RESEARCH

32 years of changes in river paths and coastal landscape in Bangladesh, Bengal Basin

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Abstract

This study examines the geomorphological changes and environmental impacts on the coastline and the evolution of major river systems in Bangladesh over the past 32 years using remote sensing and GIS analyses. The central coastal area, characterized by fine sediments, has experienced significant land erosion due to the dynamics of the Meghna Estuary and its depositional patterns. In contrast, the southwestern Sundarbans Forest coast has remained relatively stable, aided by mangrove root stabilization despite anthropogenic threats. Channel migration analysis revealed the Brahmaputra River's persistent braided configuration, while its tributaries, Teesta and Dharla, increased meandering nature due to reduced water availability and human interventions. The Ganges-Padma system displayed a shift towards a more sinuous channel pattern driven by reduced water discharge due to the Farakka Barrage construction in the upstream and a minor decrease in precipitation. The Upper Meghna River maintained moderate sinuosity with stable anastomosed patterns, whereas the lower Meghna River's convergence with the Jamuna and Padma Rivers increased its susceptibility to erosion. These findings highlight the interplay of natural processes and human activities in shaping the coastal and fluvial landscapes of Bangladesh and the Bengal Basin, emphasizing the need for sustainable land-use practices and adaptive management strategies to mitigate future risks associated with sea-level rise and river course changes.

Keywords Channel Migration · Coastal Landscape Evolution · Sundarbans Mangrove Forest · Remote Sensing · GIS · Geological Map of Bangladesh

1 Introduction

The Ganges-Brahmaputra-Meghna (GBM) delta or Bengal Delta is the world's largest delta, located in Southeast Asia (Fig. 1). Having one of the world's thickest sedimentary successions of about 22 km (Curray, 1991), the Bengal Basin that hosts this delta covers an extent of approximately 200,000 km² (Alam et al., 2003). The basin rests at the meeting point of the Indian, Eurasian, and Burmese plates, roughly between 20°34'N to 26°38'N latitude and

88°01'E to 92°41'E longitude, covering mainly Bangladesh and partially a few Indian states, including Assam, Tripura, Meghalaya, and West Bengal (Fig. 1). Bangladesh and Bengal Basin are encircled by the Indo-Burman Ranges to the east, the Himalayan Mountain Ranges and the Shillong Plateau to the north, the Indian Shield to the west, and the Bay of Bengal to the south (Uddin & Lundberg, 2004).

Being one of the world's most densely populated nations with ~170 million inhabitants residing in it, Bangladesh, the primary study area of this research, is situated in the GBM delta. Three central river systems are linked with this location, including two giant rivers, the Ganges, and the Brahmaputra, and one relatively smaller river, the Meghna (Fig. 1). These rivers drain about 75% of the Himalayas, generating nearly one billion tons of sediment transported through Bangladesh annually (Reitz et al., 2015). Various geological processes, including flexural subsidence, folding, faulting, and localized compaction, permit the delta's subaerial portion to collect and deposit about 30% of the yearly sediment production through the

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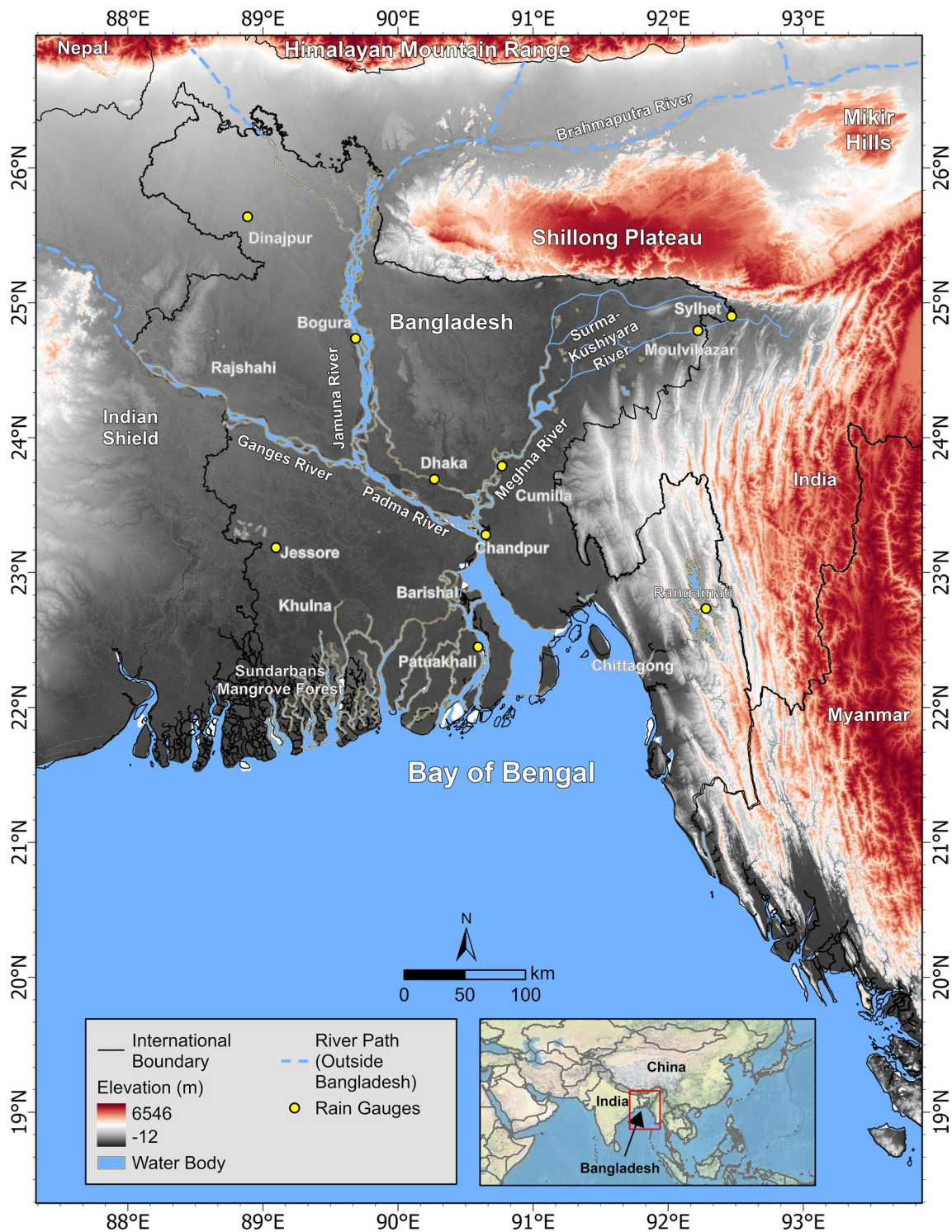
Fig. 1 Location map showing Bangladesh and the neighboring regions of the Bengal Basin, including elevation data obtained from NASADEM

active fluvial system (Goodbred & Kuehl, 1998, 1999). As a tide-dominated and morphologically active region, the study area has been experiencing continuous sedimentation through the Ganges and Brahmaputra rivers while generating faster delta progradation than most of

the largest known deltas in the world (Akter et al., 2016). Because of the high sediment supply from all rivers, the tide-dominated estuary system (Meghna Estuary) has been handling continuous erosion and accretion, covering thousands of hectares of land per year (Sarker et al., 2011).

Based on the experimental modeling of Braudrick et al. (2009) and findings from studying tropical river dynamics from Schwendel et al. (2015), it can be assumed that the sinuous Bengal River system undergoes lateral sediment transfer, with sediment migrating from the outer bank to the inner bank along expansive floodplains, ultimately forming point bars. This kind of dynamic nature of the rivers could alter the surrounding landscapes, including floodplains. The quicker delta progradation combined with diverse controlling factors makes the Bengal River system more unsteady (Akter et al., 2016). While the active features can cause the rivers and channels to migrate, many other components can play roles. Factors such as land subsidence, build-up of alluvial ridges, subterranean fluid extraction (Schumm et al., 2000), and seismic activities (Chamberlain et al., 2024; Goswami, 1986; Oldham, 1899) are likely the most common in this case. Additionally, it is necessary to understand the impact of anthropogenic processes in rivers, floodplain, and coastal evolution, regardless of their severity.

Global sea level rise over the past century is a significant concern, affecting coastal morphology and exerting substantial impacts on communities dependent on coastal areas (Bushra et al., 2021; Cazenave & Cozannet, 2014). The Bangladesh coastline is believed to be one of the world's most vulnerable areas to rising sea levels. Coastal flooding poses a significant challenge for countries with low-lying landscapes like Bangladesh, where safeguarding communities from the consequences of rising sea level relies on sustainable flood prevention strategies within the mangrove ecosystem (Borsje et al., 2011; Temmerman et al., 2013; Van Hespen et al., 2023). The effectiveness of long-term mangrove afforestation on vulnerably exposed beaches along the Bangladesh coast remains to be determined due to data constraints. It is also essential to understand the stability of the Sundarbans—world's largest mangrove forest enlisted as a UNESCO World Heritage Site (Fig. 1)—and other coastal parts of Bangladesh concerning rising sea levels.

One of the main objectives of this research is to update Bangladesh's surface (Quaternary) geological map, which has been outdated for more than three decades. The primary reason to update the surface geological map is linked to understanding the country's fluvial system and coastal landscape evolution over the past 32 years. Since the current published geological map of Bangladesh (Alam et al., 1990) contains essential surface geological information with the then most accurate river flow paths, we can analyze how rivers have changed their flow directions while comparing with the most recent high-resolution Sentinel-based remotely sensed data. A similar process is also helpful in understanding the country's coastal landscape changes, where coastal stability can be analyzed from a GIS-based investigation. Climatic factors like changes in annual precipitation are essential to better understand river or shoreline water levels in dry or wet periods, as well as to apprehend the increasing or decreasing trends of surface water levels and their contribution to landscape alterations. Since there is a scarcity of multi-decadal studies focused on near-shoreline landscape evolution of the Bengal Delta, this remote sensing analysis will help understand dynamic natural processes of the Bangladesh floodplain and coast, and any associated human-induced challenges.

