High-Resolution Topographic Mapping Using Remote Sensing and GIS to Identify Geomorphic Controls on the Location of Ancient Civilization Sites in the Indian Sundarban Delta

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By

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Statement of Originality

I **Ms. Sanjibani Banerjee (D-7/ISLM/44/18)** registered on **20/02/2018** do hereby declare that this thesis entitled **"High-Resolution Topographic Mapping Using Remote Sensing and GIS to Identify Geomorphic Controls on the Location of Ancient Civilization Sites in the Indian Sundarban Delta"** contains literature survey and original research work done by the undersigned candidate as part of Doctoral studies.

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CERTIFICATE FROM SUPERVISOR

This is to certify that the thesis entitled " **High-Resolution Topographic Mapping Using Remote Sensing and GIS to Identify Geomorphic Controls on the Location of Ancient Civilization Sites in the Indian Sundarban Delta**" submitted by **Ms Sanjibani Banerjee** who got registered (registration no **D-7/ISLM/44/18** dated **20/02/2018)**. his/her name under the Faculty of Interdisciplinary Studies, Law & Management for the award PhD (Arts/Science/Engineering/Pharmacy) degree of Jadavpur University is absolutely based upon his/her own work under the supervision of **Prof. Dr Sugata Hazra** and that neither his/her thesis nor any part of the thesis has been submitted for any degree/diploma or any other academic award anywhere before.

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Table of Content

List of Tables

List of Figures

Abstract

Early human settlement in the lower Ganga delta, commonly known as the Sundarban delta. has occurred over the past 7,000 to 6,000 years up to the colonial times, with archaeological evidence dating back to 500 BCE (2,000 Y.B.P). This offers a fresh perspective on the reinterpretation of ancient historical development, taking into account the changing climate, river avulsion, and changing geomorphic patterns, which align with the development of the Sundarban region of upper Holocene delta of Bengal.

The first objective of this study to attempts to collate and map the already established archaeological sites in the lower Ganga delta plain using a state of art Remote Sensing and GIS techniques. Study of palaeochannel and palaeo- levees is one of the main objectives to estimate the palaeo-riverine environment and impact of changing river course on ancient civilization. Beside this, it is felt necessary to find the distributional pattern of ancient civilization, if any to make a link with existing known archaeological site with surface elevation. The study of geomorphic features, changing course of rivers and paleogeography and palaeoenvironment from available secondary data and aps of the lower Bengal delta lain is another objective of present study. Several techniques of digital elevation modelling, mapping of palaeo- channels, estimation of relative water saturation, landcover mapping have been employed to understand the distribution of archaeological remains of historic settlements and their relation with geomorphic features and changes. This study assesses the influence of ancient river on early historic civilization especially on Chandraketugarh on the delta, an early historic port city connected with European and Asian countries with trade. This study also assesses the sequence of palaeochannel development of Padma nala and river Bidyadhari that would flow in an around Chandraketugarh to find out the main connecting channel with port city. Modern remote sensing data analysis techniques like NDVI and PCA have also been applied in present study to find out the sequence of palaeochannel development. Details of archaeological artifacts and nature of findings were collected from the State Museums and nearest site museum of Chandraketugarh and also from private collections. Besides, some expert opinions have also been taken to assume knowledge about the stylistic age of artifacts. As the southern part of Lower Bengal Delta has been bestowed with rich assemblages of archaeological artefacts, terracotta figurines, seals, beads, utensils of grey, black, and red potteries and stone carvings belonging to different historical periods and dynasties, finding out of new sites also been emphasized and explored in this study. To reach this goal some image processing techniques have been applied in this study by which some new probable archaeological sites have been

