IDENTIFICATION OF GEOMORPHOLOGICAL FEATURES OF MAHANADI DELTA USING ARCGIS

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Abstract

In the present investigations, the geomorphological features of the Mahanadi Delta have been described during the year 2019 using the corresponding Sentinel-2A data. It is found that the geomorphological features varied substantially during the above period, mainly at Hukitola Bay, which is located on a barrier island north of the Mahanadi River Delta system in the State of Odisha. Important geological features identified in the delta included active distribution routes, dead or useless channels, ancient beach ridges, coastal sand, tidal flats, wetlands, and saliva. Sediments brought by the Mahanadi River are distributed by the river and marine agents, generating the vast deltaic plain. Winds and littoral flows played an important role in the reconstruction of the deltaic sediments and contributed to the development of the sea-marginal transition zone of the deltaic plain. Based on the displacement of geographical features, four major stages in the evolution of the Mahanadi delta have been identified.

Keywords: Sentinel-2A, Geomorphologic features, Delta plain, Beach ridges, Tidal flats, Coastal sand

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INTRODUCTION

The Mahanadi River delta is formed by the union of three sub-deltas that are formed by the Brahmani-Baitarini River in the north, the Mahanadi River in the middle, and the Devi River in the south. The Mahanadi River delta in Odisha is one of the east coast deltas which have been receiving wide attention in respect of their morphology, evolution, and applied aspects. There are several studies on the geomorphology of the Mahanadi delta (Babu, 1978, Sambasiva Rao et al., 1978, Mahalik, 1984, Bharali et al., 1991, Das, 1992). They recognized the ancient rivers and strandlines of different stages on the present-day delta plain. Geomorphological mapping involves the identification and characterization of elemental units in the landscape. A geomorphic unit is defined as a separate and genetically homogeneous landform produced by a particular constructive or destructive geomorphic process (Fairbridge, 1968). Each part of the land surface is the outcome of an evolution governed by its parent geological material, geomorphological processes, past and present climate, and time (Demek, 1972). Detailed information on geomorphic units and their processes in a neighborhood is extremely useful in the evaluation and management of natural resources, environmental planning, and developmental activities (Cook and Doornkamp, 1974; Crofts, 1974; Demek, 1982; Panizza, 1978). Geomorphological features are manifestations of underlying parent materials and therefore, the nature and duration of geomorphic processes that have produced the associated geomorphic units (Wright, 1993). The geomorphic position on a topo-sequence plays an important role in the classification of geomorphic units.

Remote Sensing techniques have become the most efficient tools for geological, structural, and geomorphological studies and their mapping because of their synoptic view and multi-spectral and multi-temporal capabilities (Krishnamurthy and Srinivas, 1996). Geomorphic units have a specific set of characteristics that determine their image signature. High-resolution satellite data area reliable source for delineating and generating comprehensive and detailed inventories of geomorphic units in a neighborhood (Mukerjee, 1982). The geomorphological mapping of a terrain, and analysis of their processes also help in soil resource mapping, groundwater potential zone identification, landscape ecological planning, hazard mapping, and other environmental applications (Reddy et al., 2001). In the present study, the Mahanadi River delta has been selected for the delineation and characterization of geomorphological units using Sentinel-2A satellite imagery. The Remote Sensing approach has been used to infer various geomorphic features in the present study.

The Study Area

The Mahanadi Basin is one of the five sedimentary basins in the Indian subcontinent. The Mahanadi River delta lies between longitudes 80°28′ & 86 ° 43′ E and between latitudes 19°8' & 23°32' N and extends for about 9,810.7642 km^2 in Odisha (Figure 1). This delta has four main types of mainland territories: fluvial, fluvio-marine, marine, and aeolian landforms. The development of the arcuate shape of the delta has four stages due to sea violations and regression processes (Mahalik et al.,1996). Kumar et al., (2003) identified four phases of delta progradation based on strandlines and palaeo-deltaic lobes of the Mahanadi River. However, limited regional studies have been conducted using geospatial technology in this delta.