2 Methodology

2.1 Accessing the current geological map

The geological map of Bangladesh prepared in 1990 was digitized by the Geological Survey of Bangladesh (GSB) in 2001, which was used as the base map in this research to provide a spatial representation of the area's geology. All information on exposed geological units displayed in this map was obtained from the data gathered by GSB. This map is publicly accessible from the United States Geological Survey (USGS) website as a GIS shapefile (Persits et al., 2001). The shapefile is in a vector data format and stores information as a collection of polygons representing different geological exposures around Bangladesh. This map was utilized as the foundation for mapping the changes in the landscape (Fig. 2), allowing us to examine the relationship between geology and landscape change between 1990 and 2022.

Fig. 2 A systematic approach to interpreting the development of floodplain and coastal landforms and river-switching processes in Bangladesh
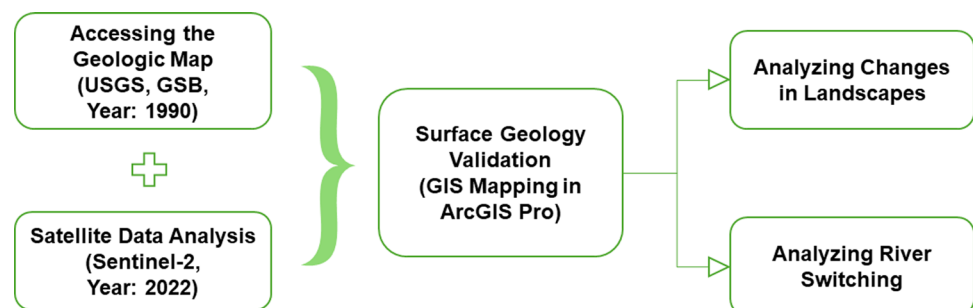
2.2 Satellite data acquisition

The European Space Agency (ESA) launched the high-resolution optical satellite sensor, Sentinel-2 in June 2015. The satellite offers systematic global coverage of multispectral images with a high spatial resolution and a frequent revisit rate. These features make Sentinel-2 images valuable for creating next-generation operational products, such as land-cover change detection maps. The up to 10 m spatial resolution and 10-day revisit frequency, as well as its free accessibility, make Sentinel-2 images particularly useful for mapping regional water bodies, rivers, and coastal areas. The Sentinel-2 multispectral image consists of 13 bands, with four bands (blue, green, red, and near-infrared) having a spatial resolution of 10 m, four bands (including near-infrared) having a spatial resolution of 20 m, and two bands (including the short-wave infrared band) having a spatial resolution of 20 m (Table 1; Drusch et al., 2012).

This study utilized 37 Sentinel-2 image tiles of Bangladesh obtained from the USGS EarthExplorer website, which were captured by both Sentinel-2A (19 images) and Sentinel-2B (18 images) satellites. The investigation aimed to gather a recent and accurate representation of the land coverage, with a focus on assembling images portraying the moderately dry winter season from January to March 2022. To streamline the data collection strategy, a polygon was drawn on the EarthExplorer web map to encompass the entire study area of inland and offshore Bangladesh instead of manually inputting the latitude and longitude values. Before downloading images in JP2 format, a stringent constraint on cloud cover within 0% to 10% was used to ensure

Table 1 Spectral band information for the Sentinel-2 sensors

Band number	Spatial resolution (m)	Central wavelength (nm)	Band-width (nm)	Description
B1	60	443	20	Ultra Blue (Coastal and Aerosol)
B2	10	490	65	Blue
B3	10	560	35	Green
B4	10	665	30	Red
B5	20	705	15	VNIR
B6	20	740	15	VNIR
B7	20	783	20	VNIR
B8	10	842	115	VNIR
B8A	20	865	20	VNIR
B9	60	945	20	SWIR
B10	60	1375	30	SWIR
B11	20	1610	90	SWIR
B12	20	2190	180	SWIR

SWIR short wave infrared, *VNIR* visible and near infrared

clear visibility of the landscapes. The use of satellite images with low winter cloud cover proved to be highly effective in the data analysis, allowing optimal topographic observation.

The utilization of satellite imagery during a specific time frame, in conjunction with the convenient web-mapping method (EarthExplorer), guarantees the precision of the information amassed for the study. Captured Sentinel-2 images are raster datasets that store the spatial information and attributes of the inland and coastal Bangladesh surface cover. Various spatial analysis steps were used, including different band combinations of Sentinel-2 images in Arc-GIS Pro, to identify the most useful mode of depicting the surface cover. Initial processing was executed by operating the "Symbology" option and different "Stretching" operations available in the ArcGIS Pro software to ensure that all information, including background values, was correctly displayed. The "Stretching" procedures, including techniques such as "Percent Clip" and "Histogram Equalize," assisted in enhancing the data's visual representation.

2.3 Validation of the surface geology

Dry season Sentinel-2A and -2B images were gathered by satellites from January 16 to March 22, 2022. ArcGIS Pro, a robust spatial data analysis tool, was used to analyze these data. As satellite imagery often misses finer details, analysis was focused solely on the 10 m spatial-resolution images (Phiri et al., 2020). Specifically, we imported Band-2 (Blue), Band-3 (Green), Band-4 (Red), and Band-8 (VNIR) data into the ArcGIS Pro map, as these spectral bands can capture high-resolution surface information. False color combinations (Red: Band 10, Green: Band 7, Blue: Band 2) were an effective method in this research to distinguish different surface features, including vegetation, industrial areas, agricultural areas, and water bodies.

The geological map of Bangladesh (Alam et al., 1990; Persits et al., 2001) was used as a base map in the ArcGIS Pro, where it was imported as a shapefile and subsequently modified using Sentinel-2 surface information as well as information published in Abdullah et al. (2015), Khan et al. (2018), Jahan & Uddin (2022), and Hossain et al. (2022). By applying the "Geology Field" (GLG) Symbology tool, a visual representation of the surface geology of Bangladesh was generated. This map comprises several GIS polygons of distinct colors and textures that denote different lithological units based on the lithological expressions suggested by GSB. Other maps focusing on specific locations such as the Chittagong-Tripura Fold Belt (CTFB) (Hossain et al., 2022), Sylhet (Jahan & Uddin, 2022), Sitakund anticline (Abdullah et al., 2015), and Lalmai anticline (Khan et al., 2018), were incorporated into the GIS database as raster layers. Digitization was this study's most frequently used technique, employing a combination of modification, splitting,

merging, and reshaping tools. When mapping an area with less information, satellite images were used principally for digitization. However, published field data from Hossain et al. (2022) was primarily used to modify the surface lithology of the CTFB, while Sentinel-2 data was used to map areas where field data are not available.

2.4 Landscape change analysis

In the Bengal Basin, changes in the landscape, particularly in riverbanks and nearshore areas, are quite active, requiring proper quantification. In this study, we used ArcGIS Pro to compute the land cover changes over a 32-year period. To demarcate the area covered by new geological units and to evaluate the total eroded area and development of accretion, the unique value of "Area" from the Symbology option of the GIS map was used. The attribute tables generated by GIS were employed to calculate the total area of the study region with the "Calculate Geometry" and "Statistics" tools. To quantify the percentage of landscape change, we used the following statistical equation that can be used to determine changes in the land area *(ΔA)* over time.

$$\Delta A = A_f - A_0$$

Here, A_f is the land surface area of Bangladesh in 2022, whereas A_0 is the surface area shown in the base map of 1990.

After finding the change in surface area, the percentage of landscape change *(L_c)* was determined using the following formula, where L_g is land gain and L_l is land loss.

$$L_c = \frac{L_g - L_l}{A_0} \times 100$$

2.5 Analysis of river meandering

The changes in the Ganges River network between the 1990 and 2022 maps were determined by calculating the average distance between the older and newer river paths. The calculation was based on several measurements of distances between the older and newer river directions, where *n* is the number of measurements.

$$\text{Average river avulsion distance} = \frac{(a_1 + a_2 + a_3 + \cdots + a_n)}{n}$$

Utilizing the acquired Sentinel-2 imagery with georeferencing information, our methodology employed manual tracing of channels in ArcGIS Pro for river extraction and sinuosity determination. After importing the satellite imagery into ArcGIS Pro map view, the automatic placement of the image based on georeferencing metadata ensured accurate

mapping of river courses within Bangladesh. Subsequently, digitization of the rivers within the GIS environment enabled precise measurements of the total stream length (Sl), including meanders. Leveraging the georeferencing information, valley length (Vl) or straight-line distance measurements between primary river endpoints were also obtained. From these georeferenced measurements, we then calculated stream sinuosity (S) as suggested by Schumm (1963) and Mueller (1968): *S = Sl / Vl*.

To facilitate the landscape-change analysis and to identify potential causes of these changes, precipitation data for the past three decades (1990 to 2019) were acquired from 10 distinct locations within Bangladesh (Fig. 1). Data collection was mostly implemented around major fluvial networks with standard rainfall patterns. These data were obtained freely from the Climate Information Management System (CIMS) of the Bangladesh Agricultural Research Council (BARC) (Table 2).