successfully identified in this deltaic area especially in the mangrove cover part of delta which is not easily approachable. The influence of the now-relict courses of the Bidyadhari River and its distributaries on the location of early historic sites, such as Chandraketugarh, Tilpi, Dhosa, and those near the Adi Ganga River, as well as early medieval sites like Atghara, Kankandighi, Monir Tat, and Jatar Deul in the North and South 24 Parganas, has been examined through high-resolution mapping of known archaeological sites. It has been observed that during the Roman Warm Period, higher solar insolation and stronger monsoon, early historic sites thrived along the northern Bidyadhari and Piyali Rivers. In contrast, during the 'Medieval Cold Period', early medieval sites developed further sea ward along the emergent Adi Ganga River and its distributaries, including the Mani River. A significant shift in the location of settlements from early historic to early medieval periods is interpreted as a response to changes in the river system, particularly the main flow moving from Bhagirathi-Bidyadhari to Bhagirathi-Adi Ganga. These changes are believed to have been driven by variations in solar insolation, declining monsoon activity, and changes in sea levels. Additionally, the connectivity between the early historic delta port city of Chandraketugarh and the renowned Mauryan port of Tamralipta on the Rupnarayan River has been mapped. This route was likely controlled by the now-relict 'Proto-Bhagirathi River; linked to the ancient Bhagirathi River via the NNE-SSW "Chinsura-Krishnanagar" lineament. This waterway served as a vital trade and travel route, facilitating visits by travellers such as Fa Hien in the early historic period and Hiuen Tsang in the early medieval period to the capital city of Pataliputra on the Ganga in Bihar. Although various works have been done by different scholar to find out the evidences of ancient livelihood from early historic time period, but the application of state of art remote sensing techniques and geoarchaeological studies together was the main research gap in this field. Contrary to the common beliefs of no human presence in the Sundarban region before the colonial rulers, the present study spatially analysed evidences and sites of historical settlement in the lower Ganga delta to suggest existence of human civilisation during early historic, early and late medieval times with changing pattern of settlement and trade depending on possible climatogenic and geomorphic changes.

The present research, through a comprehensive review of various archaeological studies and reports, coupled with field observations of artifacts in both local sites and museums, aims to establish the existence of an extensive early history and early medieval civilization in the Sundarban delta, covering an area of nearly 100 km^2. This was made possible by applying high-resolution elevation mapping using Coastal DEM data, alongside advanced NDVI and PCA analyses from high spatial resolution Sentinel 1 data. These findings suggest that the civilization's spread may have been influenced by shifts in climatic patterns, sea levels, neotectonic movements, and delta dynamics.

Through contour and elevation mapping using Coastal DEM data, along with local archaeological evidence, several new potential archaeological sites have been identified for future exploration. It is recognized that systematic paleoenvironmental studies, incorporating palynological evidence, precise radiometric dating using AMS, and subsurface structural imaging using Ground Penetrating Radar, will be crucial for further understanding the historical context of this deltaic wetland before large-scale excavation efforts are undertaken in the future.

Chapter 1 Introduction to the study

1.1 Introduction

The Bengal Delta, also known as the Ganges Delta, is the world's largest delta and has undergone significant changes in sediment deposition, channel activation, and river formation due to sea-level fluctuations and increased water discharge during the Pleistocene-Holocene transition (Umitsu 1987, Umitsu 1993, Goodbred and Kuehl 2000, Singh 1996). The floodplain of the Bhagirathi River contains numerous wetlands and abandoned meander loops, resulting from the changing course of the Ganga River due to avulsion, erosion, and accretion along the southern part of the delta (Rudra 2015).

As stated by Majumder (1942) and Morgan and McIntire (1959), the easterly tilting of the Bengal Delta during the Holocene, along with the continuous diversion of the main flow of the Ganga through the Padma, has been a major cause of the decay of the Bhagirathi-Hugli River. Among the decayed distributaries, the Adi Ganga, Bidyadhari, Piyali, Suti, and Noai rivers are particularly significant. Various experts have examined these decayed distributaries and highlighted their geoarchaeological importance, as many archaeological sites have been excavated along their courses and levees (Chakraborty, 2017).

The Adi Ganga, one of the decayed distributaries of the Bhagirathi, was a medieval outlet that once flowed into the sea through the Saptamukhi estuary. The Bidyadhari River is another important decayed channel, where the ancient port of Chandraketugarh, dating back to 300 BCE–500 CE, played a crucial role in maritime trade between India and Rome (Ray, 1979).