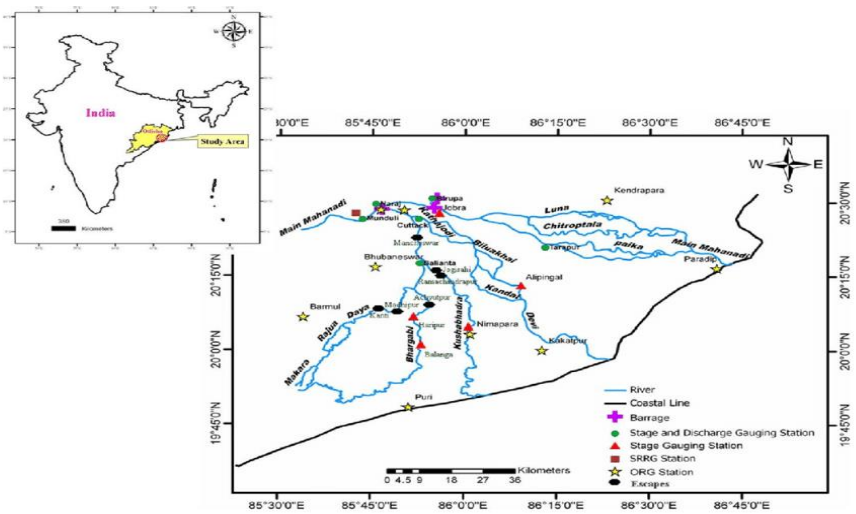

Figure 1. Location Map of the Mahanadi Delta.

METHODOLOGY

The Sentinel-2A satellite data for January 2019 were collected at a scale of 1:750,000 using ArcGIS version 10.5, and from the topographical sheets prepared by the Survey of India. Surface lithological analysis of the study area by visual description of satellite data is based on a geographical quadrangle map prepared on a scale of 1:750,000 (GSI1978). The boundaries of the geographical units are modified based on image features and field observations.

Visual interpretation techniques that support the tone, texture, shape, drainage pattern, color, and differential cutting properties of satellite images combined with collateral information were used in the imaging of the geomorphic units. Appropriate field inspections have been conducted to obtain information on geomorphic units and to determine the relationship between the image elements and geomorphic unit properties. The different types of land use/land cover identified from satellite images were also considered in the imaging of the geomorphic units. The boundary description of geomorphic units corresponds to changes in topographic slopes, relief patterns, crest type, drainage pattern, and image features. Linear, equalization, and route improvement methods were used to analyze satellite images for a better description of geographical units. The drainage, contour, and delineated geological units were overlaid on Sentinel-2A satellite imagery to better illustrate and classify different geomorphic units. Subsequently, detailed geographical analysis has been conducted to identify their features and processes in conjunction with image features. The drainage parameters were analyzed to assess their impact on the origin of geological units, characteristics, and their processes. Vector layers have been imported to GIS to produce geographical maps. Diverse geological processes were analyzed, supporting the geomorphic unit position, slope, and morphometric properties of the unit. Field inspections were conducted at selected sites to verify the boundaries and characteristics of the geomorphic units.