2.6 Limitations of remote sensing data

While this study leverages Sentinel-2 satellite imagery to analyze the fluvial system and coastal landscape evolution of Bangladesh, certain limitations of the data and methodology must be acknowledged. Sentinel-2 images, although offering high spatial resolution (up to 10 m), may still miss finer landscape features or small-scale changes in riverbank or shoreline morphology that require higher-resolution imagery. Additionally, the temporal resolution, though adequate for observing seasonal changes, might not capture rapid geomorphological events, such as sudden erosion or flooding caused by storm surges or seismic activity. Atmospheric conditions, such as cloud cover, can also impact data quality, obscuring critical observations in tropical regions like Bangladesh. Moreover, errors in data interpretation may arise from classifying land cover types, as spectral similarities between different materials (e.g., wet soil and water) could lead to misclassification. These limitations should be considered when drawing conclusions about the landscape evolution of the Bengal Delta.

2.7 Integration of field data

In this study, no new field data were acquired to validate the results obtained through remote sensing techniques. Instead, previously published field data from relevant studies (e.g., Abdullah et al., 2015; Hossain et al., 2022; Jahan & Uddin, 2022; Khan et al., 2018) were integrated to provide context and refine the surface lithology in specific areas such as the CTFB. While this approach offers preliminary validation, the absence of direct field data limits the overall accuracy of the geological interpretations, particularly in regions where remote sensing imagery may not

Table 2 Local precipitation data collected from 10 distinct locations across Bangladesh (Fig. 1) over thirty years (1990–2019) depict the average winter precipitation in the country

| Year	Location-wise annual precipitation (mm)										Yearly total rainfall (mm)	Mean annual precipitation (mm)
	Bogura	Chandpur	Cumilla	Dhaka	Dinajpur	Jessore	Moulvibazar	Patuakhali	Rangamati	Sylhet		
1990	2077	1956	2211	2103	2081	1686	2964	3212	2176	4484	24,950	2495
1991	2291	2346	2914	2850	2012	2052	2429	3083	2957	4627	29,552	2955
1992	1367	1346	1285	1159	1649	1333	1739	2359	1728	3516	17,481	1748
1993	1908	2191	2802	2767	2179	1802	2610	2654	3895	4846	27,654	2765
1994	1342	1572	1384	1540	1142	1260	1800	2439	2028	3521	18,028	1803
1995	2257	2009	2102	1751	2613	1397	2031	3174	2403	3604	23,341	2334
1996	1926	1718	2036	2044	1587	1775	1954	3061	2663	4011	22,775	2278
1997	1301	1874	2134	1921	1809	1553	2149	2881	2765	3637	24,021	2402
1998	2601	2092	2518	2312	2391	1490	1924	3217	2930	4388	25,863	2586
1999	1610	2621	2351	2374	2536	1467	2116	3314	2754	3332	24,475	2448
2000	1838	1785	2044	2193	1498	1811	3127	2885	2733	4513	24,427	2443
2001	1393	2176	1950	1685	2226	1611	2901	3469	2066	3473	22,950	2295
2002	2011	2476	2136	1789	2549	2120	3145	2825	2784	3468	25,303	2530
2003	1692	1718	1825	1693	2057	1892	2295	2435	2474	3556	23,640	2364
2004	2157	2383	2424	2347	2293	2444	3056	2472	3113	4264	26,953	2695
2005	2091	1539	2424	2637	2975	1678	2375	3348	2124	4163	25,354	2535
2006	1106	1714	1898	1919	1285	1769	1967	2648	2316	3526	20,148	2015
Year	Location-wise annual precipitation (mm)										Yearly total rainfall (mm)	Mean annual precipitation (mm)
	Bogura	Chandpur	Cumilla	Dhaka	Dinajpur	Jessore	Moulvibazar	Patuakhali	Rangamati	Sylhet		
2007	1919	2338	2497	2885	1579	2119	2517	3231	3076	4338	26,499	2650
2008	1791	2140	2057	2385	1772	1888	1875	3024	1780	3351	22,063	2206
2009	1410	1546	1824	1931	2025	1668	2452	2289	2395	3287	22,836	2284
2010	1274	1765	1578	1523	1641	1380	2290	2568	2645	4939	21,603	2160
2011	1721	2128	1884	1776	1644	1361	2050	3092	2361	3101	21,118	2112
2012	1140	1757	1929	1329	1511	1305	1927	2628	2817	4610	20,953	2095
2013	1219	2545	1643	1590	1827	1676	2352	3120	1950	3825	21,747	2175
2014	1708	1774	1635	1399	1398	1318	2282	1877	1923	3372	18,686	1869
2015	1581	2804	2155	2166	1965	1867	2518	3151	3342	4521	28,085	2809
2016	1081	2350	2174	1365	1660	1366	2546	2784	2032	4296	21,654	2165
2017	2163	3006	3179	2892	1752	2178	3813	3344	3819	5944	32,090	3209
2018	1650	1973	1712	1732	920	1142	2186	2961	2987	3581	20,844	2084
2019	1633	1637	1851	1837	2288	1061	1978	3095	2706	3668	21,754	2175

capture fine-scale geological features. To strengthen future analyses and ensure a more robust correlation between satellite-derived data and ground truth, it is recommended that comprehensive field surveys be conducted. These surveys should target key geological units and dynamic landscapes, particularly in coastal and fluvial regions, to provide ground-based validation of the remote sensing results and to better understand the drivers of observed landscape changes.

3 Results

3.1 Exposed geological units

The Paleogene and Neogene bedrock sedimentary units, including the Tipam, Surma, and Jaintia Groups, are primarily located in the Surma Basin and elevated CTFB regions (Fig. 3). In contrast, six types of Quaternary

Fig. 3 Geological map of Bangladesh, based on a comprehensive analysis of Sentinel-2 satellite imagery, published data, and 1990 GSB geological map (Modified from Alam et al., 1990; Persits et al., 2001; Khan et al., 2018; and Hossain et al., 2022)
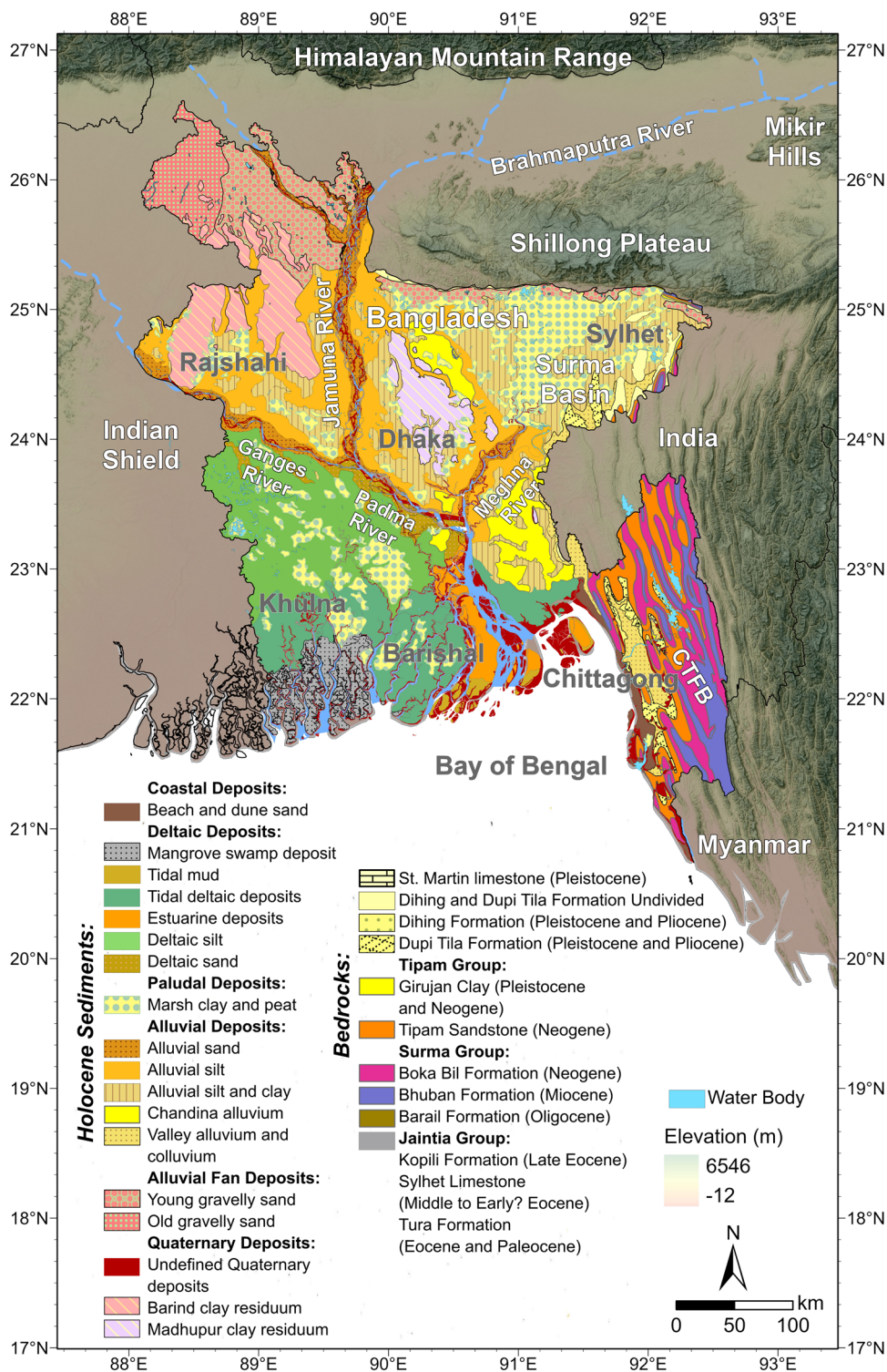
surficial deposits are commonly found across the country: coastal, deltaic, paludal, alluvial, alluvial fan, and residual (Fig. 3). The deltaic sediment mostly shows abundance of deltaic silt and tidal-deltaic deposits from the right banks of the Ganges and Padma rivers to the coastal regions. The downstream Brahmaputra (Jamuna) river, flowing through Bangladesh from India, deposited vast amounts of alluvial fan deposits in the northwest part of the country. The older and younger gravelly sands are primarily deposited over the stable shelf platform, except for some of the region

covered with Barind Clay Residuum on the Barind Tract, the northwestern elevated Pleistocene terrace. Similarly, Madhupur Tract is the central upland location covered with Madhupur Clay, another variety of residual deposits.

