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Spatio-Temporal Analysis of Channel Morphometry and Morphological Dynamics of the Lower Subarnarekha River Basin, Odisha, India: A Geo-informatics Approach

Mintu Jana [1,*], Dipak Bisai [2] and Taniya Roy [3]

[1] *Research Scholar, Coastal Environmental Studies, Egra Sarada Sashi Bhusan College, Egra, West Bengal, India.*
[2] *Associate Professor, Department of Geography, Egra Sarada Sashi Bhusan College, Egra, West Bengal, India.*
[3] *State Aided College Teacher, Department of Geography, Bajkul Milani Mahavidyalya, Egra, West Bengal, India.*

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Abstract

The morphological evolution of river channels is a continuous process driven by hydrodynamic fluctuations and human interventions. This study evaluates the spatio-temporal changes in the channel geometry of the lower Subarnarekha River basin in Balasore, Odisha, over several decades. Utilizing multi-temporal Landsat imagery (MSS/TM 4-5 and OLI 8) integrated with ArcGIS and Google Earth Pro, the research quantifies shifts in river course and estuary dynamics. Statistical validations were performed using Origin-Pro 2022 and MS EXCEL. Findings reveal significant morphological instability, particularly between 2015 and 2020, characterized by an increase in the Sinuosity Index within specific grids (A5) and river points (5-6). A notable reduction in water volume has been observed since 2014, while sand dunes and sand banks have shown a declining trend since 2004, likely due to intensive sand mining and monsoonal discharge variations. Interestingly, the Braided Index showed a gradual decrease from 1985 until a rapid resurgence in 2005. Furthermore, localized analysis of the Subarnarekha estuary (Grid A7) indicates a steady increase in sand bar formation since 2005. These results underscore the highly dynamic nature of the Subarnarekha riverbed, providing a critical baseline for flood management and sustainable river-resource regulation.

Keywords: Subarnarekha River; Channel Geometry; Sinuosity Index; Braided Index; Remote Sensing; Morphological Change

1. Introduction

River systems are among the most dynamic geomorphological features on Earth, constantly undergoing changes in their channel geometry and morphological characteristics. These transformations are a result of the complex interplay between natural hydrological processes and human-induced interventions. The Subarnarekha River, an interstate river in eastern India, serves as a significant example of such a dynamic system, particularly in its lower basin within the Balasore district of Odisha. The channel morphology of the Subarnarekha River is characterized by a high degree of instability and a persistent tendency to shift its course over time. This shifting nature is primarily attributed to monsoonal hydrodynamic behavior, where heavy seasonal discharge triggers significant erosion and sedimentation processes. Furthermore, intensive anthropogenic activities, specifically unregulated sand mining from the riverbed in the middle and lower courses, have accelerated these morphological shifts, leading to substantial changes in the river's physical structure. Understanding these spatio-temporal variations is crucial for effective river management and environmental conservation. This study utilizes multi-temporal satellite data, including various Landsat series (MSS/TM and OLI/TIRS), to assess the long-term changes in the channel geometry and geomorphic landforms of the lower Subarnarekha basin. By integrating advanced Remote Sensing (RS) and Geographic Information System (GIS) techniques, such as the Modified Normalized Difference Water Index (MNDWI) and supervised classification, the research aims to quantify the magnitude of channel migration, sinuosity fluctuations, and changes in small

* Corresponding author: Mintu Jana; ORCID ID: https://orcid.org/0000-0002-0566-8822

morphological features like sand bars and dunes. The primary objectives of this research are: 1) To evaluate the spatio-temporal changes in the channel geometry of the Subarnarekha lower basin. 2) To identify and measure the direction of river shifting at various critical points and within the estuary region. 3) To perform a chronological assessment of small geomorphic landforms and their response to environmental and human pressures. Preliminary results indicate a significant increase in the Sinuosity Index (SI) between 2015 and 2020, particularly in specific grids (A5), along with a sharp rise in the Braided Index post-2005. Furthermore, a critical depletion of sand dunes and a reduction in water volume since 2014 highlight the severe impact of sand mining on the river's health. The study concludes that the Subarnarekha lower basin is in a state of geomorphic distress, requiring immediate policy intervention for sustainable resource management and flood control.

1.1. Study Area

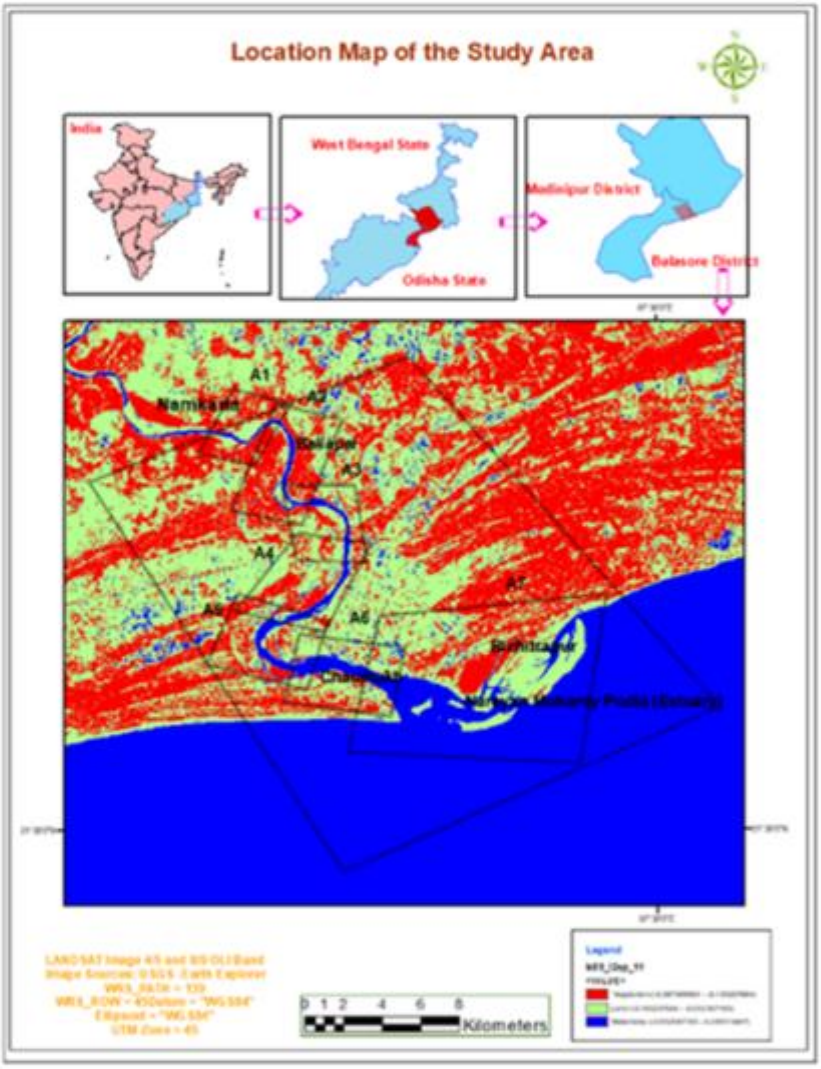


Figure 1 Location Map of the Study Area

The study area focuses on the lower reaches of the Subarnarekha River Basin, specifically located in the Balasore district of Odisha, India. The Subarnarekha, meaning "Streak of Gold," is one of the major rain-fed interstate rivers in eastern India, flowing through the states of Jharkhand, West Bengal, and Odisha before discharging into the Bay of Bengal. *Geographical Location:* The lower basin area under investigation lies approximately between the latitudes of 21°30' N to 21°45' N and longitudes of 87°05' E to 87°25' E. This segment is critical as it includes the river's meandering course and its eventual confluence with the sea at the Subarnarekha estuary. *Topography and Climate:* The region is characterized by a flat alluvial plain with a gentle slope towards the south-east. The climate is dominated by the tropical monsoon system. The area receives heavy rainfall (averaging 1500-1600 mm annually), primarily during the southwest monsoon season (June to September). This high seasonal discharge is a major driver of the river's hydrodynamic behavior and subsequent morphological changes. *Hydrological Significance:* In its lower course, the river exhibits a high degree of sinuosity and frequent channel shifting. The estuary region is particularly dynamic, featuring various geomorphic landforms such as sand bars, dunes, and tidal creeks. The study area is not only ecologically sensitive but also economically significant due to extensive agricultural activities and sand quarrying along the riverbanks.

Objectives of the Study

The primary goal of this research is to analyze the dynamic nature of the Subarnarekha River's lower course through a multi-decadal lens. The specific objectives are as follows:

- To Assess Spatio-Temporal Channel Geometry: To quantify the long-term changes in river width, depth, and cross-sectional variations using multi-temporal satellite datasets.
- To Analyze Sinuosity and Braiding Indices: To calculate and evaluate the fluctuations in the Sinuosity Index (SI) and Braiding Index (BI) to understand the river's meandering behavior and channel instability, specifically focusing on critical grids (A5, A7).
- To Measure River Shifting and Migration: To identify the rate and direction of lateral migration of the riverbank at various selected points from the lower basin to the estuary.
- To Monitor Morphological Landforms: To track the evolution of small-scale morphological features, such as sand bars, sand dunes, and sand banks, over different time periods (1985–2022).
- To Evaluate Anthropogenic and Natural Drivers: To examine the impact of monsoonal hydrodynamic discharge and intensive riverbed sand mining on the overall channel stability and water volume reduction.

