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ASSESSING THE IMPACTS OF TIDAL INUNDATION AND SEAWATER INTRUSION ON AGRICULTURE AND WATER RESOURCES IN DISTRICT BADIN, SINDH

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By

Ibrahim Zia[1], Tehreem Zafar[1], Rizwan Akhtar[1], Bassam Nasir[1]

Abstract:

Seawater intrusion is a problem in many coastal estuarine and waterways in various parts of the world. Pakistan, the Tidal Link Drain is a man-made drain which delivers saline drainage water from irrigation land of upper Sindh on the left side of the Indus River into the Arabian Sea via Creek. The Tidal Link is 41 Km long in the North–East up to the Indus system. The tidal link was designed to carry about 3,118 cusecs of drainage waters. In May 1999, a Cyclone–TC 02A had devastated 160 km coastline of Sindh, the catastrophic effects of the cyclone resulted in severe damage to Tidal Link drain and embankments on both sides of the Tidal Link were partially washed out and about 56 breaches occurred in several locations. As a result, the seawater intrusions into saline/brackish water lakes which relate to the tidal link drain causes the drastic change in salinity levels. An intrusion of sea water up to 43km was recorded, where the large brackish water bodies are located. The analysis of data and samples collected in the study area shows that a small tidal creek type system of drainage channels has now developed the "Hydraulic Gradient (measure of the change in hydraulic head (water pressure) per unit distance in a fluid flow system)" for the discharge of irrigation water through tidal link drain into the creek water at the same level as well as entire delta. This finding also discussed the entire deltaic variation with respect to climate change impact and Sea water intrusion.

Introduction

The Indus River basin stretches for about 2,900 km across four countries (Pakistan, Afghanistan, India and China) in an area that is 30% barren.(Wong, C. M., n.d.) The Indus River begins at Lake Manasarovar, north of the Himalayas, in Kailash, China Mount Parbat, at an altitude of 5500 m. It then travels through India to Pakistan, where it flows along the entire length of the earth (Fig. 1). The Indus River forms the Indus A watershed that covers 65% of Pakistan's area. It is one of the oldest known rivers to the person. The Indus River was formed when the Indian and

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Eurasian plates collided more than 45 million years ago(Clift). Pakistan accounts for ~56% of them the total area of the Indus River basin, which is 970,469 km2 (Kidwai et al., 2019).The Indus River basin includes Pakistan and neighboring states, as well as its tributaries (Table 1). The two main catchment areas of Pakistan are Indus Basin and Baluchistan Dry Area with a catchment area of 55,3413 km2 (UNDP-NDMA 2010). Milder winters, reduced glacier water over the years, and low precipitation during normal dry periods affect freshwater and sediment flows. The construction of agricultural canals and sewers diverts water and is water intensive crops and industries around the basin and coast contribute to the country's agroeconomy but have serious implications for the delta and its adjacent coastal zones in terms of coastal stability or ecosystem integrity.