While alluvial sand and silt units are predominantly seen along all the main channels, the coastal section has different geological features. Sundarbans Mangrove Forest (mangrove coast) and encircling province in southwest Bangladesh are covered mainly with mangrove swamp deposits (Fig. 3). The rest of coastal Bangladesh is near Meghna Estuary, and the surrounding is primarily covered with tidal deltaic and estuarine deposits. Our study detected new lands with undefined lithology along riverbanks and coastal regions. Owing to the unavailability of adequate geological field data, this study

suggests the nomenclature of these newly exposed landforms as Quaternary sedimentary deposits.

3.2 Landscape evolution

In 1990, the primary land area of Bangladesh, excluding offshore regions, was calculated to cover 134,382 km^2 using the surface geological map of the Geological Survey of Bangladesh (Fig. 4a). By 2022, the total land surface has expanded to 137,656 km^2 (Fig. 4b). These findings indicate a net land-growth of 3,274 km^2, equating to an overall increase of land area of 2.44% compared to the original extent in 1990. By comparing the 1990 base map with 2022 Sentinel-2 imagery, the study found that riverbank and coastal erosion had

Fig. 4 Satellite data-based mapping revealing landscape evolutions in Bangladesh between 1990 and 2022. **a** The extent of mainland Bangladesh in 1990 was 134,382 km^2 based on the surface geological map of the Geological Survey of Bangladesh. **b** The 2022 assessment revealed an expansion in total land surface area to 137,656 km^2, **c** despite a loss of 2,399 km^2 area (black colored area) to the riverbank and coastal erosion. **d** This was because of the growth of 6,022 km^2 land area, mapped as an undifferentiated Quaternary deposit (red colored area), which was previously underwater
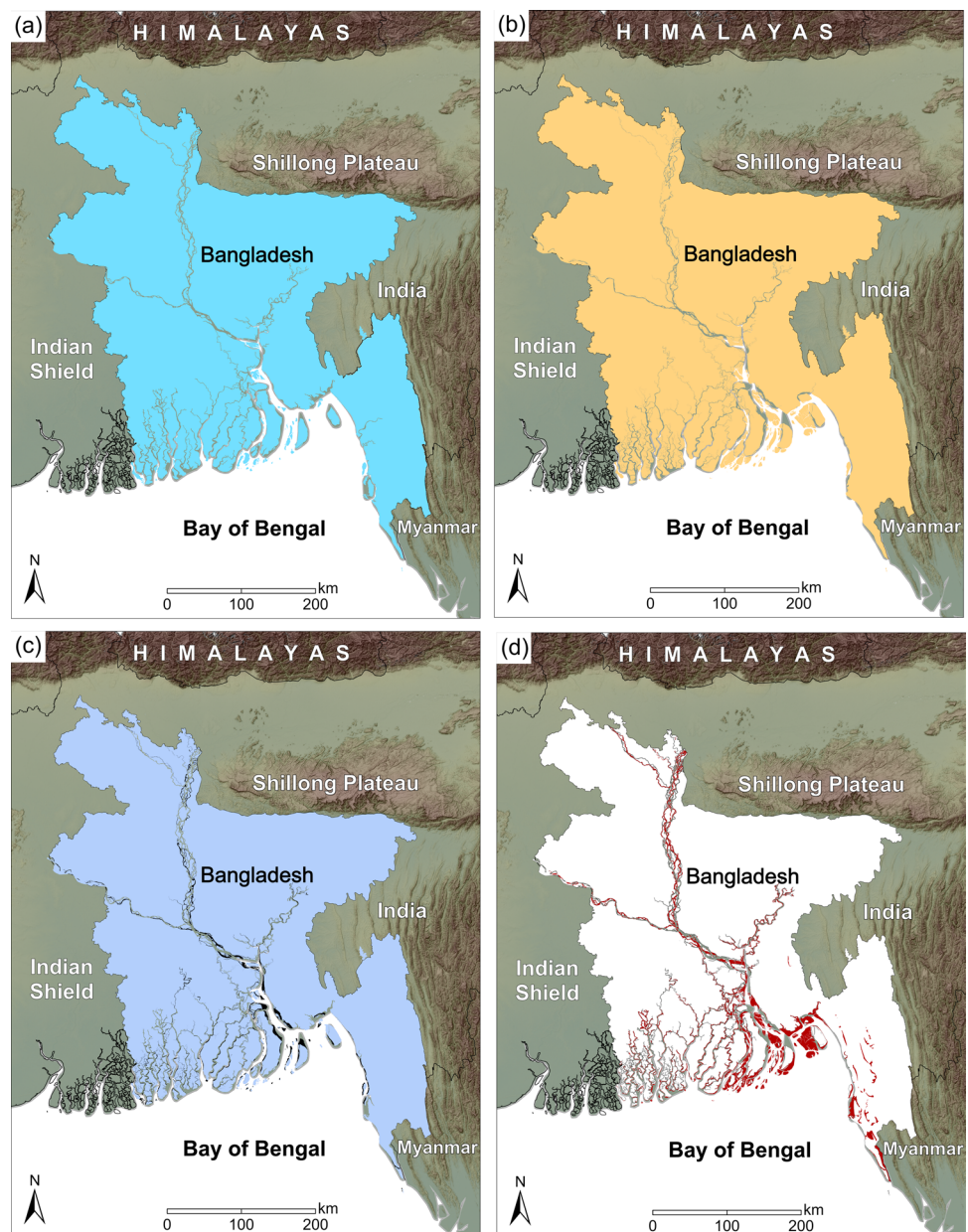
engulfed 2,399 km^2 land area of Bangladesh over 32 years (Fig. 4c). Whereas the combined extent of the newly mapped unit of undifferentiated Quaternary deposit was measured at 6,022 km^2 (Fig. 4d). Around rivers and coastal areas, a total land increase of 5,673 km^2 was observed, accounting for roughly 94% of the new Quaternary deposit. The remaining 6% of this new unit is mainly situated in Chittagong Hill Tracts with undefinable conditions. Statistical mapping also revealed that the Bangladesh coastal area was approximately 17,653 km^2 in 1990, notably expanding to 20,330 km^2 by 2022.

Table 3 compares the changes in the coastal landscape between 1990 and 2022. Six distinct geological units are identified here, each with calculated surface areas. The table presents changes in land area over time, including the erosion-induced land loss percentage. The new Quaternary deposit covers approximately 20% of the 2022 coastal province, totaling 3965 km^2. The lowest amount of landscape erosion (1.4% decrease) occurred in the marsh clay and peat deposits near the mangrove coast, while estuarine deposits of the central coast underwent the most erosion (14% decrease) over the study period (Table 3 and Fig. 5).

In Bangladesh, land accretion outweighs erosion, with a new Quaternary unit now safeguarding 19% of the coastline. Winter 2022 Sentinel-2 images revealed a net land gain of 2,677 km^2 since 1990, largely concentrated near the Meghna Estuary at an average annual rate of 84 km^2 (Figs. 4b-c). Despite the significant landform growth, a considerable 7% (equivalent to 1,221 km^2) coastal land loss occurred due to erosion in the past three decades (Table 3 and Fig. 5).

3.3 Annual precipitation patterns

Table 2 shows the annual precipitation in millimeters (mm) for ten distinct locations across Bangladesh (Fig. 1) from 1990 to 2019. The data portrays noteworthy fluctuations in precipitation levels across different regions and periods (Fig. 6). For example, Sylhet experienced the highest precipitation of 5,944 mm in 2017, while Bogura had the lowest of 1106 mm in 2006. Over the entire duration, Sylhet consistently received high annual rainfall, frequently surpassing 4,000 mm. Dhaka, the capital city, displayed varying precipitation levels, reaching a peak of 2,892 mm in 2017. The annual rainfall data for three decades shows varying mean precipitation levels, ranging from a minimum of 1,748 mm in 1992 to a maximum of 3,209 mm in 2017 (Table 2; Fig. 7). Notable fluctuations are evident throughout the period, with some years such as 1991, 1993, 2005 and 2017 experiencing higher precipitation levels. The mean annual precipitation for the entire period is 2,356 mm.

3.4 Channel migration

For the past 32 years, significant changes in river paths were mapped around the Ganges, Brahmaputra (Jamuna), Padma, and Meghna Rivers in Bangladesh (Fig. 8). Figures 8b-c depict new channel paths in northwest Bangladesh for the Jamuna River and its three main tributaries. For the Ganges River entering Bangladesh from the northwest, we calculated an average distance of 3.7 km between its present-day (2022) and abandoned (1990) river paths (Figs. 8d-e). Similar calculations were not executed for the other rivers due to their twisted nature and irregularities in the developments (Fig. 8).