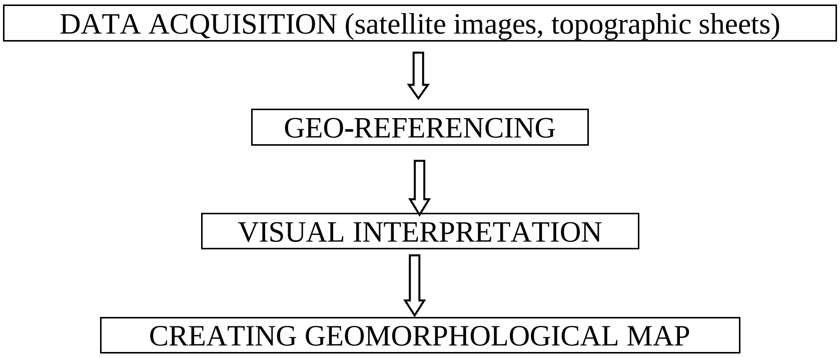

Figure 2. Flowchart of Methodology

GEOLOGY OF THE STUDY AREA

The geology of the Mahanadi River delta is shown in Figure 3 and the stratigraphy is presented in Table 1. The eastern continental margin of India refers to as the passive margin that emerged in response to continental rifting. There is a regional tectonic element on the east coast of India. During the late Jurassic-early Cretaceous, India seceded from the southern supercontinent of the Gondwanaland but split during the Permeo-Triassic before the continental partition. Rift initiation occurs in the form of linked rift triple junctions. One of these rifts north of the Mahanadi Basin is the exploitation of the Mahanadi River system (Mahanadi Graben). These algogens, which indicate favorable locations for the development of flywheel systems, have provided great drainage basins for the progressive cutting of the Cratonic Antipura. Mainly continental sediments of the Upper Polyzoic and Mesozoic eras were deposited and preserved in this algogen the great river Graben. Mahanadi Graben's rifting continued in the Jurassic and Early Cretaceous.

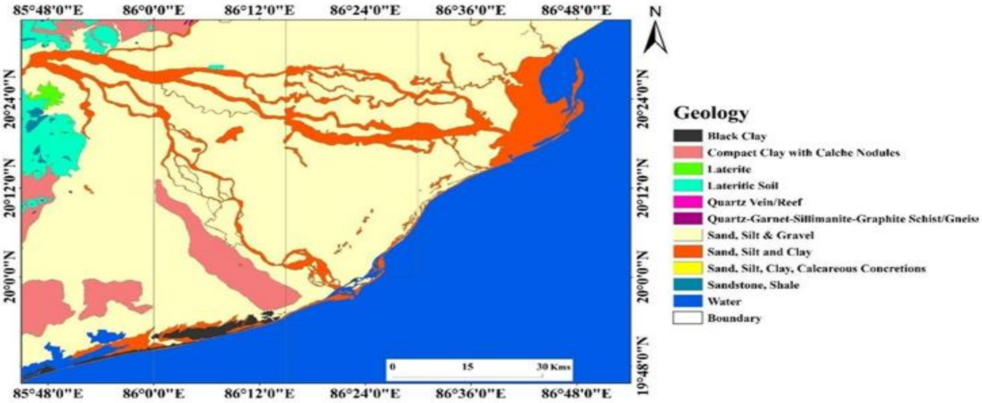

Figure 3. Geology of the Study Area

Table 1. Stratigraphy of the Mahanadi Deltas

Age	Formation	Lithology
Holocene	Puri formation	Coarse sand and gravel with laterite fragments and Recent marine shells.
Late Upper Pleistocene	Bhagbanpur Formation	Limestone-bearing sand with minor shell fragments, mostly weathered.
Early Upper Pleistocene	Rench Formation	Yellowish brown sand and gravel of fluvial origin
Unconformity		
Mio-Pliocene	Tolapada Beds	Dark grey sediments with well-preserved organic shell remains and ferruginous oolites.
Unconformity		
Archaeans	Eastern Ghats crystalline rocks	Khondalites, charnockites and granites.

Available regional geographical data indicate that the basement of the Mahanadi inland and shallow offshore area belongs to the continental type of present north of the Eosin Hinge Zone, and maybe more of the oceanic type to its south. Different parts of the basin may have a transition zone of varying widths from continental to oceanic crust. The continental basement is composed of granulites of the Eastern Ghats and the gneisses of the Pre-Cambrian era. The Mahanadi wells have not yet been drilled in the seabed but are likely to be associated with early Cretaceous volcanic rocks encountered in a few drilling wells. The upper age limit of the seabed may be early Cretaceous. The Bougainville anomaly map indicates that the oceanic opening line is parallel to the coast, indicating that rifting and amplification are at least somewhat controlled by the NE-SW Trending Achaean Eastern Ghats trend. NNW-SSE trending errors divide the basin into inverted blocks. This strike caused significant lateral movement along with slip defects during basin development. As mentioned earlier, both the basin strike and the alignment of the eosin keys take a sharp turn towards NE with one of these defects, indicating post-eosin movement.