2. Material and methods

To achieve the research objectives, a robust methodology combining Remote Sensing (RS) data and Geographical Information System (GIS) tools was adopted. The study follows a systematic approach of data acquisition, image processing, and statistical validation.

2.1. Data Acquisition

Seven grids are mosaic shape create on the lower course of Subarnarekha river in Google Earth. And geometrical assesment on targated five sleceted year are 1985, 206, 2011, 2016 and 2022. Another mesure of small geomorphic landforms change detection on selected years of my study area. This Seven grids moasic name are A1, A2, A3, A4, A5, A6 and A7.

Table 1 Tudy Area Grid and Point Details

Grids Name	River Points Name	Latitude	Longitude	Area (Sq.km)	Perimeter (Km)
A1	1	21°41'13.53"N	87°16'37.85"E	4.28	13.7
	2	21°41'55.07"N	87°18'39.12"E		
A2	2	21°41'55.07"N	87°18'39.12"E	21.5	19.2
	3	21°39'31.49"N	87°18'57.17"E		
A3	3	21°39'31.49"N	87°18'57.17"E	14.9	15.6
	4	21°37'46.94"N	87°20'43.88"E		
A4	4	21°37'46.94"N	87°20'43.88"E	21	19.2
	5	21°36'3.19"N	87°18'48.20"E		
A5	5	21°36'3.19"N	87°18'48.20"E	20	18
	6	21°34'30.24"N	87°19'8.54"E		
A6	6	21°34'30.24"N	87°19'8.54"E	20.3	18.5
	7	21°34'8.10"N	87°21'50.60"E		
A7	7	21°34'8.10"N	87°21'50.60"E	95.5	40.3

In the study, the satellite imageries of three different Landsat sensor (ETM, TM, OLI_TIRS) were considered for channel geometrycal analysis during 23 years (1999– 2022). The images were selected depending on the year of availabality of Landsat ETM image availabality (ETM 1999). The six images of 1999, 2004, 2009, 2014, 2018 and 2022. All thye images were projected and resampled in the Universal Transverse Mercator (UTM) projection with zone 45 north and world geodetic survey 1984 (WGS84 datum in the ARC GIS pro 10.8 software. The seven grids are create of my study area A1, A2, A3, A4, A5, A6 and A7. The green band are more sensitive to the turbid environment and the spectral values of near-infrared (NIR) region have also an effect on the watreborne surface, it can delineating wetlands, water surface, soil moisture and flooded areas. In addition, mid-infrared (MIR) for Landsat 7 and Shrotwave-infrared (SWIR) for landsat 5 and 8 have the using for easily contrast vegetation and water. The ARC GIS 10.8 and Google Earth pro using for satellite image assesment. The Origin Pro 2022 software using for data tabulation of Subarnarekha river channel geometry. Another application MS Excel using for data tabulation.

2.2. Landsat Image Details

I have using the three different type of Landsat images, Such as Landsat 4-5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and Landsat 8-9 Operational land Imager (OLI) and Thermal Infrared Sensor (TIRS). Thess three typ esensor and their different band using for the classification of different componets and data acquisition.

Table 2 Landsat 4 and 5 Details

Landsat 4-5	**Wavelength**	**Resolution**
	(micrometers)	(meters)
Band 1	0.45-0.52	30
Band 2 (Green)	0.52-0.60	30
Band 3	0.63-0.69	30
Band 4 (NIR)	0.76-0.90	30
Band 5	1.55-1.75	30
Band 6 (Thermal Infrared)	10.40-12.50	120 (30)
Band 7	2.08-2.35	30

Table 3 Landsat 7 ETM+ Details

Landsat 7	**Wavelength**	**Resolution**
	(micrometers)	(meters)
Band 1 (Blue)	0.45-0.52	30
Band 2 (Green)	0.52-0.60	30
Band 3 (Red)	0.63-0.69	30
Band 4 (NIR)	0.77-0.90	30
Band 5 (SWIR 1)	1.55-1.75	30
Band 6 (Thermal)	10.40-12.50	60 (30)
Band 7 (SWIR 2)	2.09-2.35	30
Band 8 (Panchromatic)	.52-.90	15

Table 4 Landsat 8-9 (OLI & TIRS) Details

Landsat 8-9 Bands OLI & TIRS	**Wavelength**	**Resolution**
	(micrometers)	(meters)
Band 1 - Coastal aerosol (ultra-blue)	0.43-0.45	30
Band 2 - Blue	0.45-0.51	30
Band 3 - Green	0.53-0.59	30
Band 4 - Red	0.64-0.67	30
Band 5 - Near Infrared (NIR)	0.85-0.88	30
Band 6 - SWIR 1	1.57-1.65	30
Band 7 - SWIR 2	2.11-2.29	30
Band 8 - Panchromatic	0.50-0.68	15
Band 9 - Cirrus	1.36-1.38	30
Band 10 - Thermal Infrared (TIRS) 1	10.6-11.19	100
Band 11 - Thermal Infrared (TIRS) 2	11.50-12.51	100

Table 5 Satellite Image Details

SL. No	**Image Attributes**											
	Spacecraft ID	**Sensor ID**	**WRS TYPE**	**WRS Path**	**WRS Row**	**Date Acquired**	**Scene Center Time**	**Cloud Cover Land**	**Sun Azimuth**	**Sun Elevation**	**Earth Sun Distance**	**Sensor Mode**
1	Landsat-7	ETM	2	139	045	08/12/1999	04:30:29.1659370Z	0.00	151.39321732	40.15342191	0.9850977	SAM
2	Landsat- 5	TM	2	139	045	29/12/2004	04:23:29.3090810Z	0.00	147.33396296	37.63771473	0.9833607	BUMPER
3	Landsat- 5	TM	2	139	045	24/10/2009	04:27:46.0730880Z	0.00	144.84006963	50.09372386	0.9946493	BUMPER
4	Landsat-8	OLI_TIRS	2	139	45	28/03/2014	04:37:49.0786370Z	0.00	124.33385977	59.42861181	0.9980776	-
5	Landsat-8	OLI_TIRS	2	139	45	18/11/2018	04:37:31.0189279Z	0.06	153.05993454	44.71604624	0.9885298	-
6	Landsat-9	OLI_TIRS	2	139	45	06/02/2022	04:37:50.3608609Z	0.00	142.27012952	44.19991861	0.9860731	-

Multi-temporal satellite datasets were used to monitor the changes over several decades. Satellite Data: Landsat 4-5 MSS/TM, Landsat 7 ETM+, and Landsat 8 OLI/TIRS series were acquired from the USGS Earth Explorer. Software: ArcGIS 10.x: Used for spatial mapping, channel digitization, and change detection. Google Earth Pro: Used for ground-truth verification and cross-checking historical bank lines. Origin-Pro 2022: Used for advanced statistical tabulation and generating geometrical graphs.

Image Processing and Water Extraction

To extract the river channel accurately, the Modified Normalized Difference Water Index (MNDWI) was utilized, as it is more effective than the standard NDWI in suppressing noise from built-up areas and vegetation. The formulas used for water index extraction are:

For Landsat 4-5 & 7: $NDWI = \frac{GREEN-NIR}{GREEN+NIR}$

Sensor	Green Band	NIR Band	Formula
Landsat 4-5 (TM)	Band 2	Band 4	(Band 2 - Band 4) / (Band 2 + Band 4)
Landsat 7 (ETM+)	Band 2	Band 4	(Band 2 - Band 4) / (Band 2 + Band 4)

For Landsat 8: $MNDWI = \frac{GREEN-SWIR}{GREEN+SWIR}$

Sensor	**Band Name**	**Band Number**	**Wavelength**
Landsat 8	Green	Band 3	$0.533 - 0.590 \ \mu m$
Landsat 8	SWIR 1	Band 6	$1.566 - 1.651 \ \mu m$

Calculation of Morphological Indices

Two key indices were calculated to understand the river's complexity:

Sinuosity Index (SI): Calculated as the ratio of the actual channel length to the straight-line distance.

$$SI = \frac{CL}{VL}$$

Where:

CL (Channel Length): The actual distance measured along the center of the river channel (the "curved" path).

VL (Valley Length): The shortest straight-line distance between the start and end points of that same river reach.

Braided Index (BI): To measure the intensity of channel branching, calculated by measuring the total length of all segments of bars/islands divided by the reach length. Friend and Sinha (1993) or Howard (1979) method, which focuses on the number of channels:

$$BI = \frac{Sum\ Lct}{Lctr}$$

Measurement of Channel Geometry

The study area was divided into several grids (A5, A7) to perform a localized analysis of:

Channel Width: Measured at multiple cross-sectional points (Point 5-6).