Table 4 provides a detailed comparison of various river characteristics for 1990 and 2022. In 1990, the Dharla River exhibited a stream length of 64 km, a valley length of 39 km (Fig. 9), and a sinuosity of 1.64, which changed to 74 km, 39 km, and 1.9 by 2022, respectively (Fig. 10). The Dudhkumar River grew in stream length from 38 to 57 km, valley

Table 3 Comparison of coastal deposits, changes in land surface area, and erosional vulnerability of the Bangladesh coast between 1990 (based on Alam et al., 1990; and Persits et al., 2001) and 2022 based on Sentinel-2 data analysis (also, see Fig. 5)

Area	Type of deposits	Covered surface area (km^2)		Landscape change (%)	Vulnerability to coastal erosion
		Year: 1990	Year: 2022		
Mangrove coast	Mangrove swamp deposits	4,551	4,138	~9% decrease	Most stable
	Tidal deltaic deposits	2,045	2,010	~1.8% decrease	
	Marsh clay and peat	1,040	1,026	~1.4% decrease	
	Undefined Quaternary deposits	0	626	100% increase	
Tidal deltaic coast	Tidal deltaic deposits	4,246	4,008	~5.6% decrease	Moderately stable
	Marsh clay and peat	803	803	No change	
	Undefined Quaternary deposits	0	458	100% increase	
Central coast	Estuarine deposits	2,393	2,064	~14% decrease	Most vulnerable
	Tidal deltaic deposits	1,857	1,686	~9% decrease	
	Tidal mud	686	665	~3% decrease	
	Undefined Quaternary deposits	0	2,881	100% increase	

Fig. 5 Comparative maps
showing the Bangladesh coast,
including **a** the original geologi-
cal map of 1990, **b** high-resolu-
tion Sentinel-2 satellite images
captured during January-March
of 2022, and **c** new coastal
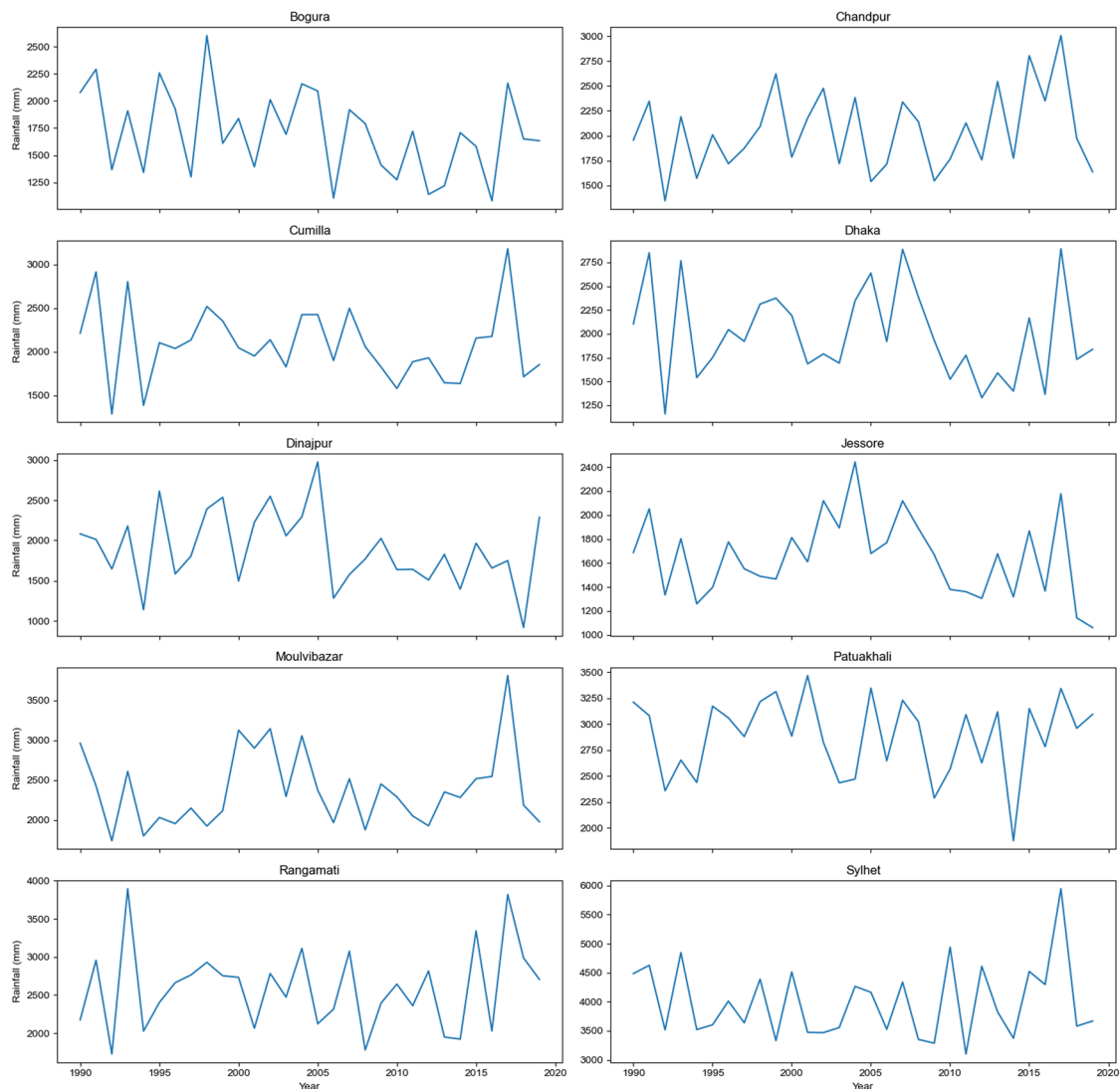geological map generated using
the Sentinel-2 images
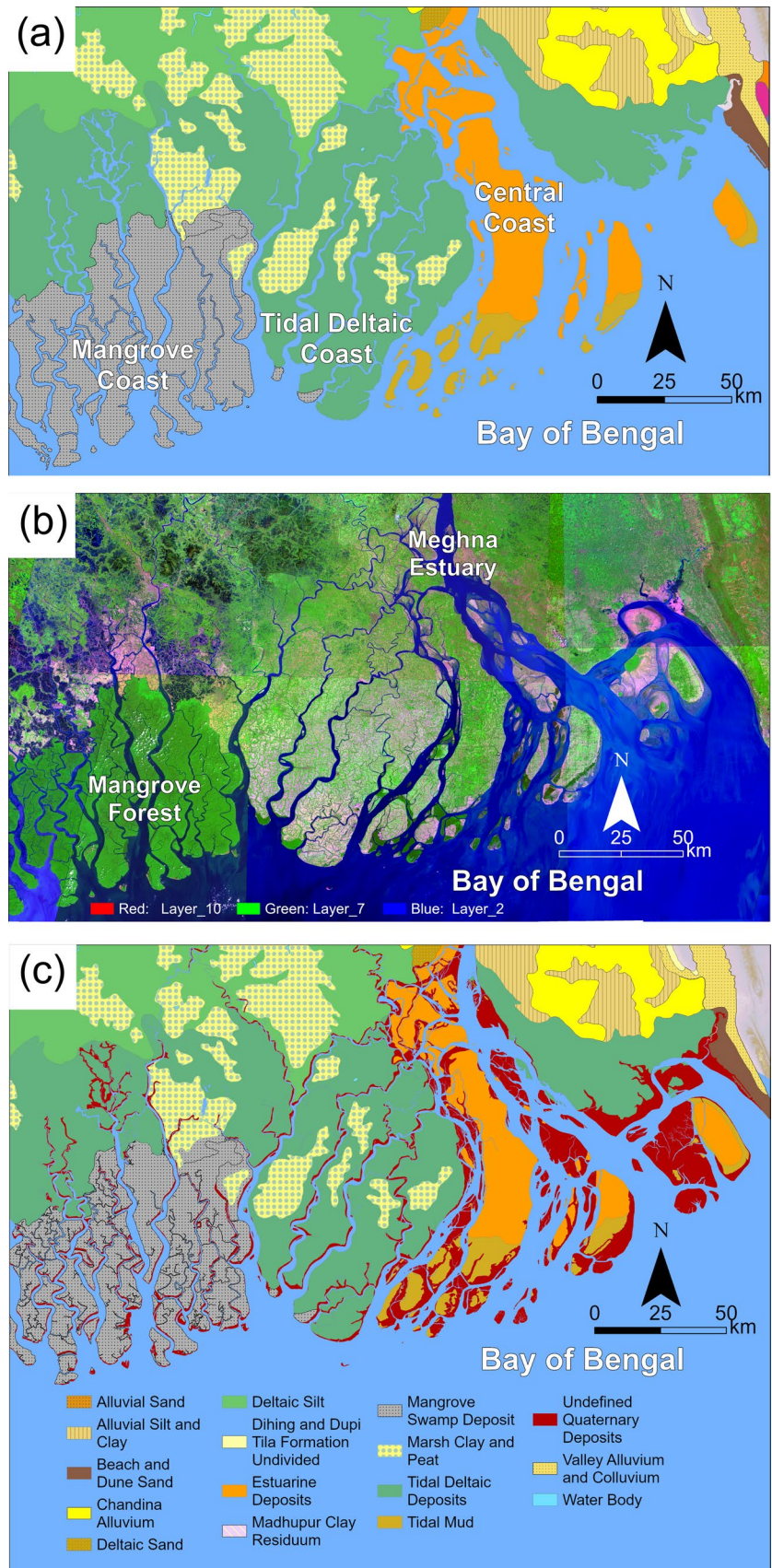
Fig. 6 The yearly variations in precipitation levels (measured in mm) across ten different locations in Bangladesh spanning the years 1990 to 2019 (See Fig. 1 for locations)

length from 31 to 36 km (Figs. 9, 10), and sinuosity from 1.23 to 1.58 (Fig. 11) over the same period. The Ganges, one of the major rivers, displayed notable changes with a stream length of 273 km, valley length of 170 km (Fig. 9), and sinuosity of 1.6 in 1990 (Fig. 11), expanding to 380 km, 202 km (Fig. 10), and 1.88 (Fig. 11), respectively, in 2022. Besides, the Padma River showed an increase in stream length from 108 to 120 km, valley length from 100 to 101 km (Figs. 9, 10), and sinuosity from 1.08 to 1.19 (Fig. 11). Teesta, known for its dynamic behavior, revealed a significant change in sinuosity, decreasing from 2.36 in 1990 to 2.11 in 2022 (Fig. 11), along with changes in stream and valley lengths. In contrast, the Upper Meghna River experienced the least changes in its stream length (147 km to 159 km), valley

length (121 km to 118 km) (Figs. 9, 10), and sinuosity (1.21 to 1.35; Fig. 11) over the specified period.