The oldest sediments on the banks of the Mahanadi Basin date back to the early Cretaceous period of the late Jurassic. These sediments cover the Precambrian basement rocks directly along the western basin margin near the city of Cuttack and are hidden in places under a wide cover of alluvium of laterite. Coarse grain sandstone, subordinate shales, and thin coal stripes from the late Jurassic to the early Cretaceous were encountered in deep wells drilled in depressions. These sediments are thought to have been deposited under occasional ocean intrusions. This range meets several streams of primary volcanic rocks of various thicknesses. However, the shallow offshore part of the basin experienced more intense volcanic activity despite some interruptions. Characterized by basalts, tuffs, and intertrappeans, this volcanic range is exceptional in the pre-Cambrian basement consisting of sub-aerial and sub-aquatic properties. The thickness of the volcano varies from 25 m in NMD (North Mahanadi Delta)-3 to 850m in NMD-7, indicating the diversity of volcanic activity over the basin. Based on palynological evidence, these volcanoes are associated with the Rajmahal Trap and date back to the Neocommian-Optian age (133–144 Ma). The accumulation of early Cretaceous sin-rift sediments in the relief of fractures, complicated by fracture development, explains their mixed and heterogeneous lithology as well as vertical and lateral variations in the basin.

MORPHOLOGICAL FEATURES OF THE MAHANADI DELTA

The geomorphology of the Mahanadi delta is represented in Figure 4. The four major landforms in the study area correspond to appositive relief: beach ridges (106.46 km^2, 3.31%), beach ridges and dune complex (57.62 km^2, 1.79%), planned beach ridges (78.08 km^2, 2.43%), and beach ridge and wale complex (872.12 km^2, 27.15%). Other small beaches include the following: beaches (10.98 sq. km^2, 0.34%), relict beach ridges (16.75 km^2, 0.52%), four tidal flats (1.73 km^2, 0.05%), intertidal flats (1.44 km^2, 0.04%), supratidal flats (0.94 km^2, 0.03%),mangrove wetlands (33.56 km^2, 1.04%), mud flats (30.99 km^2, 0.96%), salt flats (9.02 km^2, 0.28%), swales (69.34 km^2, 2.16%), backwaters (0.5 km^2, 0.01%), and spits (2.8m^2, 0.09%). Deltaic plains (1405.84km^2, 43km^2, 76%), floodplains (152km^2, 4.73%), point bars (16.92km^2, 0.53%), sand bars (25.57km^2, 0.8%), paleo channels (80.53km^2, 2.51%), convoluted scars (0.62km^2, 0.02%), and prehistoric LaRouche (5.1km^2, 0.16%) also occur. The map of the area shows the beach of the fluvial marine geomorphic landmarks that were mapped by the ridge and swale complex delta.