In the Lower Bengal Delta, the Rupnarayan River estuary and its confluence with the Hugli in East Midnapore hold significant archaeological importance. Sites such as Tamluk, Natsal, Tilda, and Panna have yielded antiquarian evidence. Excavated materials suggest habitation from the Early Historic period to the Gupta era, with signs of Mediterranean contact based on unearthed pottery vases (Basak, 2014). Several findings, including Northern Black Polished Ware (NBPW), rouletted ware, red polished ware, and semi-precious stone beads, have been discovered. According to Basak (2014), the Early Historic settlement in Tamluk covered approximately 1.5 square kilometres, with archaeological findings recovered from low-lying swampy areas. However, modern urban expansion and river course changes have disturbed the original habitation sites.

Natsal, located 10 km south of Tamluk near the confluence of the Rupnarayan and Hugli Rivers, is presumed to be the ancient port of Tamralipta. Antiquarian evidence from this site spans the Maurya-Sunga to the Gupta period (Basak, 2014). Satellite imagery and ancient topographical maps reveal significant landscape and river course changes in the lower deltaic region, particularly in South 24 Parganas. Archaeological remains dating from 400 BCE to 1300 CE confirm the existence of Mauryan to Gupta imperial rule in different parts of South Bengal, reflecting changing cultural phases.

The drying up of old river courses, known as palaeochannels (Guo et al., 2018), provides insights into past floodplain activities, estuarine evolution, and alluvial deposition prior to sea-level changes (Ryan et al., 2007; Kemp and Spooner, 2007; Nandini et al., 2013; Karmokar et al., 2021). This study aims to map palaeochannels and levees to determine the influence of ancient river courses on trade. Additionally, it seeks to identify new potential archaeological sites based on the locational patterns of known excavated sites.

Continuous geomorphic changes, including river activation and decay, have occurred in the Bhagirathi floodplain, as evidenced by numerous wetlands and abandoned meander loops (Rudra, 2014, 2015). Most rivers in the Lower Ganga Delta are now decayed, with Adi Ganga, Bidyadhari, Piyali, Suti, and Noai being among the most significant. Various scholars have highlighted the geoarchaeological significance of these distributaries due to the numerous excavated archaeological sites along their courses (Chakraborty, 2017). A rich collection of artifacts—including terracotta figurines, seals, beads, and pottery in grey, black, and red fabrics—has been found in North and South 24 Parganas, spanning different historical periods and dynasties.

The existence of ancient livelihoods and the richness of archaeological findings have been well documented, from the early studies of Kalidas Dutta to recent scholarly research. This study seeks to identify additional potential archaeological sites using remote sensing techniques, particularly in the southernmost parts of the delta and mangrove-covered islands where surface exploration is restricted. Moreover, to comprehensively analyse the geoarchaeological characteristics of this dynamic delta, a multidisciplinary approach is necessary, as emphasized by Chakraborty (2017) in her research.

1.2 Problem statement and research gaps

Remains of an ancient civilization dating back to 400 BCE–900 CE have been reported from the Lower Bengal Delta (Chakraborty, S., 2017). However, the Quaternary evolution of the lower deltaic plain of the Ganges-Brahmaputra (G-B) Delta has occurred over the last 6,000 years in different phases (Goodbred and Kuehl, 2000). It remains unclear how this ancient civilization expanded or retreated in response to active delta building, channel abandonment, and delta retreat driven by Quaternary sea-level fluctuations. This research aims to investigate the relationship between the expansion and decline of ancient settlements over the last 3,000 years in the context of coastal evolution in this region.

1.3 Research gaps

After the introductory study about the geoarchaeological study of LGDP (Lower Ganga Delta Plain), some information gaps are highlighted which need to re-search. These research gaps are:

First of all, Geoarchaeological study of known sites is very important to know how the natural phenomenon influenced the development of human civilization.

Secondly, lack of study about the effect of palaeo- riverine environment on ancient livelihood.