4 Discussion

4.1 Coastal stability and anthropogenic challenges

Fine sediments with subordinate sand particles dominate the central coastline of southeastern Bangladesh (Hoque et al., 2009). Satellite data identifies the area's adjacency to the Meghna Estuary, bordered by tidal mud and estuarine deposits to the east and tidal deltaic sediments to the west (Fig. 5). Our study underscores substantial land erosion in

Fig. 7 Average annual rainfall (mm) in Bangladesh from 1990 to 2019
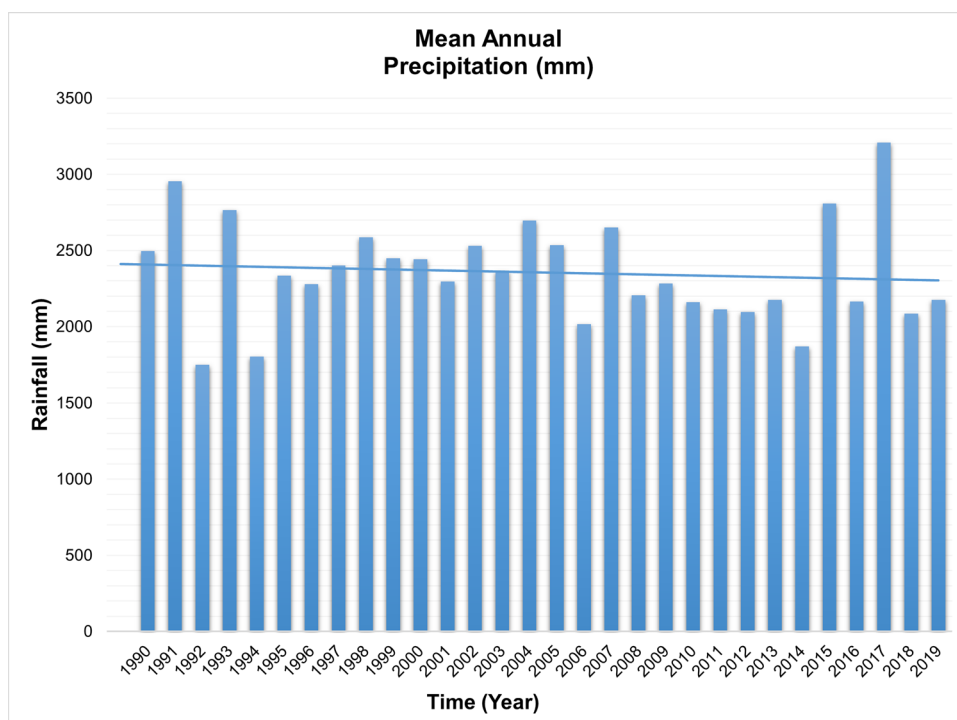
this region over the past 32 years. As the narrower Upper Meghna meets the wider Lower Meghna, the Meghna Estuary slowly joins the Bay of Bengal towards the south, where the flow velocity of the channel decreases. Since the slower-moving channel has less energy to transport sediment, it leads to extensive deposition of loose sediments, developing vast yet unstable land accretion. This suggests the high vulnerability of the central coast to sea-level rise.

In contrast, the southwestern coast is characterized by a prevalent silty or sandy clay surface attributed to tidal deposition (Allison et al., 2003; Rahman et al., 2018). In the Sundarbans Forest, a notable temperature increases of 0.5 °C per decade in surface water temperature (Mitra et al., 2009) is altering monsoonal patterns, driving sea-level rise, and exacerbating coastline erosion. However, our analysis found the relative stability of the Sundarbans Mangrove Swamp coast in the southwest over the past three decades (Fig. 5). This is likely because of the vegetations' root-stabilization and ocean-energy dissipation effects. The region's land stability is now facing anthropogenic threats from human settlements, agriculture, and fish farming, which can potentially lead to groundwater pollution (Islam et al., 2019). Despite the protective potential of the prevailing sandy clay cover along the coastline, which can serve as an aquitard to shield groundwater from surface contaminants (Yu, 2010), the unregulated land use practices loom as a significant long-term peril to the area's natural resources.

4.2 Landscape growth

Allison (1998) identified Meghna Estuary landscape growth rates of 15 km^2 annually between 1792 and 1840, and 4.4 km^2 per year from 1840 to 1984. Meanwhile, Brammer (2014a) documented a 451 km^2 land expansion in the Meghna Estuary from 1984 to 2007, averaging 20 km^2 per year. Our study also shows an accelerated annual landform development rate of 84 km^2 near the Meghna Estuary (Figs. 4b-c). These results affirm the Meghna Estuary's persistent seaward accretion over the past 230 years despite the ongoing rise in sea levels.

The average annual precipitation of Bangladesh has marginally declined since 1990 (Fig. 7). As precipitation patterns influence sediment transport and deposition, a decline in rainfall could also contribute to sediment accumulation, potentially leading to heightened land gain during this span. Although the country experienced increased mean yearly rainfall during 2015 and 2017 (Fig. 7), they are likely outliers. The accelerated coastal land growth rate around the Meghna Estuary outpaced any projected sea-level rise and land loss effects. This insight holds particular significance for Bangladesh, a low-lying nation facing an 18% risk of permanent coastal land loss with the potential for a one-meter sea-level increase in the near future (Huq et al., 1995; Sarwar & Khan, 2007).

Fig. 8 Changes in the channel paths of the Ganges-Brahmaputra-Meghna River system in Bangladesh between 1990 and 2022. In the geological maps (a, b, d, f, and h), the currently active (2022) fluvial network is indicated by blue, while the abandoned river paths, which were active in 1990, are shown in red (modified from Alam et al., 1990; and Persits et al., 2001). The focused locations (in red boxes) of the fluvial depositional systems also include river network data (c, e, g, and i) derived from Sentinel-2 images (2022). The Bengal River network is represented by serpentine yellowish areas, while the surrounding floodplains are predominantly green. Color combinations were obtained through the inverted histogram equalization image processing technique of ArcGIS Pro (false color band combination = Red: Band 10, Green: Band 7, Blue: Band 2)

4.3 Channel migration inside Bangladesh

4.3.1 Brahmaputra and tributaries

The Brahmaputra River, also known as the Jamuna River, is a transboundary river (Sivasankar et al., 2020) that originated in Tibet and flows through China, India, and the northwestern part of Bangladesh before eventually emptying into the Bay of Bengal (Fig. 1). All the primary tributaries of the Brahmaputra including Teesta, Dharla, and Dudhkumar are located upstream of their confluence with the main river (Fig. 8). This study validates that, over the past 32 years, the Jamuna River adhered to its innate braided configuration while maintaining an overall similar valley path and flow direction (Fig. 8a). However, individual channels of this multi-thread river system have significantly changed their flow paths (Figs. 8a-c).

The braided Jamuna River is abundant with sandy mid-bars, where the larger bars are marked by anastomosing-like styles (Figs. 8b-c). The riverbed and valley are primarily composed of alluvial sand, leading to erosion on both banks and mid-bars with creating new bars. This is consistent with the remote sensing analysis of Bristow (1987) that also identified such patterns in this river system with Landsat imagery and a historical database. Tectonic control on the Brahmaputra River has been ongoing for the last few hundred years, which might cause the river course to shift (Morgan & McIntire, 1959). The force and motion resulting from the collision of the Indian Plate with the Eurasian Plate along the Jamuna Fault could facilitate the Brahmaputra's course to deviate, potentially leading to the growth of new channels, abandoning the old ones (Figs. 8b-c). Previously, Coleman (1969) proposed a westward avulsion of the Brahmaputra in the late eighteenth century due to a large-scale earthquake, while Hirst (1916) indicated that the Brahmaputra's switching in direction was influenced by the Teesta's avulsion in 1787.

The higher sinuosity of Teesta (2.11) suggests a high meandering nature, although it has slightly decreased since 1990 (Table 4; Fig. 11). The reduction in Teesta stream length and sinuosity over the past 32 years suggests changes
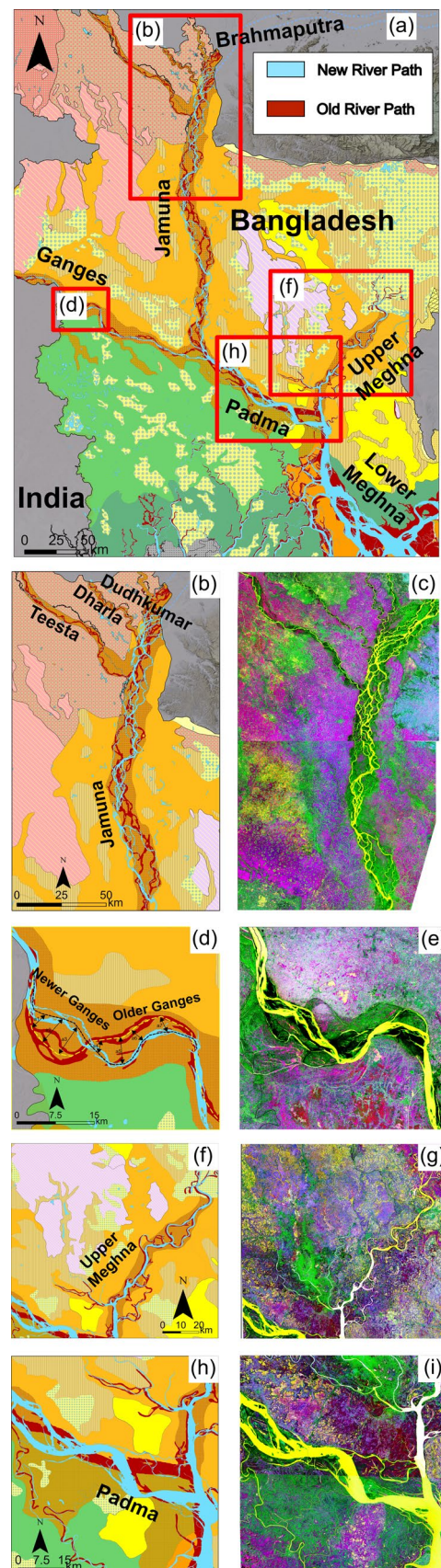
Table 4 Morphometric characteristics of major rivers in Bangladesh