Erosion and Accretion: Identified by overlaying multi-year bank lines (1985 to 2022) to determine the shifting direction.

Flow Chart

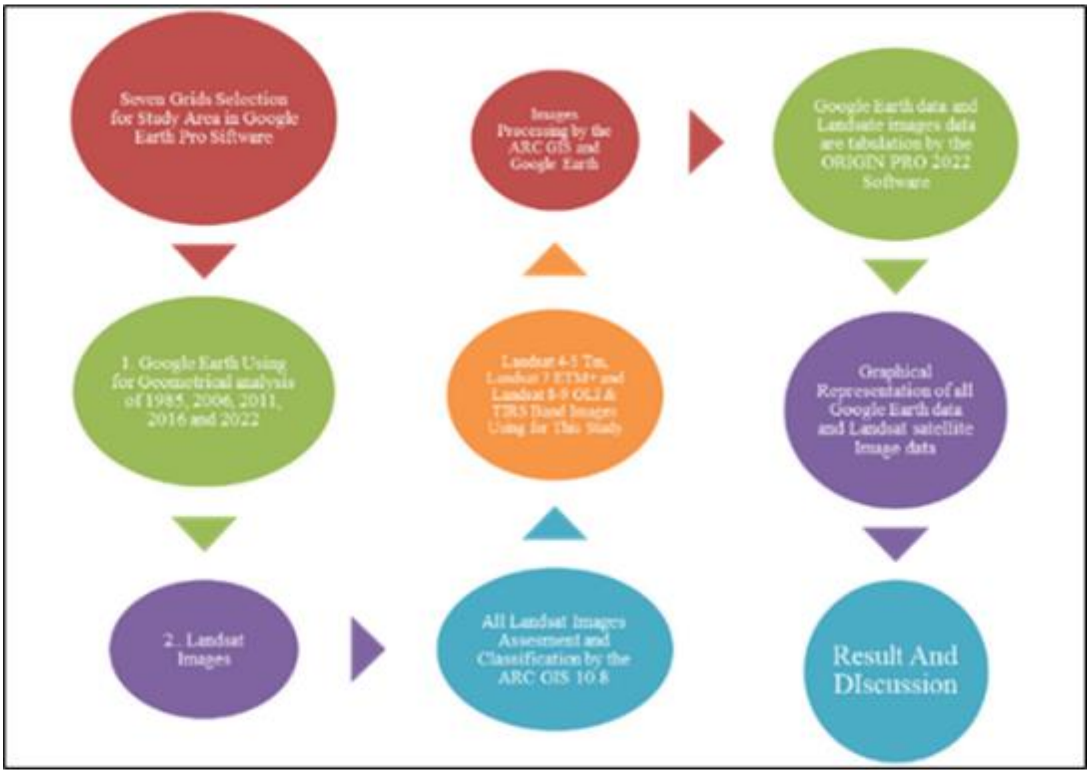


Figure 2 Methodological Flow Chart

3. Results

The spatio-temporal analysis of the Subarnarekha River reveals significant morphological instability over the past few decades. The key findings are categorized as follows:

3.1. Sinuosity and Braiding Dynamics

Sinuosity Index (SI): The study observed a notable increase in the meandering nature of the river. High sinuosity was particularly recorded in Grid A5 and across river points 5-6. The most rapid changes in the sinuosity index occurred between 2015 and 2020, indicating a phase of high channel instability.

Braiding Index (BI): The river exhibited a fluctuating pattern in its braiding nature. While there was a gradual decrease from 1985, a sharp and rapid increase in the braiding index was observed from 2005 onwards, reflecting increased sedimentation and bar formation.

3.2. Channel Geometry and Morphological Features

Water Volume and Surface Area: A significant decline in the river's water volume has been documented since 2014. This reduction is closely linked to altered flow regimes and intensive riverbed sand mining.

Sand Bars and Dunes: Sand Dunes and Sand Banks have shown a consistent decrease since 2004 due to human interventions. Conversely, in the Subarnarekha estuary (Grid A7), Sand Bars have shown a slow but steady increase since 2005, likely due to the accumulation of eroded sediments from the upper reaches.

Land use & Land cover Map :

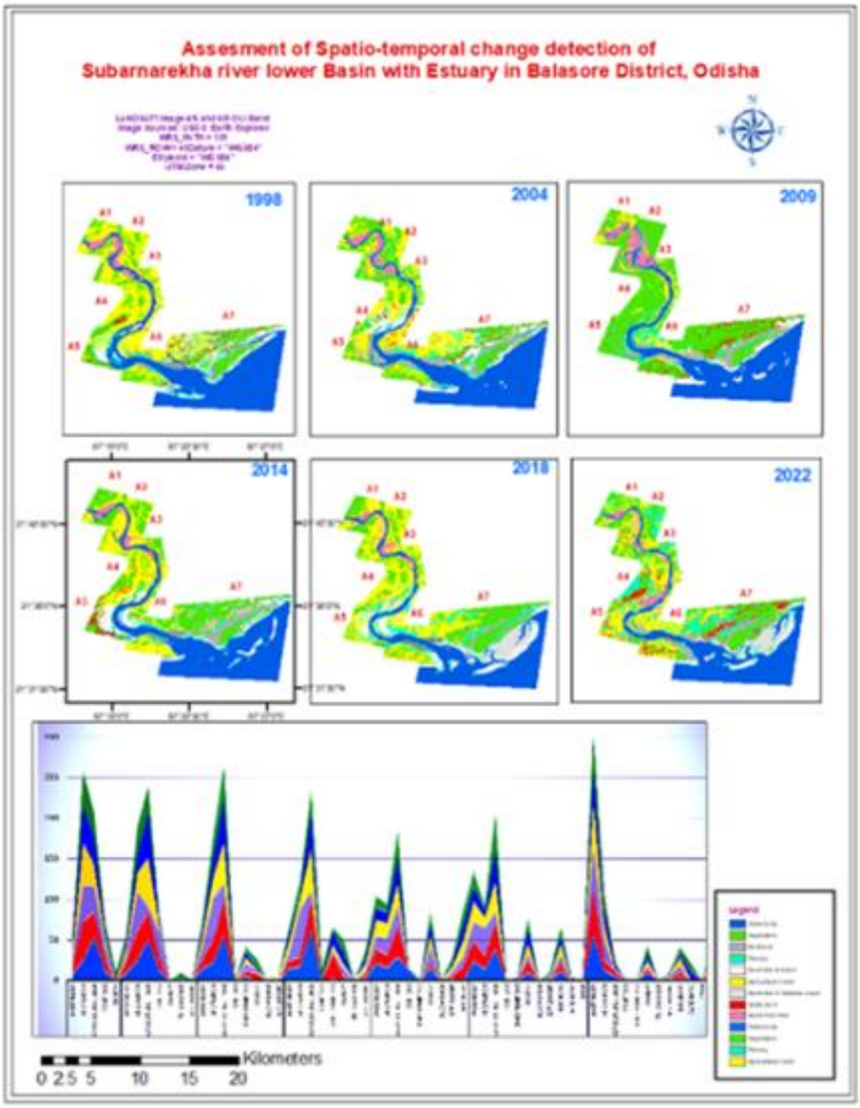


Figure 3 Grid Wise Spatio- temporal detection Analysis

Interpretation

The six maps show the physical transformation of the river basin at specific points: 1998, 2004, 2009, 2014, 2018, and 2022. *River Morphology*: You can see significant shifting in the riverbanks and the size of sandbars (yellow/white patches within the blue river channel). *Estuary Growth:* The area labeled A7 (the mouth of the river) shows a noticeable increase in "Sand Bar in Shallow coast" and "Mudbank" over time, suggesting high rates of sedimentation. *Vegetation vs. Human Activity:* In 1998, green (vegetation) was more dominant. By 2022, there is a visible increase in red patches (Settlement) and yellow/orange patches (Agricultural Land/Fishery), particularly around areas A4, A5, and A6. The study categorizes the terrain into several key types: Waterbody: The main river channel and sea. Vegetation: Natural greenery/forest cover. Fishery: Likely aquaculture ponds, which show an increase in later years. Settlement: Human habitation (marked in red), which expands significantly over the decades. Sand Bar & Mudbank: Indicators of river dynamics and coastal erosion/deposition. The stacked area chart at the bottom quantifies these changes across different zones. Spikes in Data: The high peaks represent years or specific zones where certain land types (like Vegetation or Waterbody) are most dominant. Diversification: Over time, the "stacks" become more colorful and varied, indicating that natural land is being converted into multiple uses like Fisheries, Settlements, and Agriculture. The analysis reveals that the Subarnarekha lower basin is undergoing rapid anthropization (human impact). The key trends are: Increased Sedimentation: Rising sandbars and changing estuary shapes. Urbanization: A steady rise in human settlements (red color). Economic Shift: Transformation of natural areas into fisheries and agricultural zones.