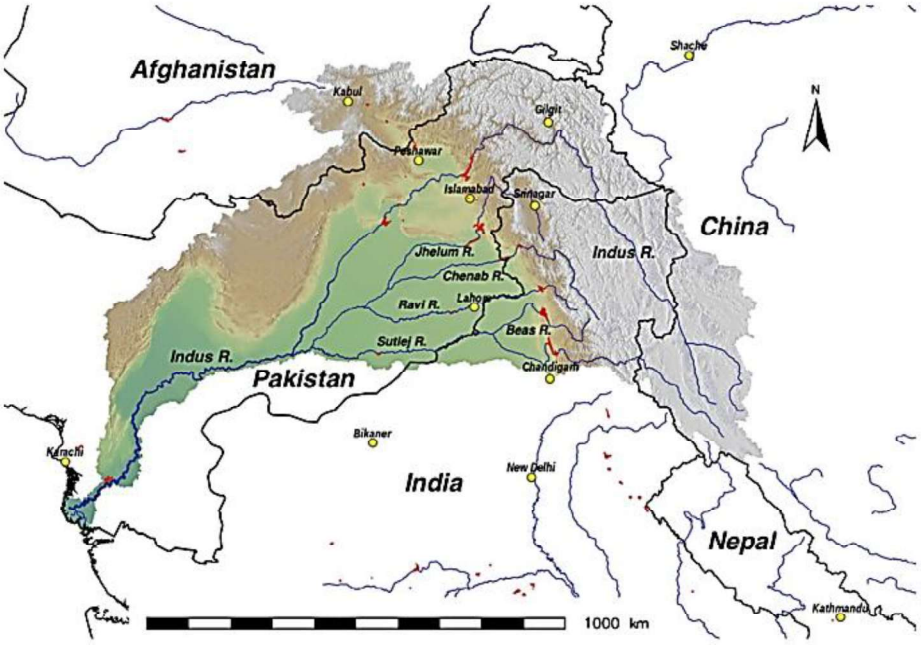
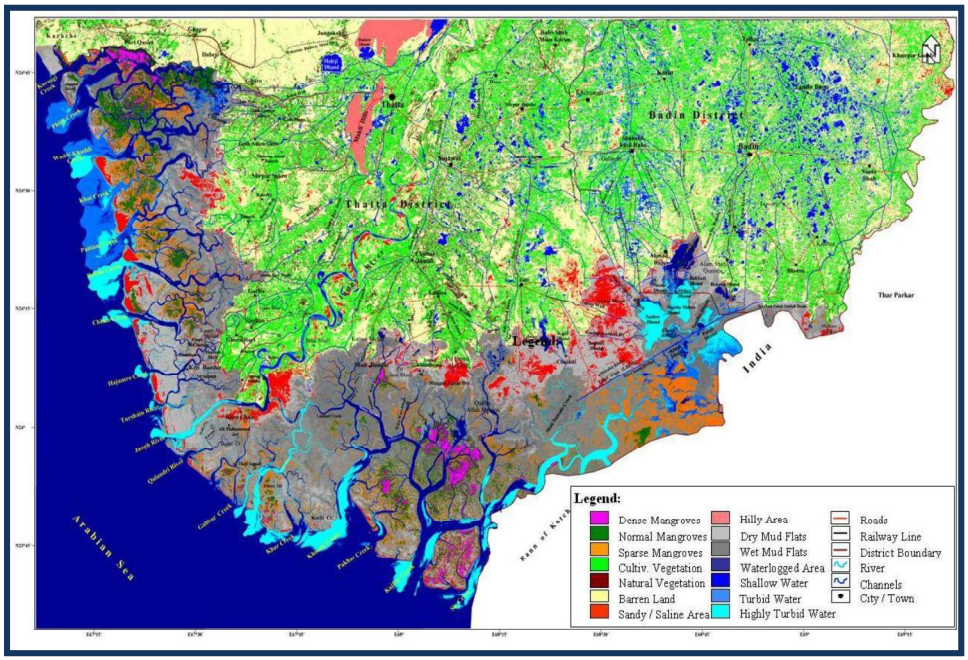


Figure-1: Map of the Indus River Basin with major tributaries. Red prominent areas are representing reservoirs.
Modified from Adams (2019)(Map of the Indus River Basin.)