Greater knowledge of archaeological sites is necessary to know how much sites are located in lower ganga delta plain as stated by Chakraborty S. 2016.

As we know the Quaternary Lower Ganga delta plain developed through different geological and climatic changes, application of multi-disciplinary analysis is required which also mentioned by Chakraborty. S 2016.

Neo-tectonics, sea level change, river avulsion, rapid channel shifting, meandering, erosion, and sediment depositions etc complicate the identification and preservation of archaeological evidences.

As field exploration is most important part to invent new archaeological site, identification of pre-field exploration is most necessary part which is not easy in such vast deltaic area especially in swampy mangrove cover area, but this can be done by remote sensing which must need to field verification.

1.4 Objectives

1. To study the geomorphic evolution of the lower deltaic plain of the G –B delta using Remote sensing and GIS, available Geomorphological map, Satellite image interpretation, Sedimentological investigation and ground surveys.
2. Mapping of the Archaeological sites in relation to geomorphic features and Identification of the main influencing river courses on ancient settlement through study of Palaeochannel and Palaeo levees using high-resolution satellite images and modern geospatial techniques.
3. Dating of selective archaeological samples and associated sediments.
4. Correlation of geomorphic and climatic events with archaeological remains within the GBM lower delta plain.
5. Making an informed opinion about the controversy whether the artifacts discovered in the Sundarban deltaic wetland are river-drifted or remnants of extensive Early Historic and Early Medieval settlements.

Chapter 2 Methodology

2.1 Spatial Mapping using High Resolution data

2.1.1 Data Used

The present Lower Bengal Delta region exhibits a complex river network with several relict meander belts visible in satellite images and Google Earth imagery. Mapping these relict and active river channels is a valuable tool for identifying the primary influencing rivers, as early civilizations were established based on water availability. For example, sites such as Chandraketugarh, Tilpi, Dhosa, and Atghara have yielded remnants of Early Historic civilizations along palaeochannels or natural levee belts of ancient active rivers.

In this study, SENTINEL-2 data has been considered the most suitable for palaeochannel identification and mapping due to its ability to minimize atmospheric contamination, such as water vapor (Sentinel-2 User Handbook, 2015). Additionally, it provides a more extensive swath coverage (~280 km^2) compared to Landsat (~185 km^2) and SPOT (~60 km^2). Several researchers, including Sola et al. (2018), Gascon et al. (2017), and Zanter (2015), have also recognized SENTINEL-2 as more effective than Landsat and SPOT for such analyses.

For this study, SENTINEL-2 images were downloaded from the Copernicus Service Element (GSEs) for palaeochannel mapping in North 24 Parganas and South 24 Parganas, using data dated February 3, 2023.

2.1.2 Error rectification and Image analysis strategies

As mapping archaeological sites in relation to geomorphic features is a key objective of this study, elevation and contour maps were prepared using Coastal DEM data in ArcGIS 10.8. Since the study area focuses on the Lower Bengal Delta Plain, the downloaded raster DEM was clipped to the outline of West Bengal using the data management clipping tool.

To refine the DEM, a Fill spatial analysis was performed to eliminate small imperfections, including sinks (cells with undefined drainage direction, manipulated by the pour point) and peaks (errors representing artificially high elevation points that are subtracted from the actual highest surface elevation). After image rectification, elevation and contour maps of the entire Lower Bengal Delta Plain, including the mangrove-covered areas, were generated. The DEM was further divided into smaller sections to extract detailed elevation information, and contour maps were created with a 2-meter contour interval. Additionally, a river map of Bengal was prepared, overlaid with the locations of archaeological sites to analyse the relationship between ancient civilizations and historical river systems, as well as to identify the primary rivers that influenced early settlements.

The downloaded SENTINEL Level-2A data was converted from JPEG to image format using ERDAS IMAGINE 2014 software, and the processed images were layer-stacked to produce a false-colour composite image. Since the European Space Agency (ESA) provides atmospherically corrected SENTINEL Level-2A products processed by SEN2COR, further atmospheric correction was not required in this study.