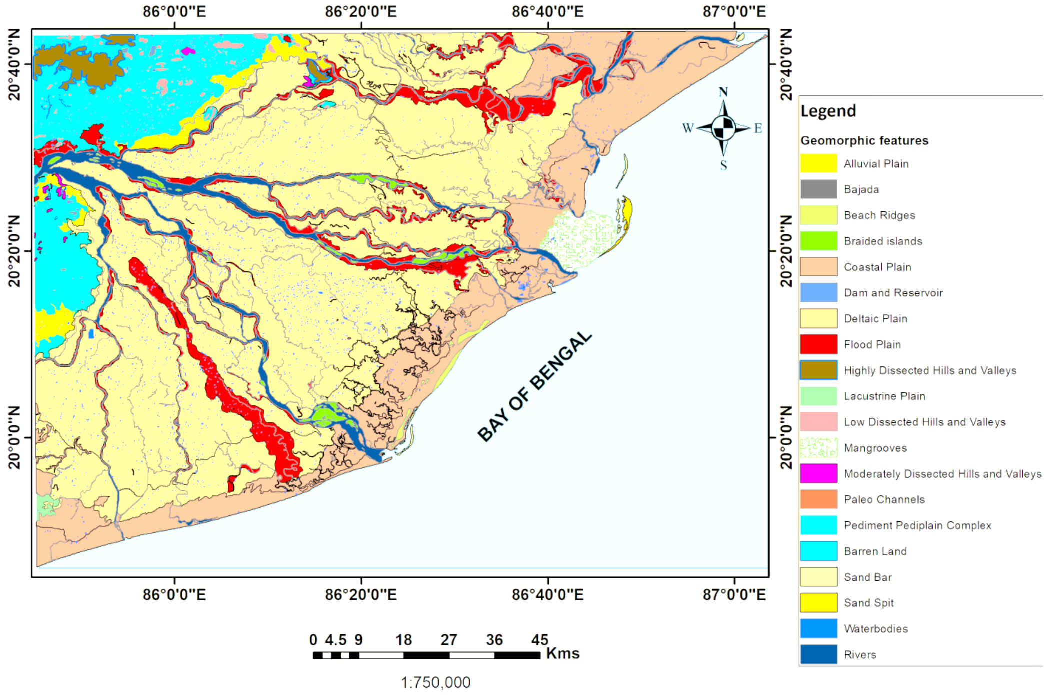

Figure 4. Map Showing Geomorphological Features of the Mahanadi Delta

Geomorphology of Mahanadi delta has been studied from satellite images, aerial photographs, topographic maps, and from field mapping along suitable traverses (Mahalik et al., 1996). Subaerial weathering and mass wasting processes generated the laterite peneplains, residual hillocks and monadnocks; fluvial processes produced distributary channels, palaeo-channels, doabs, channel bars, point bars, floodplains, natural levees, doab drainage channels, swamps, and ox-bow lakes; marine processes (waves, tides, littoral drift) generated beaches, beach ridges and palaeo-beach ridges, tidal creeks, tidal swamps, tidal flats, spits, offshore bars, bays and lagoons; and aeolian processes (marine and fluvial environments) produce beach dunes, river bed dunes, and overbank dunes.

The different morphological features of Mahanadi delta are discussed under three broad sectors: (i) Delta head and delta margin, and delta proper consisting of (ii) Central deltaic region, and (iii) Sea marginal region (Figure 5).

Morphology of the Delta Head and Delta Margin

At the delta head, the Mahanadi River splits into two major channels viz., Kathjodi on the south and Mahanadi on the north. Mahanadi River flows in a lateritic peneplain dispersed with isolated hills or hill ranges of khondalite and charnockite rocks before entering the delta head. An outlier of Gondwana rock occurs at the delta head proper forming hillocks through which the river cuts through. The Chandaka hill is an important highland which is underlain by the Gondwana rocks. Low-lying depressions occur in the hilly regions of the delta head where many small wetlands known as *Pata* are formed.

Morphology of the Delta Proper

From Upper Pleistocene time, the process of sedimentation in the delta continues till now bringing out many changes in the palaeo-geography and palaeo-environment which have been deciphered from the multiple morphologic features and subsurface sediment profile that are encountered in the bore holes. The delta plain from the delta head to the sea can be divided into two major regions, one is the upper deltaic plain, and the other is the lower deltaic plain (Figure 5).