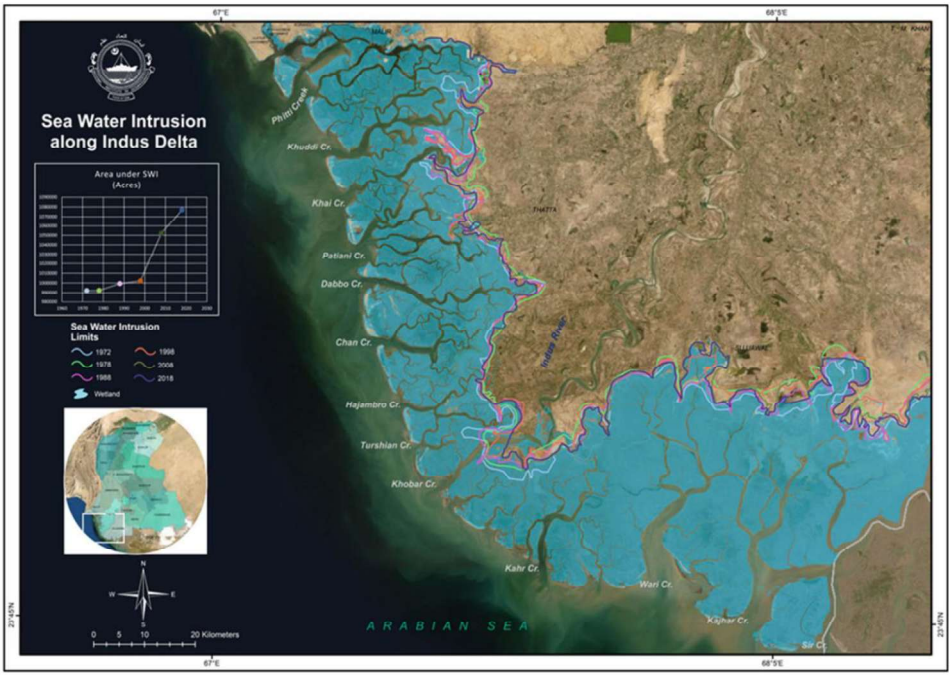
Rising sea levels and increased erosion are already starting to threaten coast of the country. Infrastructure, including roads, bridges and surrounding buildings banks are the first line to experience water runoff ((Zia et al., 2017)). Coastal spatial planning and proactive efforts to address the challenges they face because of sea level rise (SLR), coastal erosion (CE) and sea water intrusion (SWI) are essential for sustaining coastal

development. If not attended to, the situation will most likely worsen and they have a significant economic, social and environmental impact on coastal infrastructure, population and the livelihoods of average Pakistanis. Millions of people living in low-lying areas near the sea are at risk of displacement due to potential floods and storms. A study conducted by the World Bank (*Pakistan's Coastal Ecosystem and Opportunities to Tackle Climate Change*, n.d.) estimates that more than 10% of Pakistan's population lives in coastal areas which are likely to be acutely affected by climate change. The only contributing factor This problem includes the ongoing trend of global warming caused by human activity. According to recent studies, carbon emissions in the atmosphere have increased global temperatures and subsequently led to sea level rise due to glaciers melting (Arnell & Freeman, 2022). With approximately one third of all major cities124 W. Ahmed and S. Kidwai Rising sea levels are near the coasts of the entire world and pose a significant threat to a global ally – not just Pakistan itself. The situation gets worse when the impact is directly on the trade route, which is a lifeline for the country's economy. Karachi, Pakistan's main port city and commercial hub, serves more than two-thirds total transport in Pakistan; coastal erosion or loss of port infrastructure and road connectivity with the rest of the country subsequently disrupts supply chains contribute to Pakistan's economy. Each year, natural factors such as changes in weather in the form of unpredictable monsoon rains is disrupting business activities and supply chains in the country. Human communities, watersheds Coastal ecology has serious significant implications for important coastal areas wetlands and mangrove forests provide critical habitat for a range of biodiversity migratory birds and sea turtles. Rising seas cause rapid erosion of these ecosystems and threaten the existence and long-term viability of these ecosystems'.

Results and Discussion



Dynamically land use and land cover Area of Indus Delta



Sea Water intrusion

From 1972 to 2018, water intrusion in Pakistan significantly impacted the environment, economy, and society. The excessive irrigation and inadequate drainage systems led to severe soil salinization, which degraded agricultural productivity and threatened food security. Frequent flooding damaged infrastructure and displaced communities, contributing to urban migration and increased strain on city resources. Health issues arose from stagnant water, exacerbating the spread of waterborne diseases. Economically, the agricultural sector faced declining yields, resulting in loss of livelihoods for many farmers. In response, the government initiated various infrastructure projects and water management policies, though challenges in enforcement and community engagement persisted. Overall, this period underscores the urgent need for comprehensive water management strategies that balance ecological sustainability with socio-economic development. Approximately 4,655 sq km areas were affected by the seawater intrusion during these periods.