3.3. Grids wise change detection of Subarnarekha Lower Basin

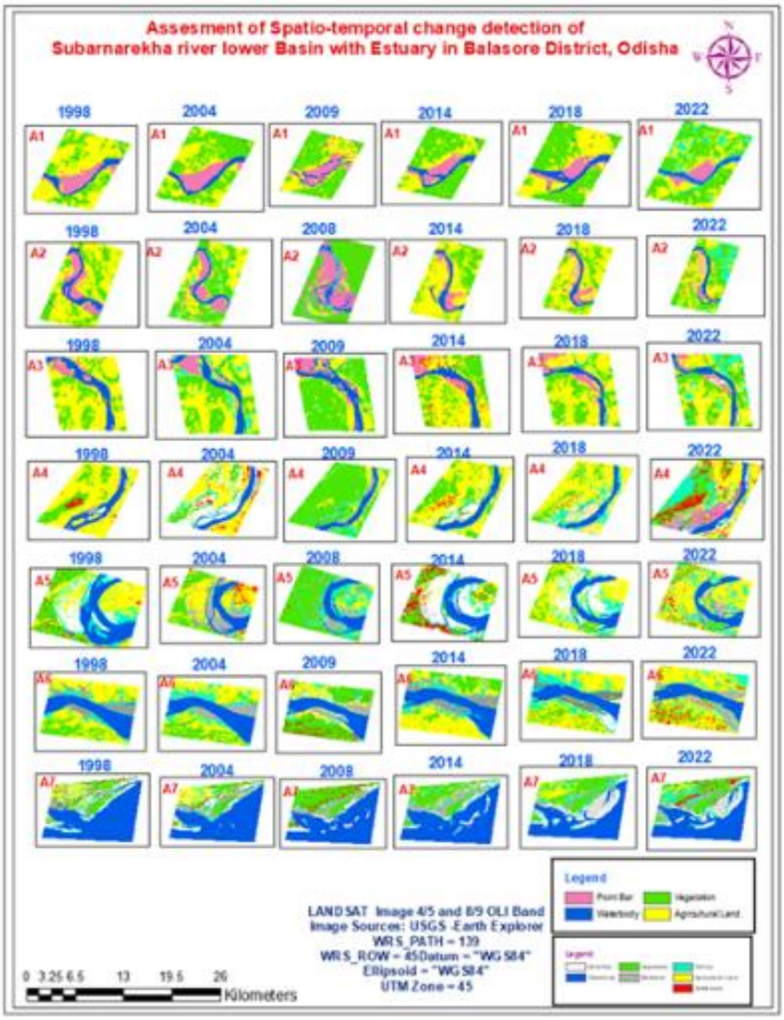


Figure 4 Change Detection of Grid Wise river Basin

3.3.1. Interpretation

Longitudinal Change Analysis (A1–A7): The map breaks the river into sections to show localized transformations over 24 years: Upper Reaches (A1–A3): These zones highlight the shifting nature of the river's path and the formation of Point Bars (indicated in pink). Over time, the size and shape of these bars fluctuate due to erosion and sedimentation. Middle Basin (A4–A5): There is a visible transition from natural vegetation (green) to human-centric land use. These areas show a marked increase in Settlements (red dots) and Agricultural Land (yellow). Estuary and Coast (A6–A7): These zones focus on the interface with the sea. You can observe the expansion of Mudbanks (grey) and Fisheries (light blue/cyan), reflecting changes in the coastal economy and sediment deposition at the river mouth.

Key Land Use Trends: The analysis uses a color-coded legend to categorize the terrain: Settlement (Red): Shows a steady expansion, particularly in the later years (2018–2022), indicating population growth and urbanization. Vegetation (Green): While still present, the density of natural greenery has been fragmented by agriculture and fisheries. Agricultural Land & Fishery (Yellow/Light Blue): These sectors represent the primary economic shift in the region, appearing more dominantly in the 2014–2022 maps. Waterbody (Dark Blue): Captures the movement of the main river channel and the coastal waters.

3.4. Technical Specifications

Data Sources: The maps were generated using LANDSAT 4/5 and 8/9 OLI Band data from the USGS Earth Explorer. Geospatial Info: The study uses the WGS 84 datum and is projected in UTM Zone 45. Summary: The maps reveal that while the river is naturally dynamic (changing sandbars and mudbanks), human activity—specifically housing, farming, and fish ponds—has significantly altered the landscape of the Subarnarekha basin over the last two decades.

3.5. Normalized Difference Water Index (NDWI)

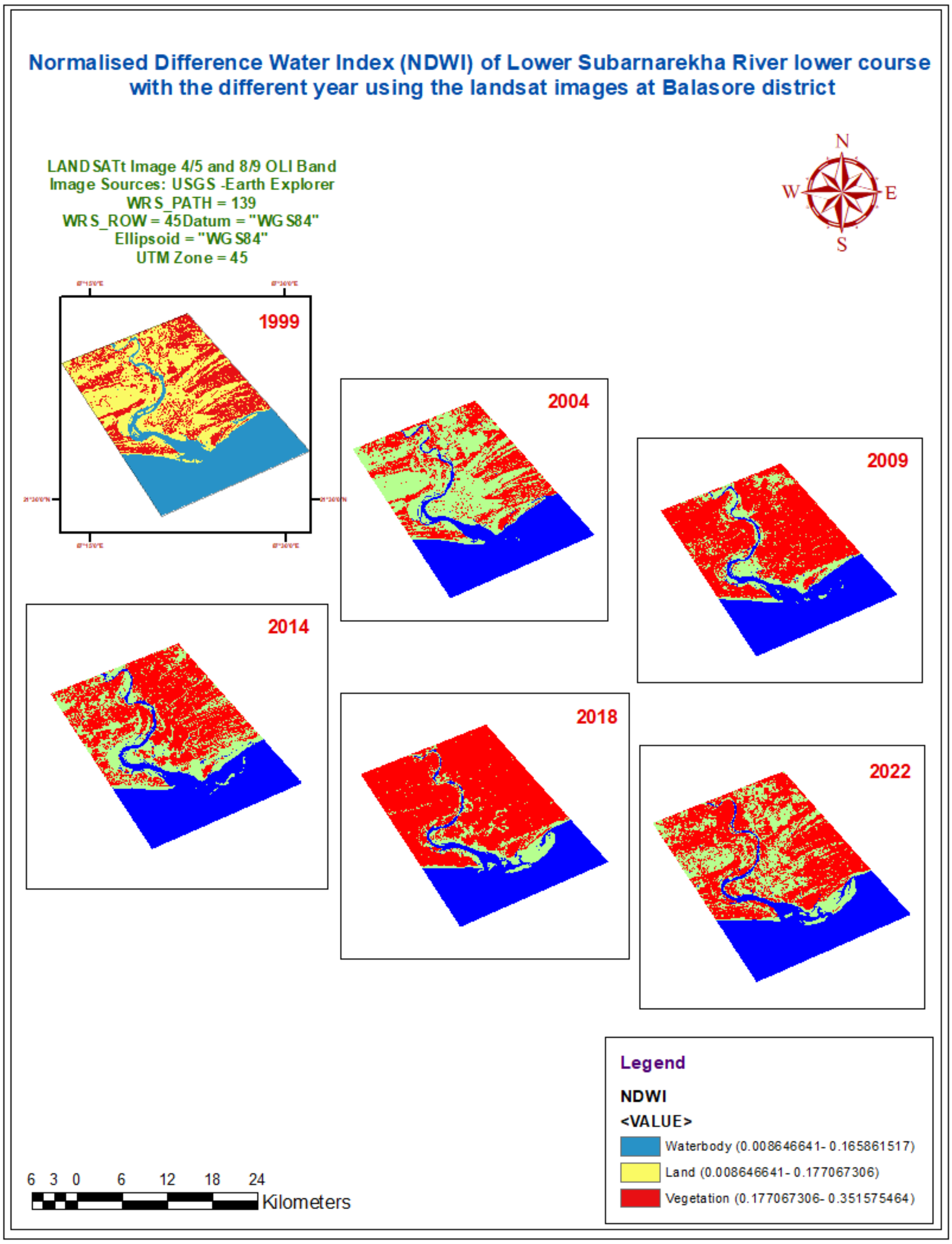


Figure 5 Normalised Difference Water Index (NDWI) Map

Interpretation

The provided images offer a detailed scientific look at the transformation of the Subarnarekha River's lower basin. Here is the interpretation of the two most recent images in English:

Land Use and Point Bar Analysis: This image provides a zoomed-in, comparative look at seven specific zones (A1–A7) across multiple years between 1998 and 2022. Point Bar Evolution (Zones A1–A3): These zones focus on the meandering curves of the river. The pink areas represent Point Bars (sand deposits on the inside of river curves). The maps show these bars shifting in shape and size, indicating natural river migration and fluctuating sediment loads. Expansion of Human Activity (Zones A4–A6): Over the timeline, there is a clear increase in red patches, which signify

Settlements, and yellow/orange patches for Agricultural Land and Fisheries. This demonstrates a transition from natural green vegetation to human-managed landscapes. Estuarine Dynamics (Zone A7): Located at the river mouth, this zone shows the most dramatic change in land-sea interaction. The grey areas represent Mudbanks, which change significantly in response to tides and river-carried silt.

