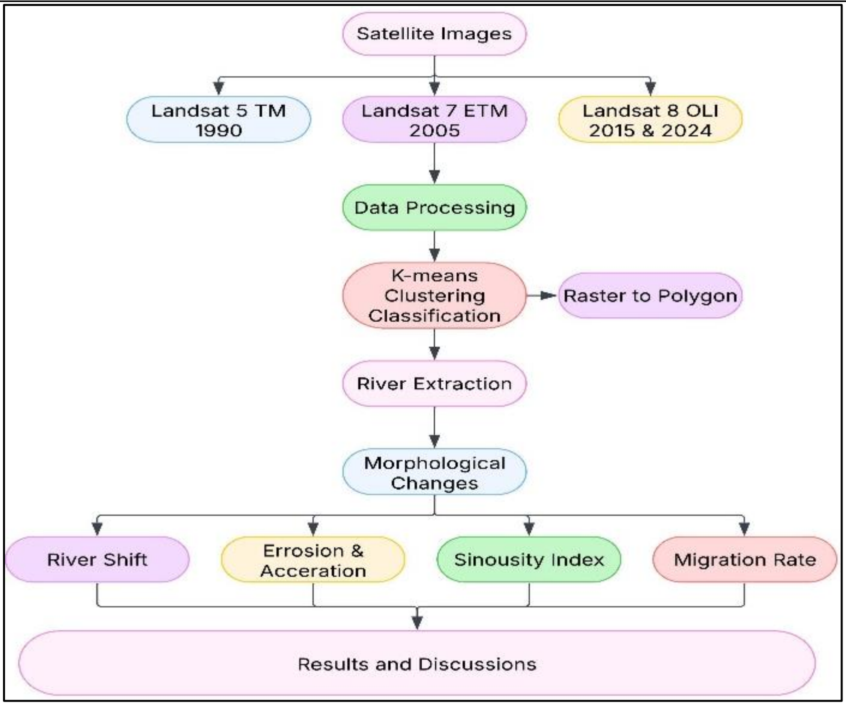

Figure 1. Methodological Framework

Results and Discussions:

River Migration:

1995-2005: There was a considerable channel shift in the river during this period (Figure 3). Such patterns of widening and narrowing were identified along various parts of the river. Major channel changes were observed, especially in the areas around the Sukkur barrage and downstream, which showed significant lateral channel adjustments and active morphological process.

2005-2015: The assessment showed that channel migration continued and that there were visible shift trends to the western (right) bank in some areas and to the eastern (left) bank in others (Figure 4). This period revealed the process of degradation and accumulation of sediments that affected the river channel. Some regions showed a higher degree of meandering, especially in areas near heavy vegetation.

2015-2024: The last interval demonstrated consistent changes in the channel; moreover, some of the sections of the river became even more narrow (Figure 5). Another area of noticeable erosion was observed on the left bank of the river downstream from Kotri barrage, with corresponding deposition on the right bank of the river.

Erosion and Accretion Analysis:

1995–2005: At this time, the river had high channel adjustment and aggradation rates. That shows that there were intense fluvial activities in the area (Figure 6).

Only 2,219 hectares of the river remained unchanged during this decade, indicating high river dynamics and fluctuations. Approximately 35,540 hectares along the riverbank were eroded, marking the greatest erosion compared to all other time intervals. Accretion of 23,737 hectares was recorded, suggesting sedimentation has occurred in many areas of the channel (Table 1).

2005–2015: This decade revealed a decrease in erosion compared to the previous interval (Figure 6). However, changes in the accretion dynamics were observed. Around 8574 hectares along the riverbed remained stable during this period, which could be considered as an increase in the channel stability compared to the data of 1995-2005.