Shoreline Change Rates (1972-2017)

The shoreline change rates for the study area from 1972 to 2017 are illustrated in Figure-2, which presents the End Point Rate (EPR), while Figure-3. displays the Linear Regression Rate (LRR). The data indicates both positive and negative EPR values, signifying areas of shoreline accretion and erosion, respectively. Notably, the EPR values for zones 1 and 2 on the left bank of the river are more negative than those for zones 3 and 4 on the right bank show in fig:2. Erosion was observed at 237, 245, 198, and 202 transects in zones 1, 2, 3, and 4, respectively. Conversely, accretion occurred at 130, 76, 127, and 167 transects in the same zones. The average erosion rates for the left bank in zones 1 and 2 were 45.69 m/year and 52.1 m/year, while the average accretion rates were 9.86 m/year and 24.21 m/year, respectively (see Fig. 4). For the right bank, the mean erosion and accretion rates were 27.21 m/year and 26.36 m/year for zone 3, and 31.43 m/year and 24.1 m/year for zone 4. Overall, the net shoreline change rate was greater on the left bank of the Indus River, measuring -30.12 ± 3.13 m/year, compared to -6.34 ± 2.85 m/year on the right bank.



Figure-2: Schematic diagram of the baseline and the transects for manual calculation of the net shoreline movement
(figure source Mehran university Indus delta report ISBN 978-969-23238-2-6)

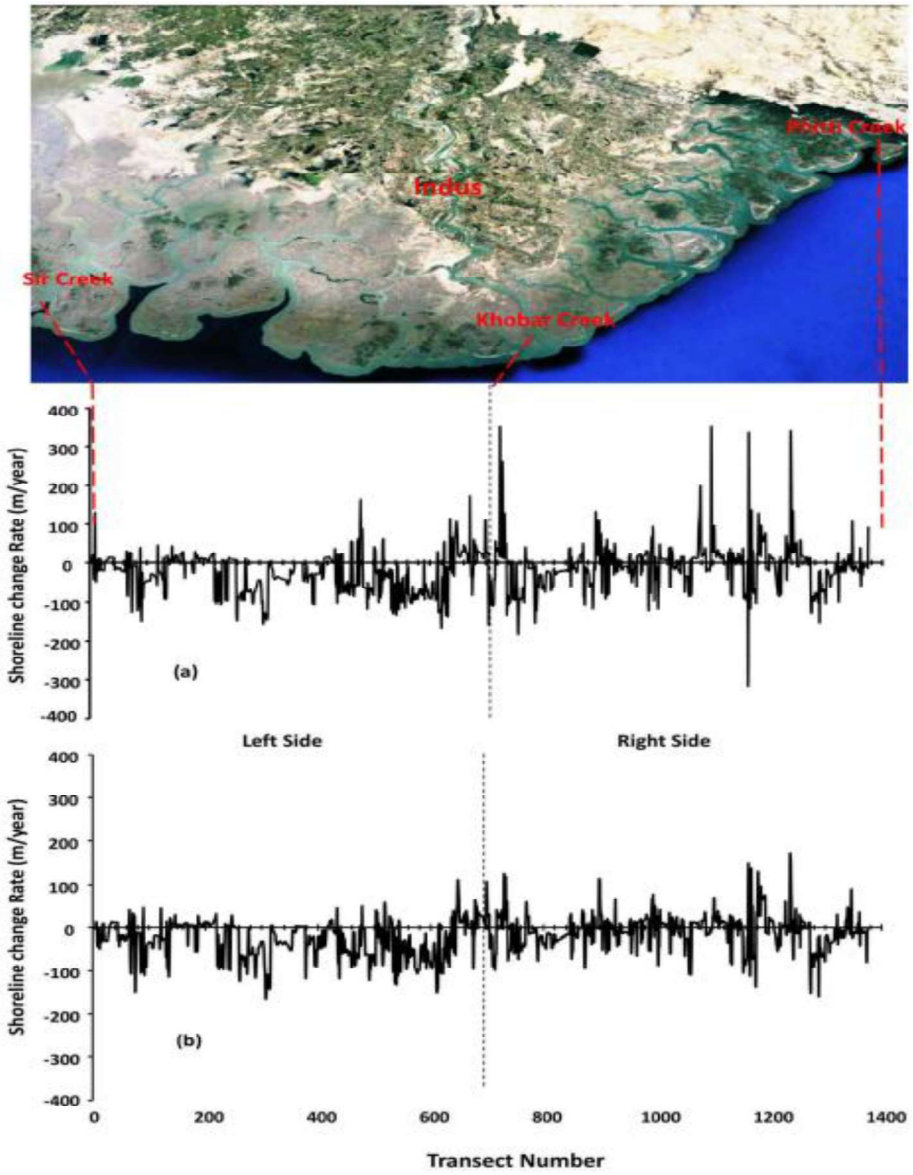


Figure-3: Shoreline change rate at different transects along coastline estimated by (a) EPR and (b) LRR (figure source Mehran university Indus delta report ISBN 978-969-23238-2-6)

This suggests that erosion rates were higher for the left side (zones-1 and 2) compared to the right side (zones-3 and-4); while accretion rates were higher for the right-side zones than on the left side zones as shown in Fig-5.