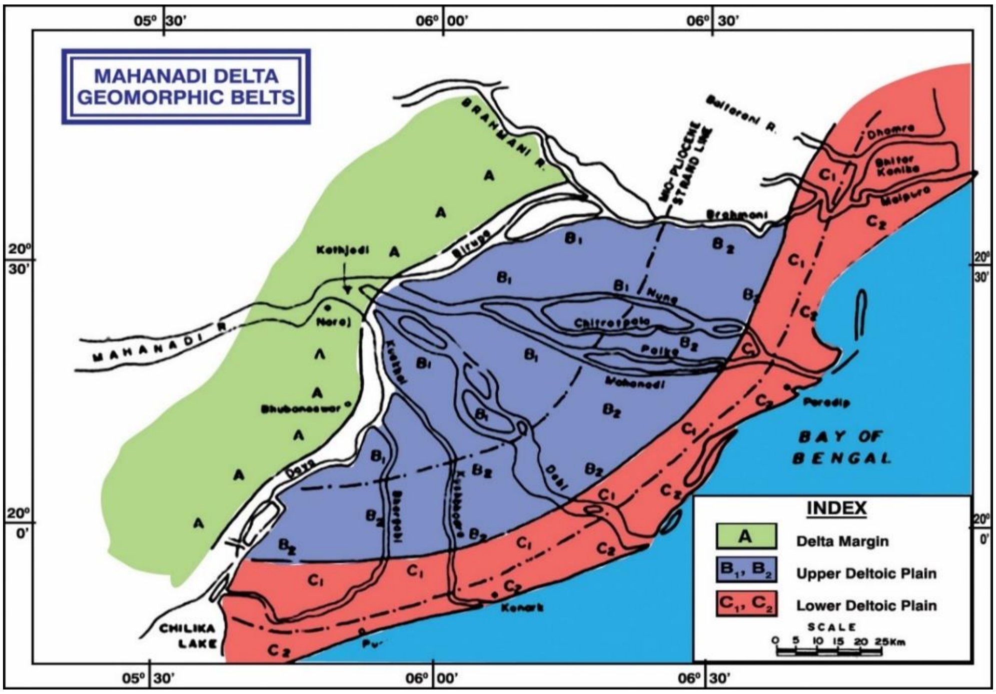

Figure 5. Geomorphic Belts in Mahanadi Delta.

The Upper Deltaic Plain

The most important morphological feature of this region is a fanning distributary system making a fan angle of 140^0 and the intervening doabs (Figure 5). The area between the distributary channels is called a doab. Natural levees are seen fringing the distributary channels. In the centre of the doabs, several drainage channels and back swamps are present. The Kuakhai River, a tributary of the Kathajodi River, originates near Cuttack, at a bed level of 2 to 2.5 m. When the flood in the Kathajodi River reaches 2500 to 3000 cusecs, the bed increases the flow of the Mahanadi system. The Kuakhai River has three distributaries: Kushabhadra, Daya, and Bhargavi. The gravity profile of the steep gradient from Delang to Puri indicates that there is a steep gradient between the two ranges of the NE hills within the SE, allowing the Daya River to flow almost directly into the ocean (Mahalik, 2006). As the Bhargavi River flows into the alluvium and changes its course over time, the fluvial shines as it encounters sedimentary deposits. New alluvial plains have developed to the south, indicating that the delta grew towards the south. Geotechnical studies have shown that the ground conditions beyond the right bank of the Daya River are due to the presence of alluvium. The green belt of cultivation was developed west of Daya River. The drainage channels that are active and responsible for the expansion of the Daya River system are responsible for the formation of the Rajua, Makara, and Vekia channels beyond the delta's southern territory. Expansion of the Bhubaneswar city and new channels called the Gangawa Canal add significant water to the Daya River. These rivers are anatomized at the tail end of the southern coastal deltaic zone. Rivers Daya and Bhargavi are converted into multichannel rivers in alluvial plains and are formed by oscillation processes and several drainage channels due to bypass or splitting.

The Lower Deltaic Plain

The part of the delta lying close to the present coast is known as the lower deltaic plain (Figure 5). The inland part of this plain is characterized by low-lying wet plains, tidal infected rivers, tidal creeks, swamps, ill-drainage of land, non-development of levees, etc. The mouth region of this area shows palaeo-channels, palaeo-creeks, and palaeo-beach ridges. Tidal rivers, series of beach ridges, intervened by tidal creeks, tidal swamps, beaches, and lakes. The sea coast consists of sand spits, sand bars, embayments, active beaches, tidal swamps, and river mouths. The nature of the current retrogradation of the coastline can be traced through the mouths of the Mahanadi and Devi rivers. The Southern Mahanadi system has several aging routes from the 47^{th} to the tail, such as Ratnachira, Sunamunhi, and Bhargavi. A new sub-system (Makara River) is being built south of the delta that originates from the Daya River. As the city of Bhubaneswar develops and extends the Daya River, much of Gangua Canal is flooded during the rainy season. The creation of the Anabranch River, the rise of the bed of the Malaguni River, and the diversion of the mainstream of the Daya River through the Makara River marks the expansion of the South Mahanadi Delta (SMD) towards further south. The tendency of the Rana River to join the Malaguni River from the top of Naraj has been observed during the past 50 years when flooding by the Daltola Earth Mass (near Khorda).