River	1990			2022		
	SI (km)	VI (km)	S	SI (km)	VI (km)	S
Dharla	64	39	1.64	74	39	1.9
Dudhkumar	38	31	1.23	57	36	1.58
Ganges	273	170	1.6	380	202	1.88
Padma	108	100	1.08	120	101	1.19
Teesta	255	108	2.36	234	111	2.11
Upper Meghna	147	121	1.21	159	118	1.35

Sl stream length, *Vl* valley length, *S* sinuosity
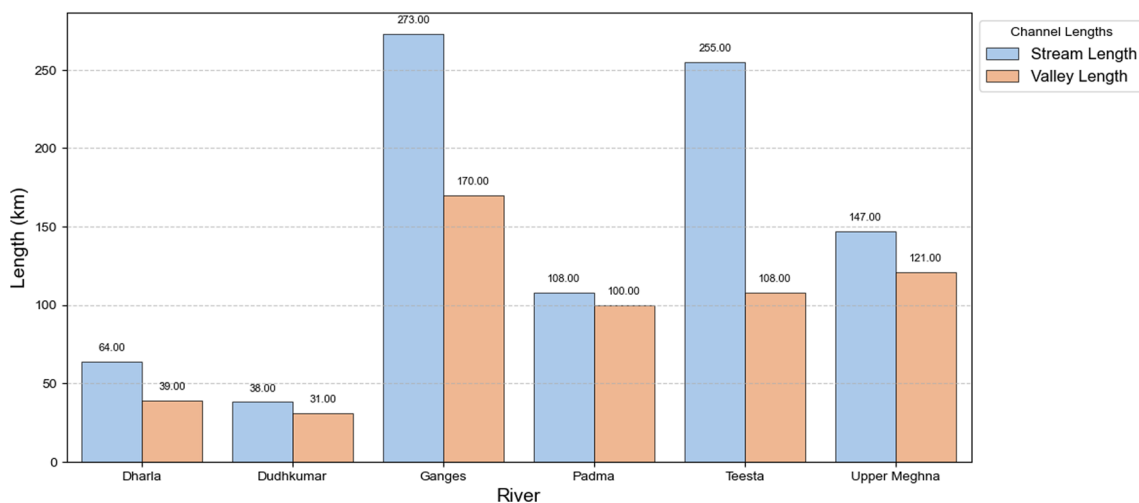
Fig. 9 Comparison of stream and valley lengths of major rivers in Bangladesh in 1990
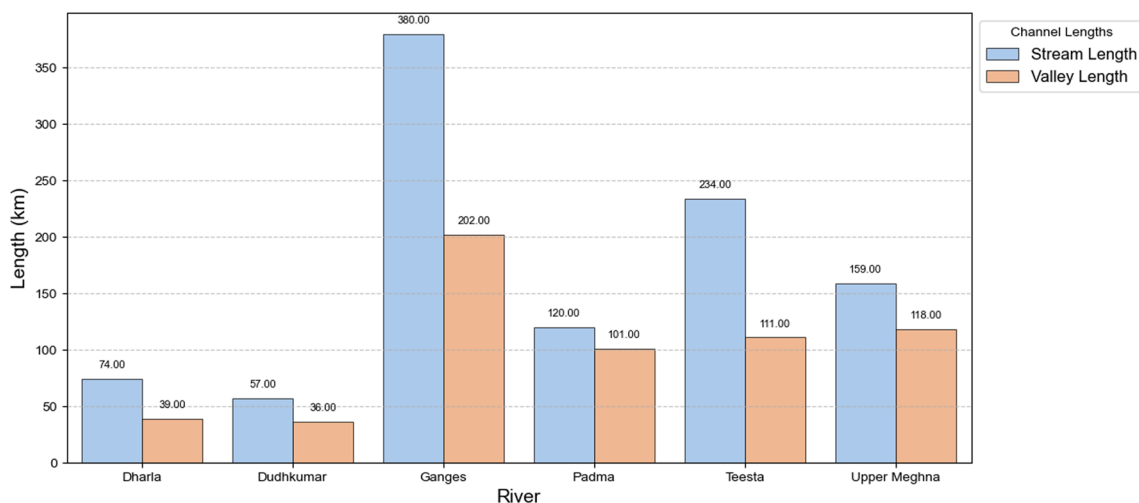
Fig. 10 Comparison of stream and valley lengths of major rivers in Bangladesh in 2022

in river course that might be controlled by the dry season surface water unavailability due to upstream Teesta Barrage developments in India (Zannah et al., 2020). Besides, after 1996, the Gozoldoba portion of the Teesta Barrage went under construction, which might trigger a lower amount of discharge and altered downstream economic and social
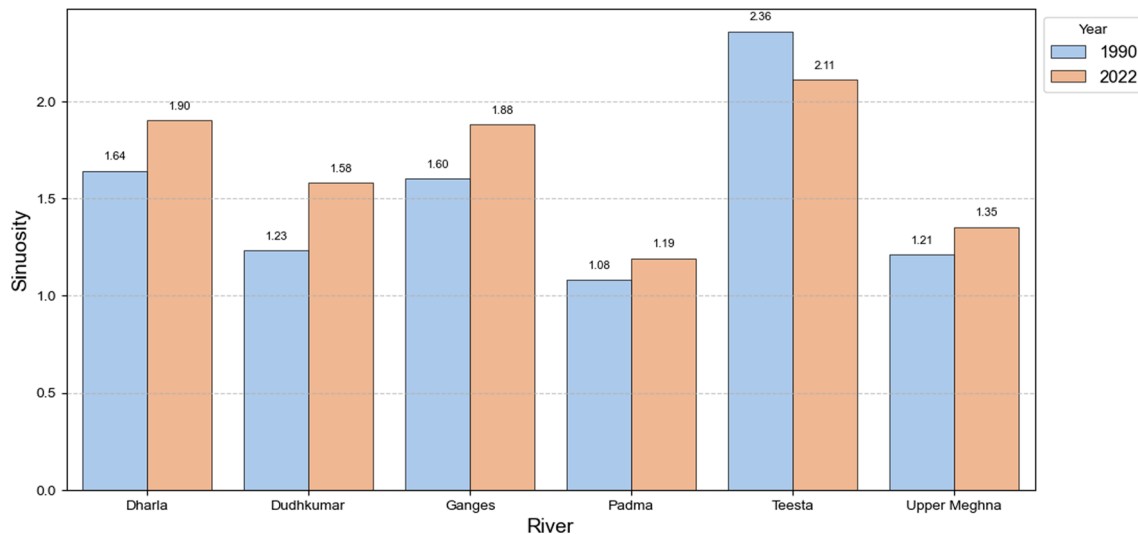
Fig. 11 Changes in river sinuosity between 1990 and 2022

circumstances coupled with agricultural practices in Bangladesh (Ahmed et al., 2022). Thus, increased human intervention is one of the most prominent factors in altering the Teesta River basin's land use pattern over time. Precipitation, as assessed in our study (Fig. 6), shows a declining trend in Bogura and Dinajpur districts (Northwest Bangladesh), which matches with the previous study by Ahmed et al. (2022), where a declining dry season rainfall trend was observed for Teesta.

The Dudhkumar River, the northernmost Brahmaputra tributary, currently exhibits a meandering pattern (Figs. 8b-c). River morphometry analysis shows that Dudhkumar currently displays a higher sinuosity of 1.58, which was only 1.23 in 1990 (Table 4; Fig. 11). Dharla River also has a similar morphology with a higher sinuosity of 1.9 observed currently that increased from 1.64 during 1990 (Table 4; Fig. 11). Therefore, both channels present high meandering style, allowing them to migrate more across their floodplains. Interestingly, the Dudhkumar River revealed signs of revival in 2022, including the formation of meander cutoffs near the Bangladesh-India border, where it showed a moribund stream pattern in 1990 (Figs. 8b-c). Several oxbow lakes were identified in the Kurigram district (Northwest Bangladesh), which developed through the meander cutoff process as Dudhkumar and Dharla abandoned meander loops during channel evolution.

4.3.2 Ganges-Padma river course

The Ganges and its tributaries, originating from the Gangotri Glacier in the Himalayas, constitute a prominent fluvial system that serves as a primary source of Bengal surface water, flowing for approximately 2,900 km before reaching the Bay

of Bengal (Fig. 1; Dey et al., 2023). The flow pattern of the Ganges River in India, situated in the bedrock location of the Mesozoic Rajmahal Traps (Singh, 2022), is assumed to be distinct from its Bangladeshi counterpart, having different geomorphic settings with the Holocene deposits (Fig. 3). The Farakka Barrage built in 1975 on the Ganges has created a significant difference in the way river water is distributed in India versus Bangladesh. The Ganges River in India has experienced high channel migration and discharge rates in recent years (Pal & Pani, 2016), while the Padma River in Bangladesh has resulted in a decrease in water and sediment discharge (Steckler et al., 2022). Analysis from Rahman & Rahaman (2018) has revealed a significant drop in annual average and minimum water discharge in the Ganges-Padma system in Bangladesh since the post-Farakka period after 1975, with a few sharp increases in yearly maximum water levels.