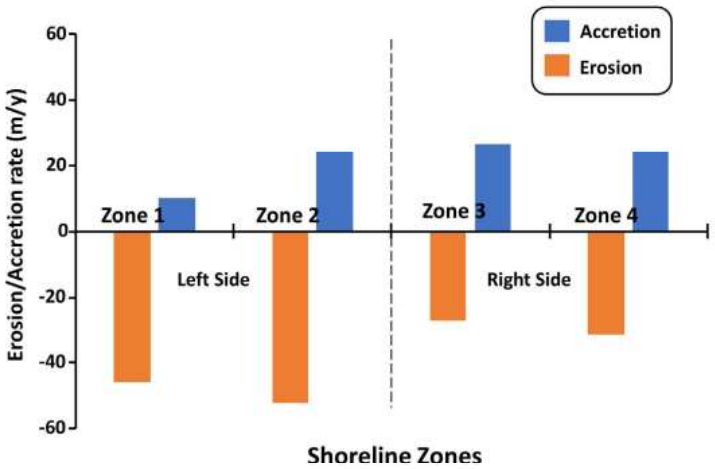


Figure-4: Shoreline change rate in different zones along the coastline (figure source Mehran university Indus delta report ISBN 978-969-23238-2-6)

A detailed examination of zones 3 and 4 revealed the presence of dense mangrove forests, which serve as a protective barrier against high average sea wave energy, as noted by Wells and Coleman (1984) and Mountjoy (2004). This area experiences less erosion on the tidal floodplain, a finding supported by Ijaz et al. (2018), who attributed this stability to the thick mangrove coverage. Additionally, the topography on the right side of the Indus delta is less conducive to erosion compared to the left side.

Figure-5 illustrates the spatial variation in shoreline change rates estimated through the End Point Rate (EPR) across various transects. The data indicates that most transects in zone 2 experienced erosion, with some erosion also noted in zones 1, 3, and 4. However, isolated transects in zones 1, 3, and 4 exhibited signs of accretion. The Linear Regression Rate (LRR) estimates align with the EPR at several transects across all four zones, although the LRR values are generally lower than those of the EPR. The figure highlights both positive and negative changes in shoreline, reflecting areas of accretion and erosion. Figure-4 further illustrates the distribution of erosion and accretion along the delta's shoreline, confirming that zone 2 has experienced the most significant erosion compared to the other zones.