Drainage Channels

Delta also has channels that accumulate in the floodplain due to rain or overflow from active distribution channels during floods, which are called "drainage channels". They occupy the lowest forms of the flood plain and flow into the sea. Many of these important drainage lines are in the floodplain, but they have a very low sediment load, which is a highly sensitive material. Important drainage lines in the study area are: Gobari between Birupa and Mahanadi; Hansua between Mahanadi and Kathajodi-Devi; Kadua between Prachi and Kushabhadra; and Dhanua between Kushabhadra and Bhargavi.

Flood Plains

The area between the two distribution lines is a lowland flood plain. It has a minimum elevation along the axial zone and a very low gradient toward the sea. The drainage channel occupied the axial zone. As floodplains have degraded in these areas, natural drainage has reduced in wetlands and lakes.

Drainage Pattern

The drainage pattern in the Mahanadi delta (Figure 6) is radial and parallel. The distributary channels fan out from the delta head to northeast, east, southeast, south, and southwest. Most of the rivers take significant right-angled turns, clockwise or anticlockwise, close to the coast before they enter the sea. The main Mahanadi and Devi channels turn at right angles anticlockwise and run parallel to the coast. The Kushbhadra, after a straight southerly course, turns eastwards and meets the sea. The Bhargavi River flows south and then takes a right angle turn clockwise and drains into the Chilika lake. The bends in the Mahanadi and Devi rivers are thought to be because of longshore currents and ancient beach ridges, whereas the bends in the Bhargavi and Kushbhadra Rivers are due to the positive topography of coastal sands between Puri and Konark.

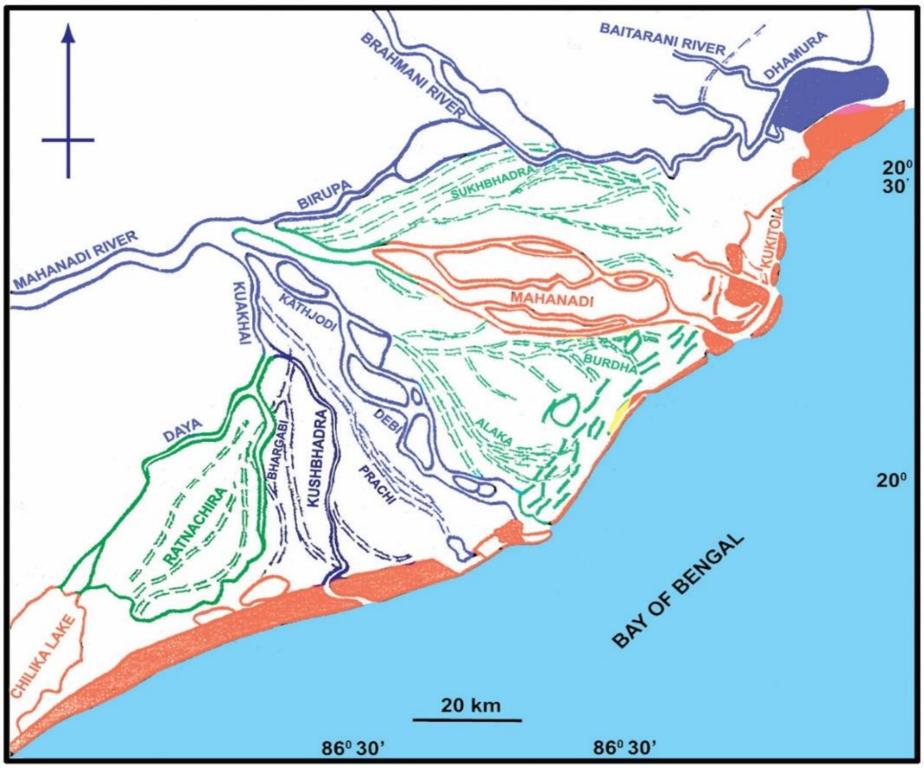

Figure 6. Drainage Pattern in the Mahanadi Delta.

Tidal Flats and Mangrove Swamps

Tidal flats and swamps are recognized all along the coast of the Mahanadi delta. Most of them have a local extent near the mouths of distributary channels and in the swales between adjacent beach ridges. Extensive tidal flats and swamps are found near Hukitola Bay and Paradeep.