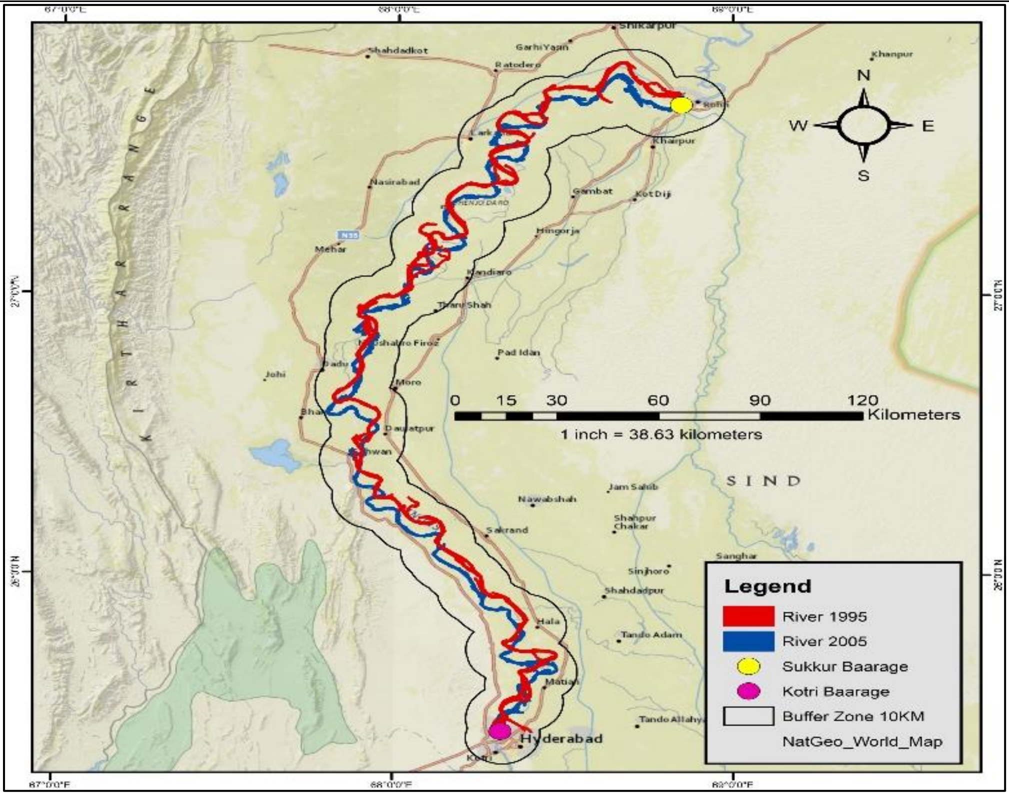

Figure 2. Migration of the River from 1995 to 2005

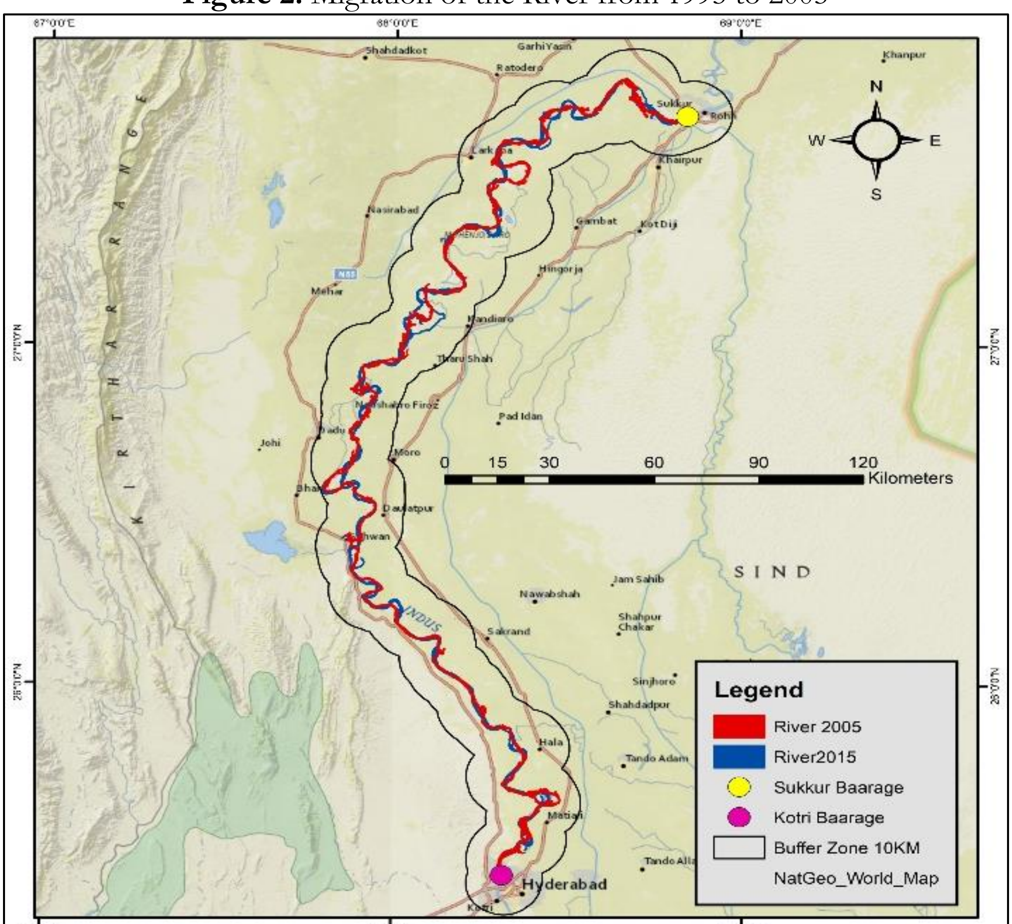

Figure 3. Migration of the River from 2005 to 2015

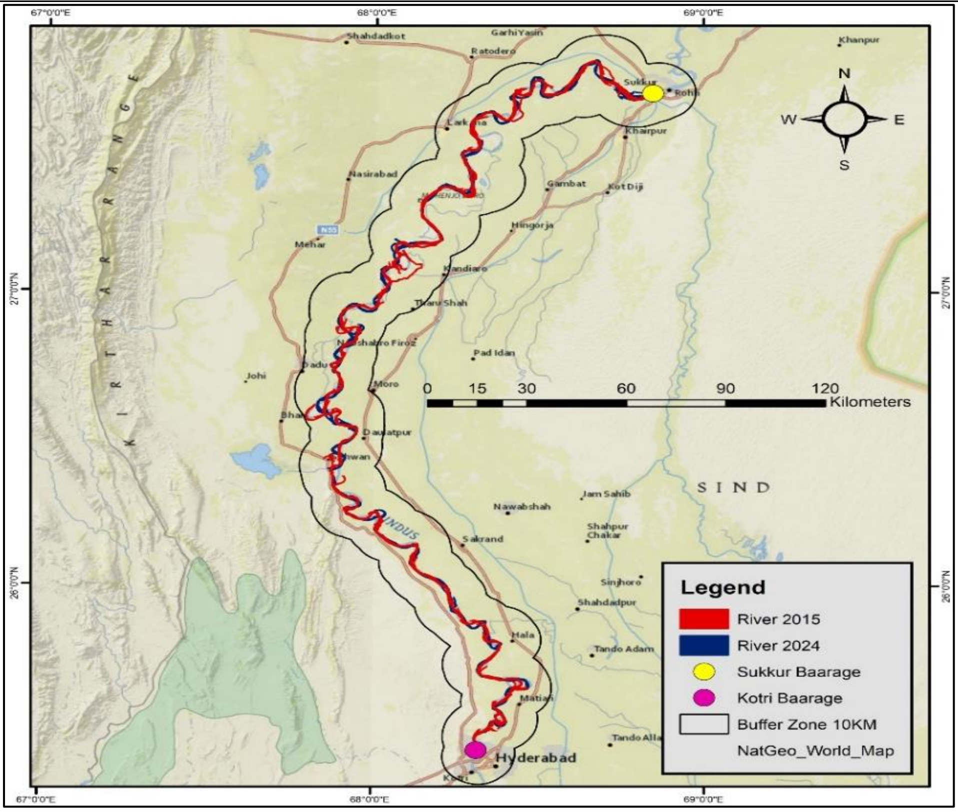

Figure 4. Migration of the River from 2015 to 2024

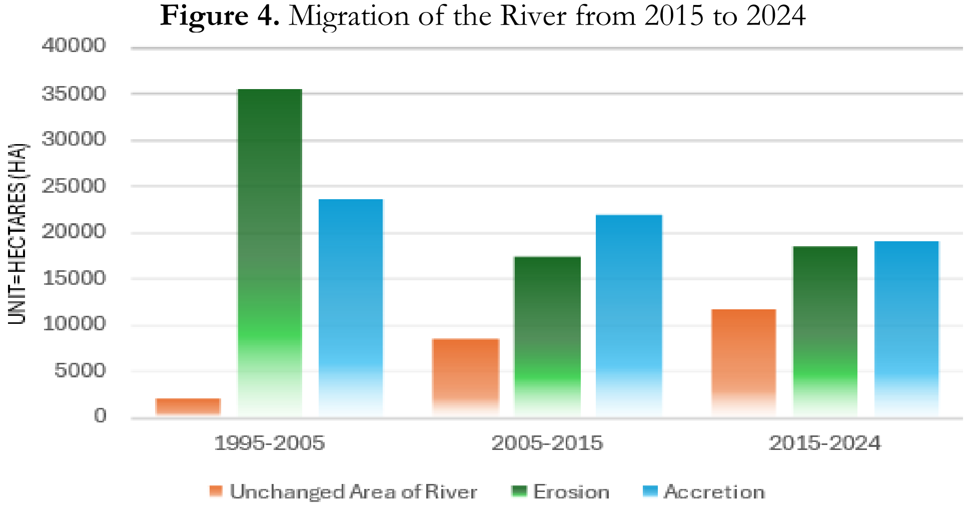

Figure 5. Demonstration of Erosion, Accretion, and Unchanged Area

Table 1. Total areas in hectares of different parameters across the period

Years	Previous Years	Next Years	Unchanged Area	Erosion	Accretion
1995-2005	37759	25956	2219	35540	23737
2006-2015	25956	30526	8574	17382	21952
2015-2024	30526	30974	11873	18653	19101

Erosion reduced to 17,382 hectares, which is lower than the previous decade. This indicates relative stabilization in certain parts of the river, with accretion increasing to 21,952 hectares (Table 1).

2015–2024: The last interval also shows a trend in the erosion and accretion processes, with the unchanged river area growing to 11,873 hectares, the highest recorded across all periods (Figure 6). This suggests a shift towards greater channel stability, though some changes continue to occur. Erosion slightly increased to 18,653 hectares, indicating a moderate rise in fluvial activity. Accretion during this period was 19,101 hectares, which was nearly equal to the erosion process (Table 1).