2.2 Elevation mapping

A key technique in spatial science is the Digital Elevation Model (DEM), which provides elevation information of terrain through remote sensing, specifically using laser pulses or sound waves. According to Deng (2007), DEMs not only provide elevation data but also offer insights into terrain shape, topographic position, and topographic context. Several researchers, including Hambly (2015), Challis et al. (2011), Chiverrell et al. (2008), Budja and Mlekuz (2010), and Hohenthal et al. (2011), have utilized LiDAR-derived DEM data for palaeochannel identification in smooth, level, and sparsely vegetated fluvial and alluvial floodplains.

In this study, Coastal DEM v1.1 with a 1-arcsecond (30 m spatial resolution) has been used to generate elevation and contour maps. While Shuttle Radar Topography Mission (SRTM)-derived DEM data is commonly used, it is often affected by vertical errors, particularly in densely vegetated areas (Kulp & Strauss, 2004). Coastal DEM v1.1 represents the first global-scale attempt to correct these errors using an artificial multilayer perceptron neural network (Kulp & Strauss, 2004).

The Coastal DEM data was downloaded from NOAA's National Centres for Environmental Information (NCEI), which provides integrated land topography and ocean bathymetry data. ArcMap 10.3 GIS Mapping and Data Analysis Software was used to prepare contour and elevation maps. Contour maps were generated at a 0.5 m interval using the spatial analysis tool, followed by the creation of elevation maps using the Create TIN 3D analysis tool. TIN, or Triangulated Irregular Network, is an irregularly spaced sample-point model that represents terrain surfaces by connecting sample points into triangles—denser points indicate rough terrain, while fewer points represent smooth or flat terrain (Ali & Mehrabian, 2009).

2.3 Mapping of Palaeochannel

2.3.1 What is Palaeochannel

According to Mohammed & Balasubramanian (2010) and Vervoort & Annen (2006), a terminated river flow of an ancient active river that remains as accumulated geologic remnants is an active source of groundwater and subsurface water. The term "paleo" refers to the old, and such remnants are also known as palaeo-valley or palaeo-rivers (Upadhyay et al., 2021). Mohammed & Balasubramanian (2010) and Vervoort & Annen (2006) explain that these ancient rivers no longer exist due to several past climatological or geological events, but their remnants remain stored as geological features. The old river course, which has dried up due to the river's cessation or deflection, is known as a palaeochannel (Guo et al., 2018).

Mohammed & Balasubramanian (2001) note that the diversity of palaeochannels arises in different climatic and tectonic environments, as the rivers adjust to changes in discharge, sediment load, and drainage diversion. Rivers are the quickest systems to respond to environmental changes.

A palaeochannel is the abandoned part of an ancient river, separated from the main flow by a process such as channel cutoff or abandonment during dynamic or catastrophic evolution (Karmokar et al., 2021). These remnants of ancient rivers are filled with sediments from different geological and climatic events, and they typically carry water only during peak flood times. Karmokar et al. (2021) explain that palaeochannels are found in the older stages of rivers, where sediment load increases and the gradient decreases, leading to meandering, which eventually results in a channel cutoff.

According to Mohammed & Balasubramanian (2010), a palaeochannel is an elongated, lobate, or sinuous fluvial landform representing a past flow course, with lengths ranging from a fraction of a kilometre to many kilometres. Wray (2009) describes a palaeochannel as the former, abandoned, and buried course of a river, which no longer carries water except during peak floods. He also notes that palaeochannels can be identified as long, shallow depressions, sometimes tree-lined, with a lighter soil texture. Rajawat et al. (2003) and Rathore et al. (2010) define palaeochannels as the remaining parts of an ancient river filled with younger alluvium.

According to Hambly (2015), palaeochannels can be categorized into two types based on morphology and fluvial depositional characteristics: prior stream and ancestral stream, as described by Pels in 1996, and migrational palaeochannels and aggregational palaeochannels, as outlined by Page & Nanson in 1996.