Coastal Sands and Dunes

Widespread coastal sand bodies occur along the coast in the southern part of the Mahanadi delta. Thes coastal sand bodies are made up of wind-blown sands covering the muddy deposits of a tidal flat or swamp origin and parabolic dunes are observed over them.

Beaches and Sand Spits

The seaward margin of the delta plain is marked by a straight and continuously regular shoreline with a sandy beach. Prominent spits are observed near the mouths of the Mahanadi and the Devi Rivers.

Palaeo-Beach Ridges

Several ancient beach ridges are found in the marine marginal sector of the delta. They are well observed in satellite images and aerial photographs. These are low sandy ridges running nearly parallel to one another. An unusual beach ridge exists near Ghorida village in southwest delta lying about 41 km from the present sea at Puri.The seaward margin of the delta plain is marked by a straight and continuously regular shoreline with a sandy beach without cliffs. Prominent spits occur near the mouths of the Mahanadi and Debi rivers**.** The event and extension of spits towards the north are due to a northerly moving littoral drift, which has constantly pushed the mouths of rivers towards the north. Thus, the rivers Mahanadi, Debi, and Kushabhadra take a northerly course parallel to the shoreline for a few kilometers before draining into the ocean. During intensive storms and high Rood stages, such spits are eroded and cut across by the rivers, which thereby flow directly into the ocean. The Hukitola Peninsula has now been cut at several places.

Paleo-Lakes

Lake formation is a common feature along the coast. This is due to the embalming of some part of the sea by the spit and the bars formed along the shore. The Mahanadi Delta contains lakes of various ages. The oldest are the marshes of the Ersama region, like the Buddha stage. Samang Lake, Saar Lake, and Jatadhar Muhan Prachi platform represent the lakes. The last generation lakes are represented by Chilika Lake and Hukitola Bay.

Paleo-Tidal Flat

Tidal flats and tidal creeks of various ages were also observed. The oldest tidal flats are far from the sea and are now actively used in cultivating paddy. The next generation of tidal flats is composed of flat open grass-covered land. The latest tidal flats are close to the ocean, where the tide is swept up and the mangroves cover the area.

Sand Spits

The sea margin of the delta plain is a steep and continuous simple beach without hills along the sandy beach. Saliva forms near the mouths of the Mahanadi and Debi rivers. The development and spread of the saliva to the north are due to the littoral drift moving northeast, constantly pushing the mouths of the rivers towards the north.

Mangroves

Tidal flats and swamps were identified along the banks of the Mahanadi Delta. However, most of them are localized around the mouth of the distribution routes and between adjacent beach ridges. Extensive tidal flats and swamps were found near Hukitola Bay and Paradip. Thus, the Mahanadi and Debi rivers take a northeastern course parallel to the coast before entering the rough sea. In intensive storms and high Roo ndstages, such as spit, they are depleted and cut off by rivers so that they fall directly into the sea. The Hukitola Peninsula is now cut off in many places.

Conclusions

Analysis of Sentinel-2A imagery data, improved drainage and geological information, and field surveys helped identifying accurately and in describing the different geographical units in the study area. The Mahanadi River, which forms a huge catchment basin, flows into the Bay of Bengal, and built up a delta during the late Pleistocene-Holocene period. The sediments brought by the Mahanadi River and its distributaries are distributed by river and marine agents, giving rise to a broad deltaic plain. Wind plays a supporting role in reworking the deltaic sediments. The rivers, and therefore, the coastline, have changed their positions over time. Thus, the radiating distributaries of the rivers of the delta have changed their course during the expansion of the delta. The strandline has therefore, receded progressively offshore owing to the outbuilding of the delta. Supported by the disposition of ancient channels and ancient beach ridges, four stages were recognized within the Mahanadi Delta through fluvial and marine processes. Processes that previously operated in the delta are still operational, creating new landforms and modifying old ones. The study of the geomorphological features in the Mahanadi delta is highly helpful in delineating the evolution and drifting of the delta which helps in the prospecting for the hydrocarbon potential zones in it.

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