Sinuosity Analysis:

The sinuosity ratio that represents the level of river meandering also reveals a gradual rise over the study years (Figure 7) (Table 2). These results suggest that the river has been meandering slightly more between 2005 and 2024. The centerline length increased from 463 km in 1995 to 490 km in 2024 (Figure 6). Meanwhile, the straight-line length remains at 254 km, which also indicates changes in the morphology of the river.

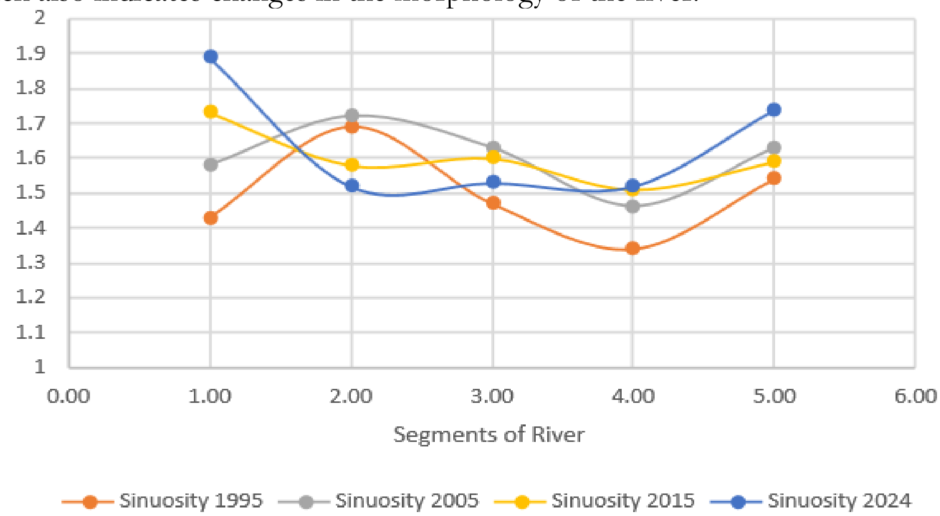

Figure 6. Sinuosity Fluctuation in different segments of the river

Table 1. Sinuosity index across five segments

Segments	Sinuosity 1995	Sinuosity 2005	Sinuosity 2015	Sinuosity 2024
1	1.43	1.58	1.73	1.89
2	1.69	1.72	1.58	1.52
3	1.47	1.63	1.60	1.53
4	1.34	1.46	1.51	1.52
5	1.54	1.63	1.59	1.74

Human Interventions and Comparative Perspective:

The modifications observed in the downstream result from both natural processes and human-caused interventions. Activities such as the construction of dams, barrages, and changes in land use produce significant impacts on river morphology. The construction of Tarbela and Mangla Dams has reduced sediment delivery to the lower Indus, which has caused natural sediment balance disruption and led to downstream channel incision and erosion [12]. Increased floodplain agricultural activities as well as expanding irrigation networks, resulting in limited natural river migration [16]. These human-made modifications affect channel shape and create threats to nearby human communities and their agricultural areas, and natural ecosystems [5][9]. Similar patterns of the anthropogenic impacts are identified in other rivers, such as the Ganges and Yellow River, where decreased sediment supply and changes in flow regimes caused the channel instability [3][5]. Furthermore, [12] reported migration and accretion trends in the lower Indus River, supporting our findings of lateral channel shifts and spatial variability in lateral channel shift. Additionally, in Yellow River it was observed that reduction in sediment load due to upstream interventions resulted in increased erosion and incision in the lower reaches [9]. These similarities highlight the broader relevance of integrated river basin management that considers both hydrological and socio-economic dynamics.