NDWI Analysis :This map uses the Normalised Difference Water Index (NDWI) to differentiate between water, land, and vegetation based on light reflection. Waterbody (Blue): Represented by values between 0.008 and 0.165, this tracks the main river channel and the sea. By 2022, the blue area at the river mouth shows a distinct change in shape compared to 1999, indicating coastal deposition and channel shifting. Vegetation (Red): In this specific index, red is used to highlight healthy Vegetation (values 0.177 to 0.351). The 2018 and 2022 maps show a more fragmented red pattern compared to the late 90s, suggesting that large continuous green covers are being broken up by other land uses. Land/Sand (Yellow/Green): Represented by values between 0.008 and 0.177, these areas identify dry soil and sand bars along the riverbanks. The data suggests that the Subarnarekha lower basin in the Balasore district is a highly dynamic environment. While the river naturally changes its path and creates new land (Point Bars and Mudbanks), human encroachment through settlements and agriculture has become the dominant force of change in the last decade.

3.6. River Geometry of Subarnarekha River lower Basin

3.6.1. Lateral Shifting

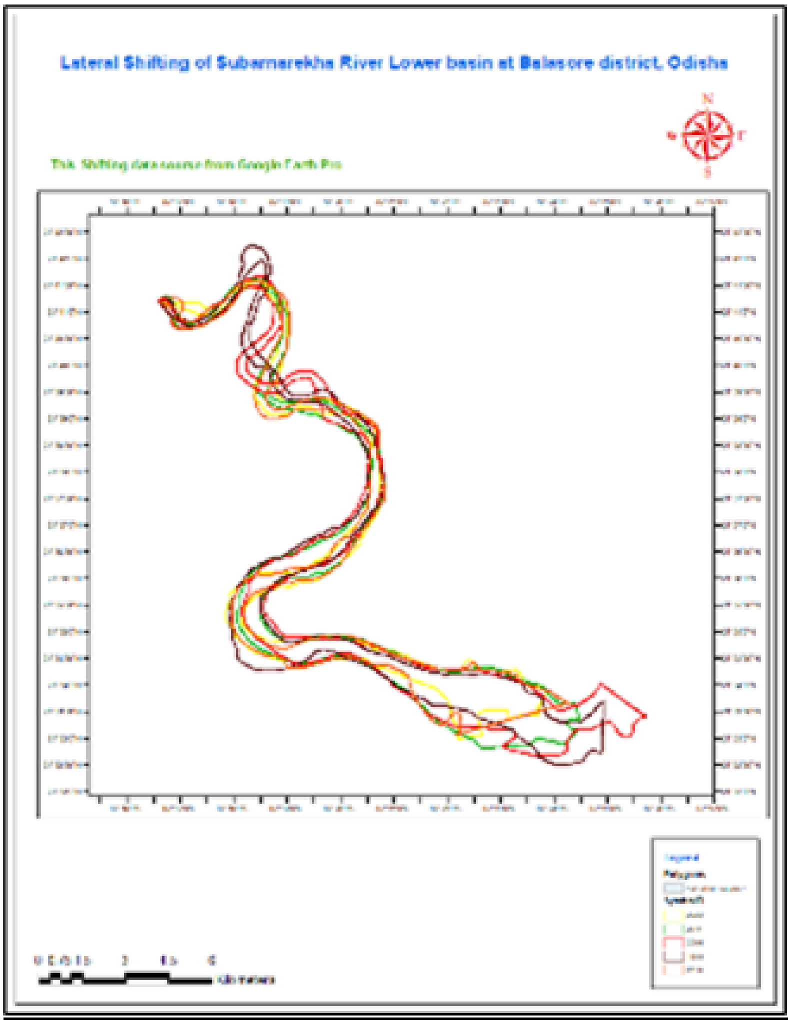


Figure 6 Lateral Shifting Status of Subarnarekha River

3.7. Sinuosity Index

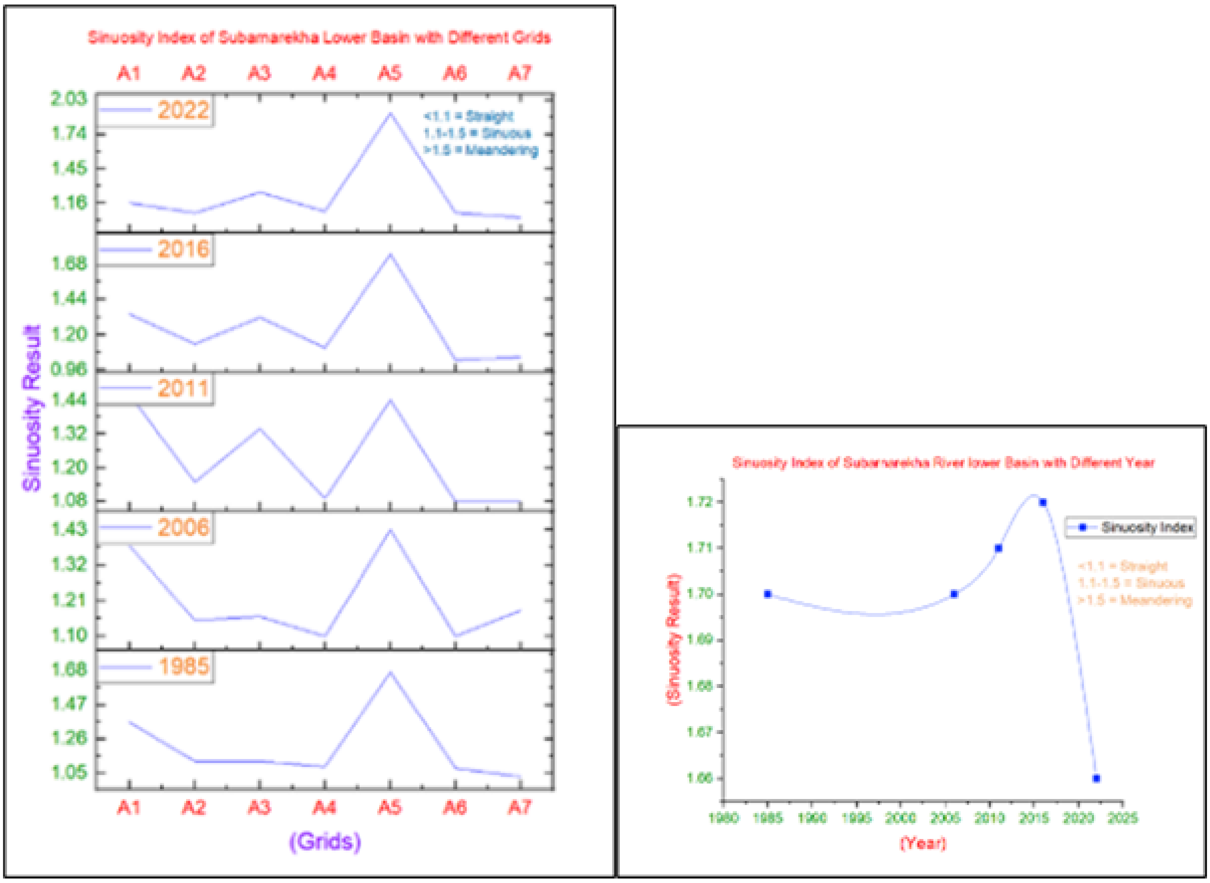


Figure 7 Sinuosity Index measure with different year

Width

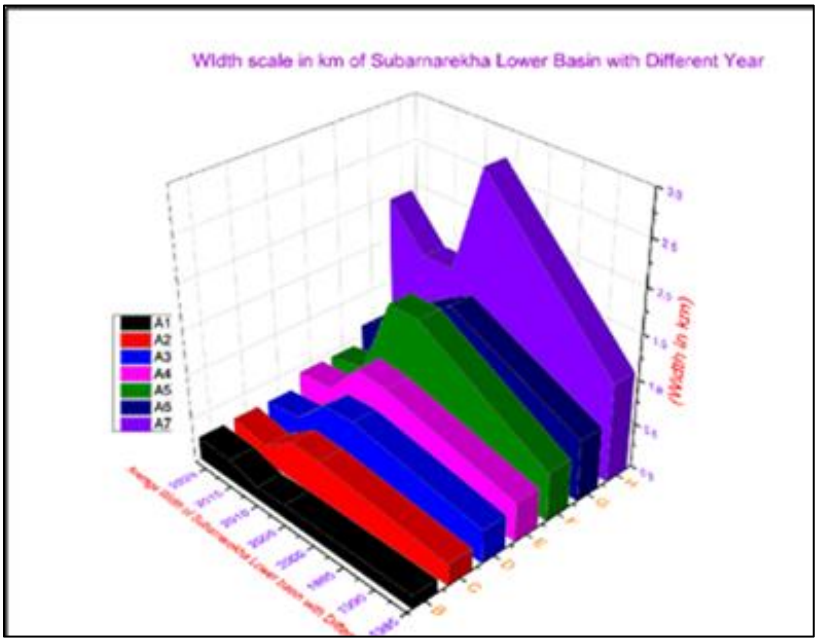


Figure 8 Width Status of Lower Subarnarekha river

3.8. Change detection of different components

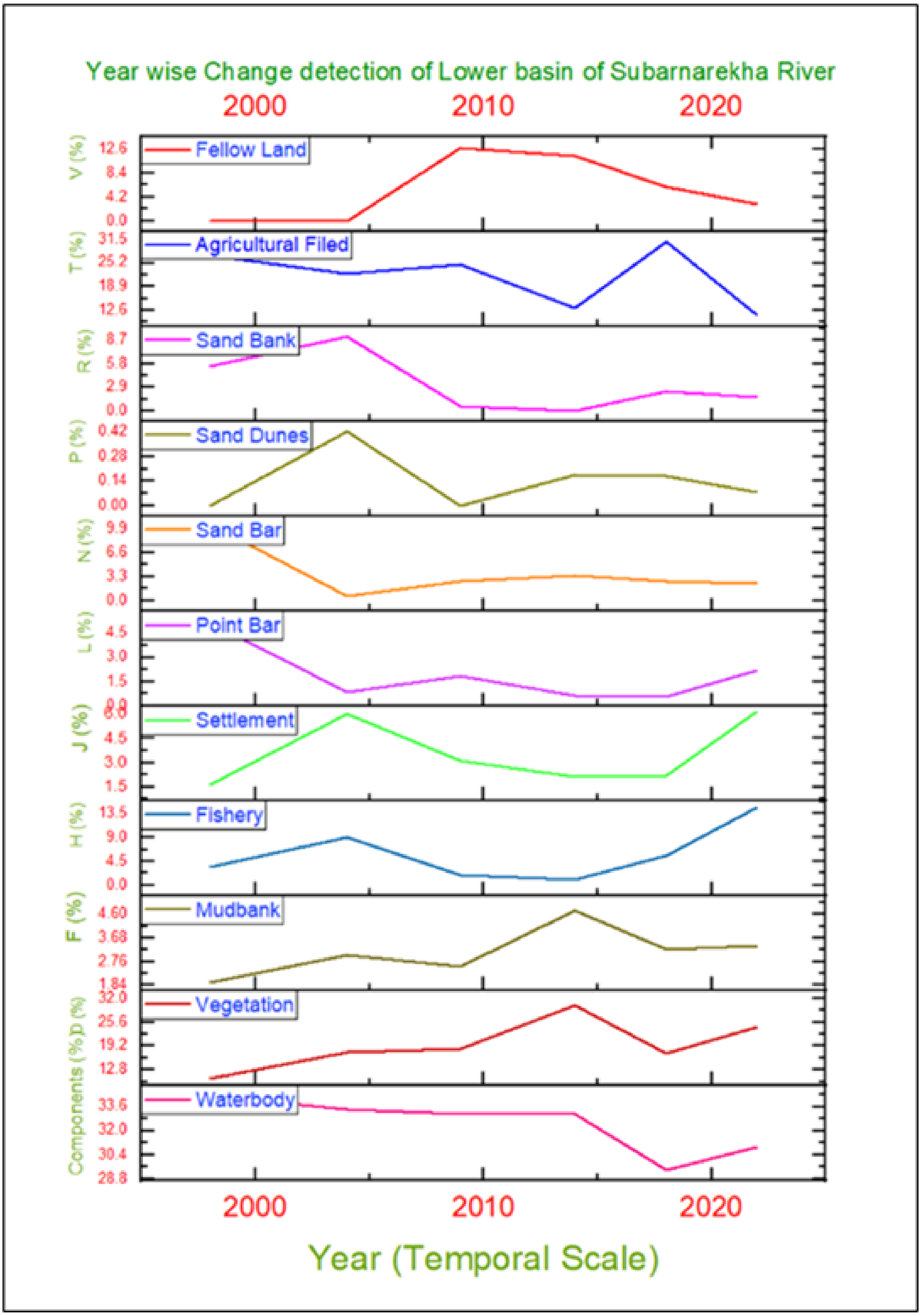


Figure 9 LULC Change Detection with different year

3.9. Grid Wise Change Detection

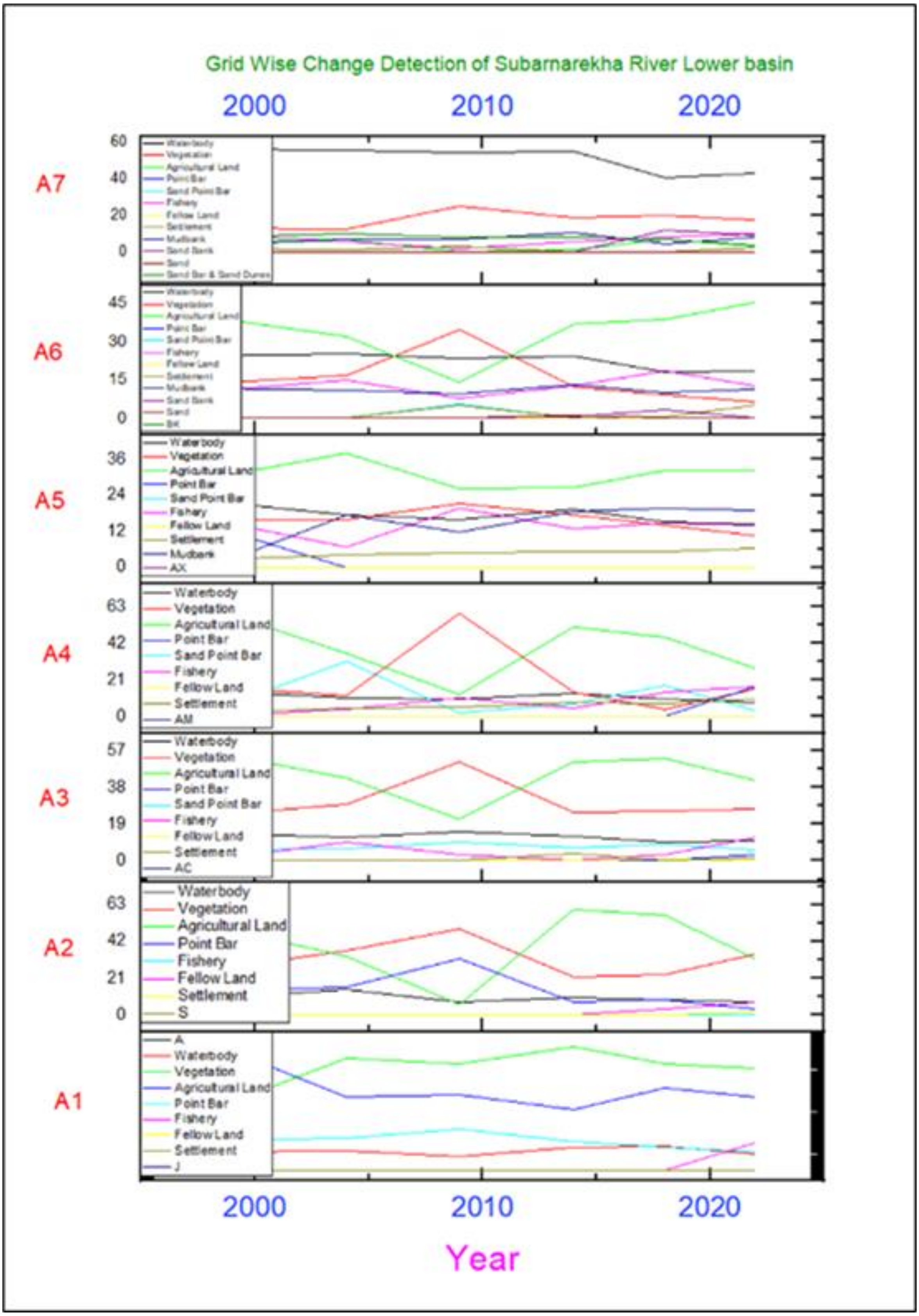
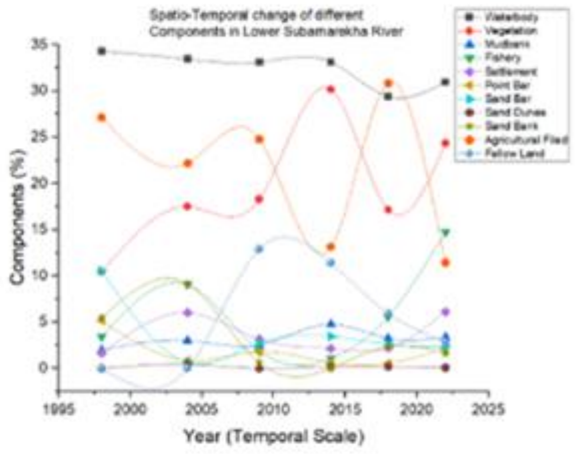
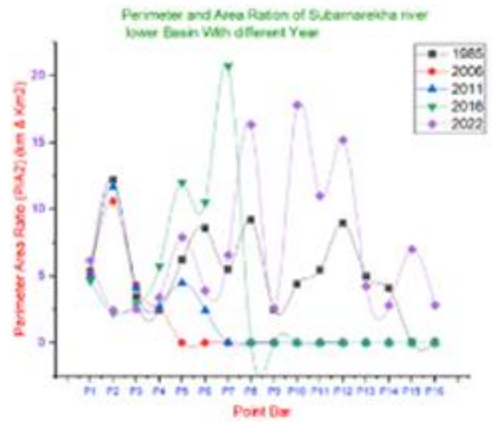