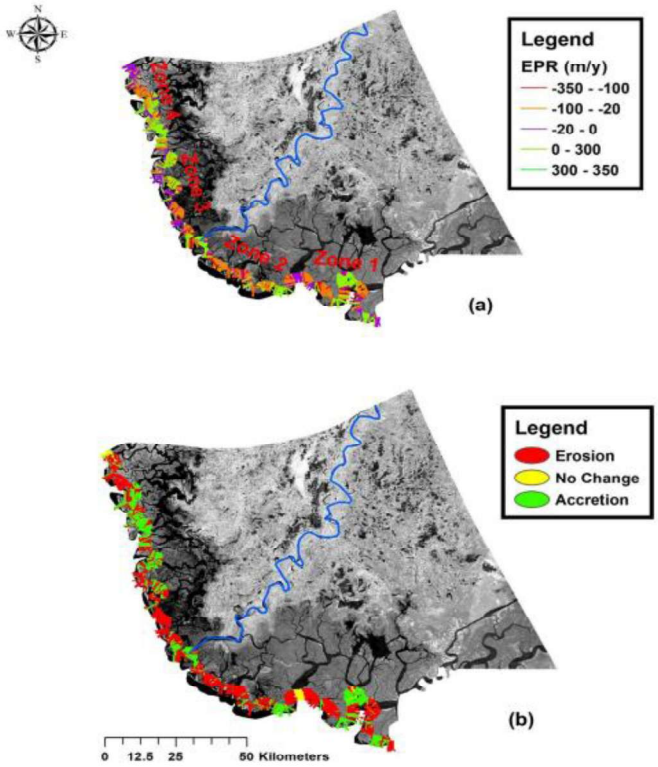


Figure-5: Spatial variation in shoreline change rates (a) estimated through EPR at different transects along the shoreline and (b) spatial distribution of erosion and accretion along the entire shoreline of the delta(figure source Mehran university Indus delta report ISBN 978-969-23238-2-6)

Mangroves

Figure-6 presents classified satellite images that illustrate the temporal and spatial changes in mangrove cover in the Indus delta from 1990 to 2017. The images indicate that mangrove forests occupy a larger area of the tidal floodplains on the right bank of the Indus River compared to the left bank. Table -1 quantifies the changes in mangrove area over the past 28 years, revealing that the mangrove cover was 103,414 hectares, accounting for 16% of the tidal floodplains in 1990. This area gradually decreased to 63,296 hectares, or 9.81%, in 2005, before increasing again to 81,324 hectares, or 12.6%, by 2017. The rise in mangrove cover in 2017 is likely attributed to large-scale plantation efforts initiated by NGOs, the Forest Department, the Government of Sindh, and civil society in 2009 and 2013 (Rehman et al., 2015; Daily Times, 2018).

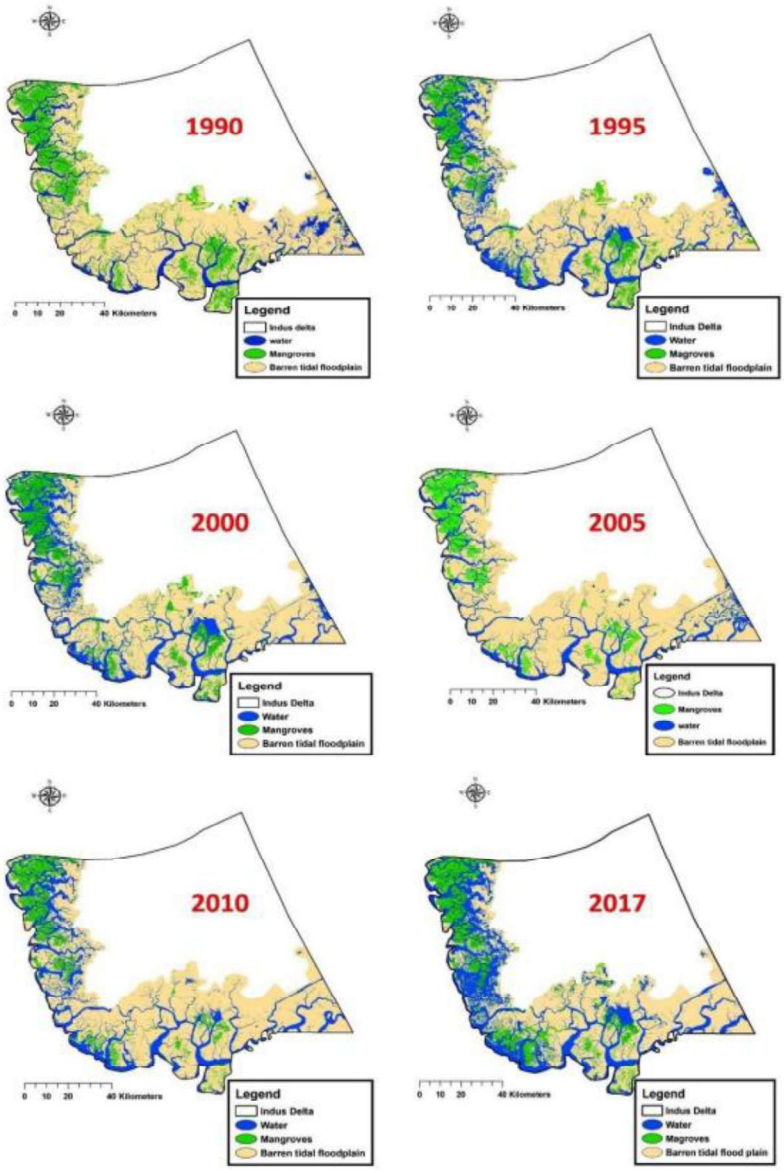


Figure-6: Spatial and temporal variation in mangrove cover in tidal floodplains of Indus delta during the last 28 years (1990-2017)(figure source Mehran university Indus delta report ISBN 978-969-23238-2-6)