Migration Rate of River from 1995 to 2024:

The right bank of the Indus River has a wider fluctuation, with displacements varying from 55m to an extreme of 8663m. For instance, the maximum lateral shift on the right bank is 8663 meters, which indicates a zone of intense geomorphic activity (Figure 8) (Figure 9).

Figure 7. Left and Right-side shift of the river from 1990 to 2024

The left bank of the Indus River shows a high degree of channel migration fluctuation in the years between 1995 and 2024. These shifts vary from as small as 55 meters to as large as 7240 meters (Figure 8) (Figure 9). Thus, it points to zones with both little and much lateral mobility. In some ways, the left bank is slightly more stable, with lesser variations shown in areas like 155 meters and 180 meters.

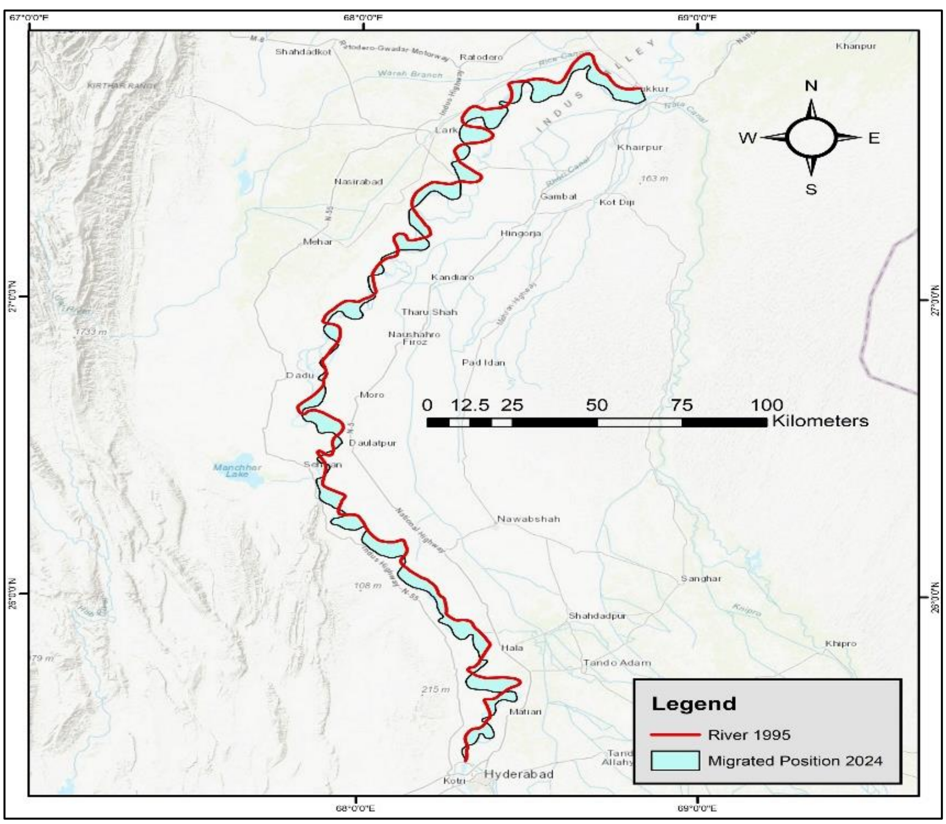

Figure 8. Migration of the river from 1990 to 2024

Conclusion:

The study concludes that the Indus River between Sukkur and Kotri Barrages has experienced significant spatiotemporal morphological changes over the past decades, reinforcing that the Indus River is dynamic and not static. Some of these changes include erosion, accretion and sedimentation that have natural causes, as well as changes due to human influences. Sustainable river management practices are needed to counter the effects of channel shifting. There is a need to implement preventive measures to address these challenges, including strengthening monitoring mechanisms, developing effective planning frameworks, and encouraging public participation in development projects. Such efforts will lead not only to the sustainable conservation of the ecological balance but also to the future socio-economic stability of the river-dependent community.

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