Moreover, a slight gradual decrease in country-wide mean annual precipitation was observed over the last three decades (Table 2; Fig. 7), aiding in narrowing the channel width and weakening the river strength. Therefore, older but more braided (multi-thread) Ganges-Padma channels have been progressively changing their patterns to a relatively single-thread, sinuous channel (Figs. 8d-e), suggesting the direct effects of the Farakka Barrage, along with a minor decrease in rainfall, that resulted in decreasing water discharge through the Ganges-Padma over time. The upper stretch of the Ganges River (Figs. 8d-e) exhibits a prominent meandering pattern deriving from India, with two extensive meander spirals unhurriedly extending on the opposite banks. Although the Padma River remained moderately sinuous (S = 1.08 to 1.19) over the study period, the Ganges River developed a very high sinuosity in 2022

(S = 1.88), which saw a sharp increase since 1990 (S = 1.6) (Table 4; Fig. 11). Therefore, the Ganges can be considered as a highly meandering river because of its growing sinuosity. As we measured the average distance of 3.7 km between the present and older flow paths, this separation distance between the abandoned and active meanders suggests a notable evolving state of the Ganges that is ongoing (Figs. 8d-e). Because of its dynamic nature, the Ganges can affect adjacent land use, infrastructure, and ecosystems, especially in the Kushtia, Ishwardi, and Pabna districts. It also indicates that Bangladeshi people residing in these locations may face significant risks of landscape alteration and environmental displacement in upcoming years.

4.3.3 Upper and Lower Meghna

The Meghna River is in the Surma-Kushiyara river system (Fig. 1) that traverses Bangladesh via the Barak River, originating from the eastern Indian hilly regions (Chowdhury, 2012). Compared to the Ganges-Padma and Jamuna River systems, the Upper Meghna River network shows a lesser tendency of channel shifting (Figs. 8f-g). The sinuosity of the Upper Meghna is still in moderate range (1.21 to 1.35) over the past few decades (Table 4; Fig. 11). With several distinct anastomosed patterns, the Upper Meghna riverbanks are more resistant to erosion, suggesting a floodplain resilience. The tectonically sinking Surma Basin with its thick and compacted sediments (Mallick et al., 2020) likely resulted in a stable and anastomosed pattern of the Upper Meghna River. The channels split and rejoined in several locations following near-identical flow paths in 1990 (Figs. 8f-g).

Despite having considerable land accretion over recent years, the Lower Meghna River is much wider near the Meghna Estuary (Figs. 5b-c) because of the convergence of the Jamuna and Padma Rivers, bringing vast amounts of water and sediments. This finding is in line with past research by Allison (1998), Brammer (2014b), and Steckler et al. (2022). Therefore, the intersection of all the primary fluvial networks at a littoral zone and the recent rise in sea level made the Lower Meghna River shore vulnerable to erosion.

4.4 Limitations and future research directions

While this study provides valuable insights into coastal stability, landscape growth, and channel migration using remote sensing data, there are inherent limitations to this approach. The primary limitation concerns the accuracy and resolution of satellite images. Remote sensing provides a two-dimensional view of surface changes, which may not fully capture subsurface processes, such as groundwater dynamics or sediment composition. Another limitation is the absence

of comprehensive field validation. While remote sensing data offer broad-scale temporal coverage, ground-truthing through field surveys is necessary to validate the observed landscape changes and sedimentary patterns. Without field data, such as sediment samples or geotechnical analysis, the study's findings on erosion, deposition, and landform stability are based solely on image-derived indicators. Future integration of fieldwork, such as soil sampling, hydrological measurements, and GPS-based surveys, can strengthen the interpretation of satellite-derived data and provide a more complete understanding of the region's geomorphological processes.

Given the dynamic nature of Bangladesh's river systems and coastal regions, continuous monitoring is essential to track ongoing landscape changes. Future research should focus on establishing long-term observation networks that combine remote sensing data with regular field validation to ensure accuracy and improve predictive capabilities. Additionally, higher-resolution satellite imagery, such as from commercial sources, could be employed to offer a more detailed analysis of small-scale landscape changes, particularly in rapidly evolving areas like the Meghna Estuary and the Jamuna-Brahmaputra River system.

Moreover, developing adaptive management strategies is critical to mitigate the risks posed by climate change, sea-level rise, and anthropogenic pressures. Future research should explore the application of hydrodynamic and sediment transport models to simulate the potential impacts of different climate scenarios on Bangladesh's coastal and riverine landscapes. Investigating the role of ecosystem-based approaches, such as mangrove restoration in the Sundarbans, could provide sustainable solutions for enhancing coastal resilience. Engaging with local communities and policymakers in developing these adaptive strategies would also ensure that scientific findings translate into practical and effective mitigation measures.

5 Conclusions

As one of the first few works on geological and landscape mapping of the Bengal Basin and Bangladesh (Fig. 3), this research found notable outcomes regarding channel migrations and landform evolution over the past 32 years. Our study focused on understanding the evolution of Bangladesh's major rivers, including the Ganges, Brahmaputra, Meghna, and their tributaries (Fig. 8). A comparative analysis of landscape maps between 1990 and 2022 revealed significant changes in river paths (Fig. 8) and coastal landscape (Fig. 5).

While past avulsion of the Brahmaputra (Jamuna) River may be due to the Jamuna Fault movement, our research identified intriguing river rejuvenations in the Brahmaputra

tributaries. Anastomosing and meandering patterns are typical for studied fluvial networks, while the Brahmaputra River exhibits a braided, multi-thread configuration with many mid-bars. Anthropogenic factors such as Teesta and Farakka Barrages control behaviors of major channels (Ganges and Brahmaputra), where a decreasing water discharge along with a minor decrease in precipitation have caused the Ganges-Padma River system to narrow into single-thread channels. Although the braided Brahmaputra River is still maintaining its multi-thread nature, it also suffered from lower discharge due to Teesta Barrage in India. All the major tributaries of the Brahmaputra River show moderate to high sinuosity, where the ongoing anthropogenic activity in the upstream Teesta exerts partial influence.

While the Ganges and Brahmaputra Rivers contain unstable floodplains, the Upper Meghna fluvial system has the most stable floodplain and channel path, possibly due to increasing subsidence of the Surma Basin. The confluence of all rivers at the Meghna Estuary widens the Lower Meghna fluvial system and facilitates rapid land accretion despite the impact of sea-level rise. Since the rivers are switching courses and the landscape is transforming, the Bengal fluvial system has significant repercussions for the millions of people living in the floodplain.

The Bengal Delta is the world's largest delta and is highly vulnerable to cyclones, flooding, and rising sea levels. This study identified stable and unstable landscapes (Fig. 5), especially in the coastal parts of Bangladesh. The updated geological map of Bangladesh (Fig. 3) enabled the analysis of lithologic variation and landscape change. However, given the prevalence of "Undefined Quaternary Deposits" along the coast and riverbanks, further field investigations can assist in determining the detailed lithology of this unit. Satellite data revealed significant alterations to alluvial sand and silt deposits along the country's river floodplains and coastal regions. The newly accreted lands along the Meghna Estuary have raised the need to compare these areas with other coastal regions to determine landform stability. This research found the Sundarbans Mangrove Forest on the southwest coast to be exceptionally stable despite the recent rise in sea levels. Given that one-fourth of the country's population lives near the coast, it is crucial to determine whether coastal shorelines can achieve geomorphic stability through natural or artificial afforestation.

Notably, the 2022 dry-season Sentinel-2 imagery revealed a significant land gain of 2,677 km^2 along the coast, which showed six times more land growth compared to the previous study by Brammer (2014a). Bangladesh's escalating phenomenon of coastal land stability has emerged as an essential topic of further investigation, with implications for other deltas. In this context, this research can serve as a valuable guide for future studies striving to address landscape and environmental challenges on a global scale.

Incorporating the study's findings into policy-making and sustainable management practices can significantly enhance efforts to mitigate the impacts of climate change and anthropogenic activities in the Bengal Basin and coastal Bangladesh. The identification of river rejuvenations, channel migrations, and landscape changes over the last, short 32 years provides crucial insights for floodplain management, disaster preparedness, and urban planning. For instance, the observed land accretion along the Meghna Estuary could inform coastal zone management policies, promoting the use of natural landform developments as protective barriers against sea-level rise and cyclones. Additionally, understanding the impacts of barrages like the Farakka and Teesta on river discharge and behavior offers valuable guidance for transboundary water management negotiations, ensuring that upstream interventions do not destabilize downstream ecosystems or communities. The stability of the Sundarbans Mangrove Forest, despite rising sea levels, highlights the importance of conserving mangroves as a natural defense against coastal erosion and flooding. These findings also emphasize the need for afforestation and reforestation initiatives to bolster coastal resilience. By integrating these insights into regional and national strategies, policymakers can better balance development needs with environmental sustainability, reducing vulnerability to climate-induced disasters while supporting sustainable livelihoods for the millions of people living in the delta.

Author contributions S.B.S. collected and analyzed all the data, prepared the figures, interpreted the results, and designed the paper. M.R.G. guided the research design, suggested figure creation and manuscript structure, and supervised and edited the manuscript. N.D.G. contributed to the GIS and Remote Sensing analysis, provided suggestions and feedback on figure creation, and supported the data analysis process.

Declarations

Conflict of interests The authors declare no competing interests.

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