Figure 10 Grid Wise change detection of LULC cover

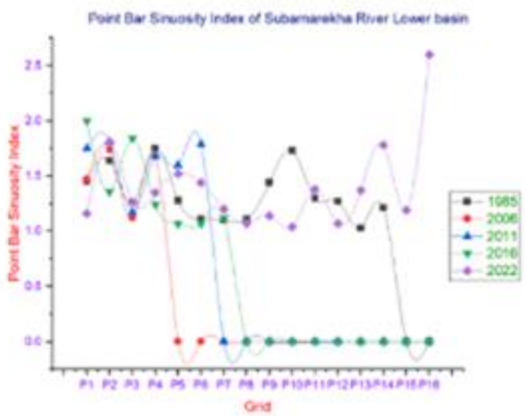
3.10. Change detection results

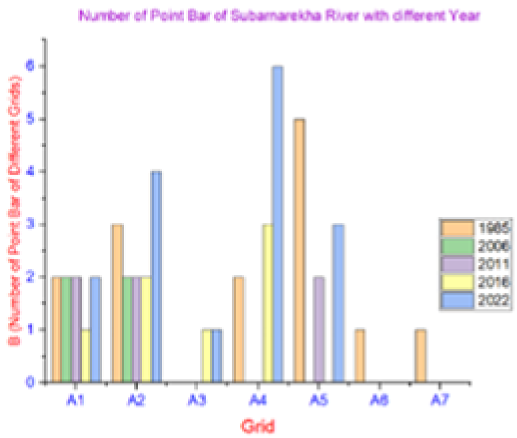
Morphological Features of Subarnarekha River

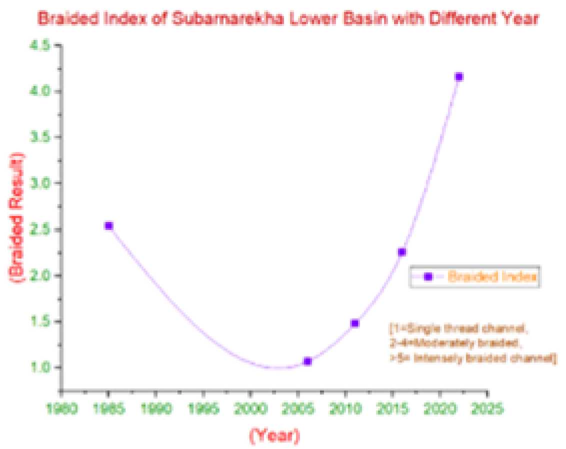


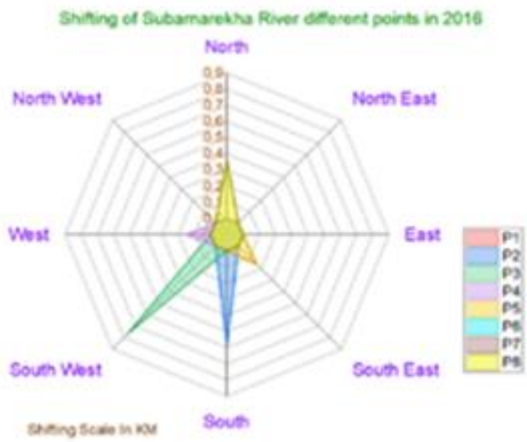


Point Bar









Braided Channel Index | *Shifting status*

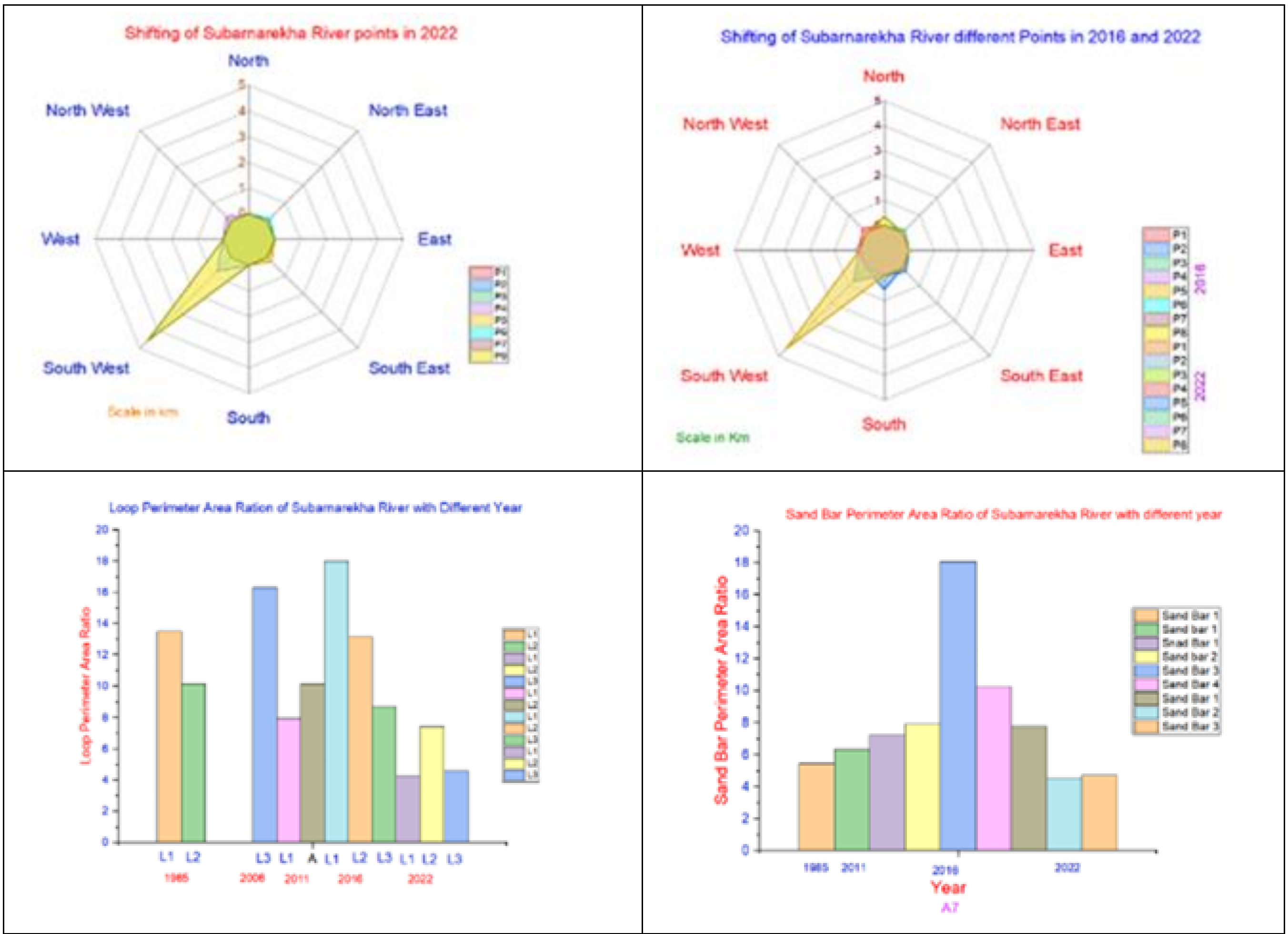


Figure 11 LULC cover change Analysis

3.11. Major Findings

Sinuosity Index (SI): A significant increase in meandering was recorded, particularly in Grid A5 and Points 5-6, with the most rapid changes occurring between 2015 and 2020.

- Braiding Index (BI): Following a gradual decrease since 1985, the BI showed a sharp increase after 2005, indicating high sedimentation.
- Water & Sediment Features: * Water volume significantly decreased from 2014 onwards.
- Sand dunes and banks have declined since 2004 due to mining.
- Estuarine Sand Bars (Grid A7) have shown a slow increase since 2005.