Table-1: Changes mangroves over the years

Year	Area (ha)	Percentage of delta	Percentage of tidal floodplains
1990	103414	7.91	16.03
1995	82059	6.28	12.72
2000	80267	6.14	12.44
2005	63296	4.84	9.81
2010	65057	4.98	10.08
2017	81324	6.22	12.60

(*USPCAS-W : U.S.-Pakistan Center for Advanced Studies in Water*, n.d.)

The satellite image of 2017 was further classified into dense and sparse forests of mangroves, and the spatial variation in mangrove cover is shown in Fig-6. It portrays that sparse mangrove forests are more on tidal floodplains located on the left bank of the Indus while dense forests are mostly concentrated in the south-west of the delta on the right bank of the Indus.

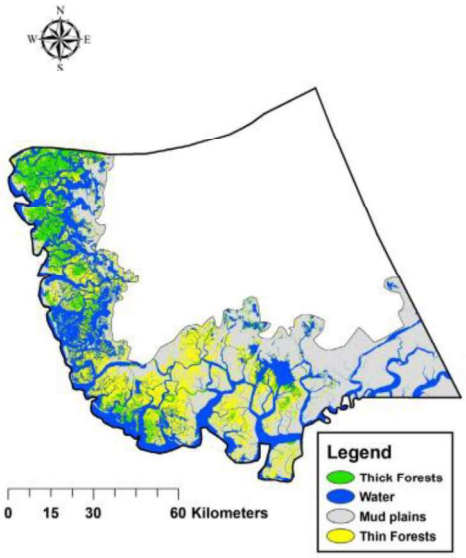


Figure-7: Spatial variation in mangrove cover in the tidal floodplains of Indus delta during Feb 2017(figure source Mehran university Indus delta report ISBN 978-969-23238-2-6)

Rainfall

The graph effectively illustrates the interplay between rainfall and river discharge during August 2016 and 2017, providing valuable insights into hydrological dynamics and the impact of monsoon rains on river systems.

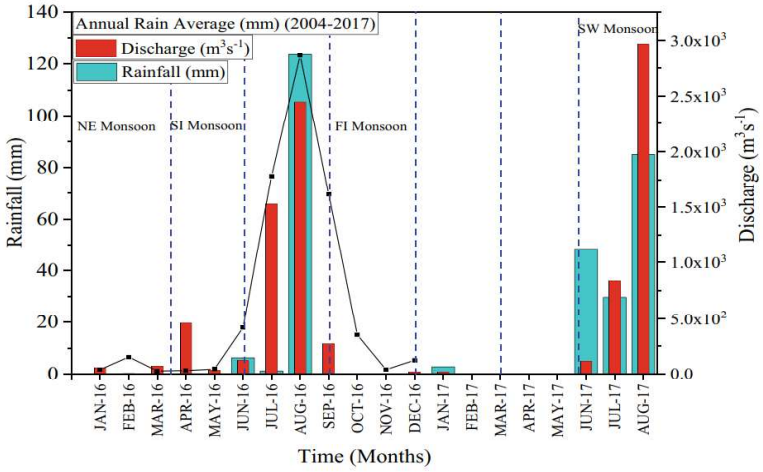
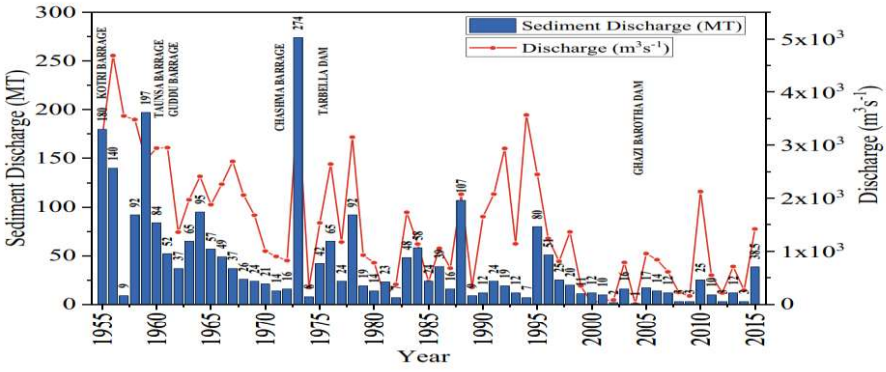