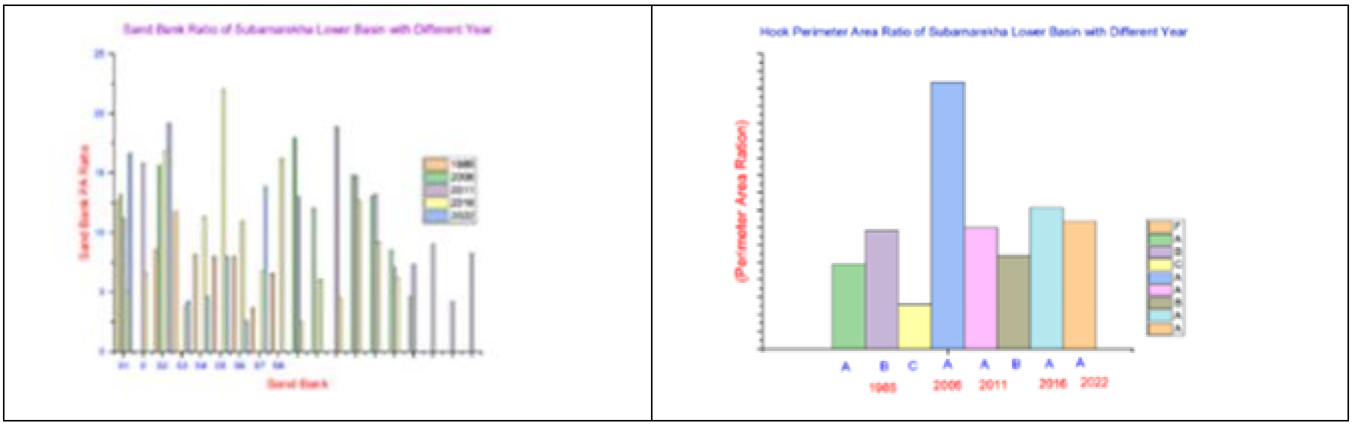


Figure 12 LULC Changes analysis

4. Discussion

The spatio-temporal analysis of the Subarnarekha River lower basin (1998–2022) reveals a highly dynamic landscape influenced by both natural fluvial processes and human intervention. River Morphology and Sedimentation: The zoomed-in maps (Zones A1–A3) show significant fluctuations in Point Bars, indicating that the river is actively meandering and redistributing sediment. The NDWI analysis further confirms this, as the waterbody shapes in 2018 and 2022 show distinct channel shifts compared to 1999. Anthropogenic Pressure: A major trend across all zones (A1–A7) is the rapid expansion of Settlements (red) and Agricultural Land (yellow). The conversion of natural vegetation into human-managed land is most evident in the 2014–2022 period. Estuarine Dynamics: Zone A7 shows the most dramatic physical changes, with the growth of Mudbanks and Sand Bars in Shallow Coast. This suggests high rates of siltation at the river mouth, which is likely a result of upstream erosion and tidal influences. Ecological Shift: The NDWI data highlights a fragmentation of Vegetation. The area chart quantifies this shift, showing that while some categories like Fisheries have grown, they often replace traditional land covers.

5. Conclusion

The present study demonstrates the significant spatio-temporal dynamism of the lower Subarnarekha River basin using geoinformatics. The integration of multi-temporal Landsat datasets and GIS-based morphological analysis reveals that the river is undergoing a transition phase, characterized by increased sinuosity and fluctuating braiding patterns. Specifically, the escalation in the Sinuosity Index between 2015 and 2020 and the rapid increase in the Braiding Index post-2005 indicate a highly unstable channel geometry. The findings highlight that while monsoonal hydrodynamics naturally drive channel migration, anthropogenic pressures—particularly intensive riverbed sand mining—have drastically altered the natural sediment-water balance. This is evidenced by the declining water volume since 2014 and the depletion of sand dunes. The steady growth of sand bars in the estuary (Grid A7) further suggests an altered sedimentation regime. In conclusion, the study emphasizes the need for immediate regulatory frameworks for sand mining and the implementation of sustainable riverbank protection strategies. The methodologies and results presented here provide a vital scientific baseline for hydrologists and environmental planners to mitigate flood risks and manage the coastal ecosystem of the Balasore district effectively.

Strategic Recommendations for Sustainable Management

The current trajectory of the Subarnarekha lower basin is geomorphically and ecologically unsustainable. Based on the spatio-temporal dynamics observed—specifically the morphological instability and the decline in water volume—the following multi-dimensional management strategies are proposed:

- Integrated Regulatory Frameworks for Sediment Management

Stringent Sand Mining Policies: There is an urgent requirement to move beyond generalized regulations and implement site-specific mining quotas based on the annual sediment replenishment rate of the river. Monitoring and Enforcement: Utilizing high-resolution satellite imagery (as demonstrated in this study) for real-time monitoring of riverbed extraction can help prevent the depletion of sand dunes and the subsequent lowering of the water table. Restoring Sediment-Water Equilibrium: Management must prioritize the restoration of the natural sediment flux to prevent the "clogging" of the estuary seen in Grid A7, which currently threatens tidal inflow and coastal drainage.

- Advanced Eco-Restoration and Riparian Buffer Zoning

Riparian Re-vegetation Programs: Implementing large-scale plantation of native species along the riverbanks is essential to replace lost vegetation. This biological "armoring" increases bank shear strength and stabilizes the fluctuating sinuosity and braiding patterns identified in Grids A1–A3. Establishment of No-Construction Zones: Based on the LULC data showing rapid settlement expansion (red patches), local authorities should enforce strict buffer zones where human encroachment is prohibited to allow for natural flood dissipation. Coastal Wetland Protection: The mudbanks and shallow coastal sandbars in the estuary require protection from over-exploitation to maintain their role as natural storm surge barriers.

- Data-Driven Informed Planning and Flood Mitigation

Early Warning Systems using NDWI: The Normalised Difference Water Index (NDWI) should be integrated into local flood forecasting models. By monitoring the seasonal expansion and contraction of waterbodies, planners can predict potential breach points along unstable meanders. Sustainable Fishery and Agricultural Practices: Since the area chart indicates a shift toward fisheries and agriculture, these sectors must be managed to ensure they do not further degrade the water quality or contribute to the fragmentation of natural green cover. Community-Led Conservation: Educating the local population in the Balasore district about the long-term dangers of sand dune depletion and flood-plain encroachment is vital for the success of any regulatory framework.

Compliance with ethical standards

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Disclosure of conflict of interest

"The authors declare that there are no conflicts of interest regarding the publication of this manuscript. We also confirm that no financial support or personal relationships have influenced the objectivity of this research."

Author Contributions

The authors confirm their contribution to the paper as follows:

- Mintu Jana : Conceptualization, Methodology, Data Acquisition (Landsat Satellite Imagery), Image Processing (MNDWI and Supervised Classification), GIS mapping in ArcGIS, Statistical Analysis using Origin-Pro 2022, and drafting of the initial manuscript.
- Dr. Dipak Bisai : Supervision, Research Design validation, Geomorphological interpretation of results, formal analysis, and critical revision of the manuscript for intellectual content.
- Miss Taniya Roy: Data curation, Accuracy Assessment (Kappa Coefficient validation), Literature review, and assistance in the preparation of figures and final formatting of the manuscript.

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Author's short Biography

I am an academician and researcher dedicated to the field of geography and environmental science. I hold a Master of Arts (MA), a Bachelor of Education (B.Ed), and a Post Graduate Diploma in Remote Sensing (RS) and Geographic Information Systems (GIS). Currently, I serve as a State Aided College Teacher at Bajkul Milani Mahavidyalaya and am pursuing my doctoral studies as a Research Scholar in Coastal Environmental Studies at Vidyasagar University. My primary research interests focus on the application of Remote Sensing and GIS in understanding coastal dynamics and environmental transitions. With several years of experience in both teaching and field research, I concentrate on analyzing the complex interactions within coastal ecosystems and the socio-environmental impacts of geographical changes. My academic journey is driven by a commitment to utilizing geospatial technologies to address environmental challenges and contribute meaningful insights to the field of coastal management. Mail id: janamintu6@gmail.com	
Dr. Dipak Bisai is an Associate Professor in the Department of Geography at Egra Sarada Shashi Bhusan College, Purba Medinipur, West Bengal. He holds a Ph.D. in Geography from Kalyani University, where his doctoral research focused on regional weather patterns and time series analysis. With over 17 years of teaching experience, Dr. Bisai has established himself as a prominent academician and researcher in the field of Earth Sciences. His primary research interests encompass Climatology, Meteorology, and Coastal Environmental Studies. He is particularly skilled in applying advanced geospatial and statistical techniques—such as RS, GIS, SPSS, and Machine Learning—to analyze temperature trends, rainfall variability, and groundwater potential. In addition to his teaching role, he serves as a Research Guide at the Coastal Environmental Studies Research Centre (affiliated with Vidyasagar University), where he supervises several doctoral scholars. Dr. Bisai has authored numerous international peer-reviewed papers and a notable textbook titled *Weather and Climate Science*. Mail Id: dbisai@gmail.com	
Authors Name: I am a dedicated researcher and academician currently serving as a State Aided College Teacher in the Department of Geography at Bajkul Milani Mahavidyalaya. My academic foundation includes an MSc, MPhil, and B.Ed, and I have achieved the distinction of being UGC JRF qualified. These credentials have provided me with a robust framework for both teaching and advanced geographical inquiry. With several years of academic experience, my primary research interests lie in Coastal Geography, Sedimentology, and Environmental Management. I am particularly focused on the application of Remote Sensing (RS) and GIS to monitor coastal hazards and environmental changes. My work aims to bridge the gap between theoretical geographical models and practical environmental conservation strategies, specifically within the vulnerable coastal landscapes of West Bengal. Mail id: Taniya.roy0801@gmail.com	