Figure-8: Rainfall in the sampling period; rain data was collected from the Pakistan Metrological Department, and water discharge data was collected from the Sindh Irrigation Department Pakistan.

Sediment discharge

The blue bars show the volume of sediment transported downstream by the river. Analyzing the height of these bars over the years can provide insights into trends such as increases or decreases in sediment transport. Peaks in sediment discharge may correlate with heavy rainfall events, flooding, or changes in land use that affect erosion rates



Figur-9: Sediment discharge (blue bars) and river discharge (red dots and line) from downstream Kotri Barrage from 1955 to 2015.

Cyclone 02-A

Cyclone 02-A, which impacted the region in May 20 1999, highlighted the vulnerability of coastal areas to severe weather events. Characterized by high winds and heavy rainfall, the cyclone caused significant damage to

infrastructure, disrupted livelihoods, and led to widespread flooding. Emergency response efforts revealed both strengths and weaknesses in preparedness and recovery strategies. The event underscored the need for improved forecasting, early warning systems, and community resilience initiatives. As climate change continues to intensify the frequency and severity of such cyclones, proactive measures and adaptive planning will be essential to mitigate future impacts and enhance disaster preparedness in affected regions.

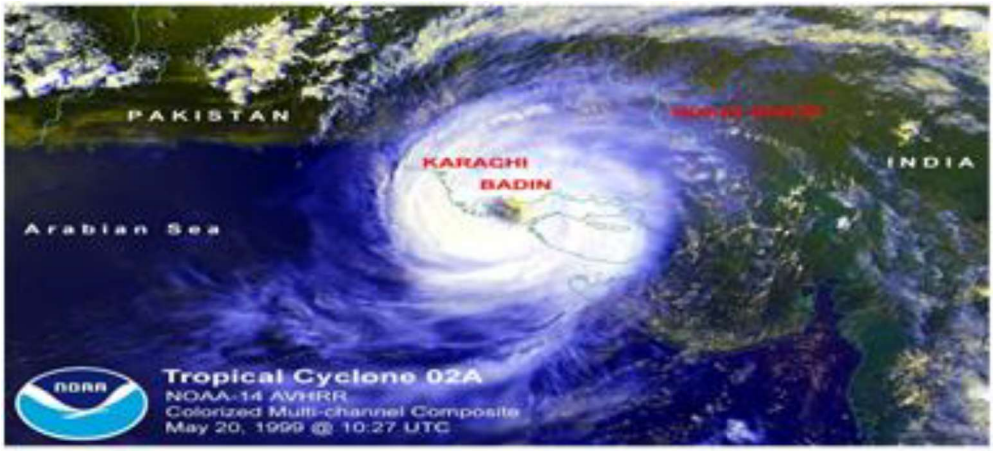


Figure-10: Tropical cyclone 02-a

Conclusion

The analysis of land use, sea water intrusion, shoreline changes, mangrove ecosystems, rainfall patterns, and sediment discharge in the Indus Delta from 1972 to 2018 reveals significant ecological transformations influenced by both human activities and climate change. Notably, the encroachment of seawater has increasingly affected freshwater availability and mangrove habitats, which are essential for coastal protection and biodiversity. Shoreline changes from 1972 to 2017 demonstrate a dynamic response to sediment discharge and sea level rise, further complicating the delta's hydrology.

In this study is the development of a small tidal creek system, facilitating the discharge of irrigation water and integrating tidal flows into the delta. This indicates adaptive responses to changing hydrological conditions. Overall, these findings highlight the interconnectedness of various ecological processes within the delta and underscore the necessity for integrated management strategies. Continued monitoring is crucial to inform sustainable development practices and enhance resilience against ongoing environmental challenges.

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