2.3.2 Significance of Palaeochannel

To understand the relationship between surface and subsurface hydrology and geological processes, it is important to map palaeochannels, as they are closely related to both surface and subsurface hydrology, as well as vegetation distribution (Srivastava et al.). According to Triantafilis & Buchanan (2009), palaeochannels can function as subsurface conduits or channels, as they often contain gravel and sand with minimal clay and silt. These permeable properties of palaeochannels can be problematic for agriculture due to the loss of irrigation water through deep drainage processes, which is a negative impact of palaeochannels. On the other hand, they also serve as suitable storage locations for groundwater, as mentioned by Chen et al. (1996) and Hambly (2015). Sustainable groundwater management can be achieved, as palaeochannels act as aquifers due to their sand layers without clay cover, which aids in groundwater recharge (Guo et al., 2018). Triantafilis & Buchanan (2009) and Karmokar et al. (2021) also note that the bed material of palaeochannels differs from that of normal riverbeds, with palaeochannel beds being rich in gravel and sand deposits. This makes them more porous and permeable, facilitating subsurface water flow or aquifer formation.

The palaeoclimatic significance of palaeochannels is also valuable, as they provide insights into past floodplain activities, estuarine and alluvial depositional responses to sea level changes (Ryan et al., 2007; Kemp & Spooner, 2007; Nandini et al., 2013; Karmokar et al., 2021). Hambly (2015) further emphasizes that the characteristics of palaeochannels provide information about local geology, as they influence surface and subsurface water flow. This nature of palaeochannels is also useful for understanding specific vegetation patterns and local ecosystems (Hambly, 2015). Furthermore, palaeochannels, as evidence of ancient river systems, can provide insights into past flood events, helping predict future flood risks in densely populated floodplains (Hambly, 2015). Sylvia & Galloway (2006) also mention that the nature of ancient flow regimes and discharge rates can be inferred from the sediment preserved in palaeochannels.

An additional significance of palaeochannels is their economic value, as described by Nandini V.C. et al. (2012). Palaeochannels are often mineral-rich, containing deposits of uranium, lignite, precious metals, high-grade silica sand, heavy minerals, and placer minerals. The sedimentary records within palaeochannels also provide valuable insights into past climatic conditions. Cudahy & Ramanaidou (1997) and Ramanaidou, Morris & Horwitz (2003) describe palaeochannels as potential mining sites, offering significant economic benefits.

Rivers are crucial natural systems that create various landforms through erosional and depositional processes, and they are an essential component of the hydrological cycle. Mohammed & Balasubramanian (2010) also note that with the increasing demand for water due to population growth, groundwater from rivers is one of the primary sources of water. In this context, palaeochannels may serve as vital sites for groundwater exploration. The economic value derived from the deposits in palaeochannel courses, through hydrochemical responses and their water supply capacity, has made palaeochannels a key focus of contemporary research (Mohammed & Balasubramanian, 2010).

2.3.3 Methods used for Palaeochannel Identification

2.3.3.1 Satellite data from Landsat

According to Wray (2009), Landsat optical and infrared imagery is highly effective for identifying and mapping palaeochannels over large areas, especially where Ground Penetrating Radar (GPR) and aerial imagery are costly. Since Landsat satellite images are now freely available, they are particularly useful for palaeochannel mapping and mineral exploration, as highlighted by Upadhyay et al. (2021) and Zani & Rossetti (2012). Nandini et al. (2013) used Landsat ETM+ and Landsat TM to identify palaeochannels in South India. Wray (2009) also utilized Landsat 7 imagery to identify ancient palaeochannels and present channels in the Namoi River floodplain.

2.3.3.2 image processing techniques

Various image processing techniques can be applied to improve image quality, such as histogram equalization, piecewise or scene-wise linear stretching, contrast and brightness enhancement, and change band combination. These techniques were used by Bhadra et al. (2009) to identify the course of the Saraswati River and its palaeochannel in Haryana (Upadhyay et al., 2021). Another study by Mehdi S. M. et al. (2016) applied advanced image processing techniques such as HIS (Intensity, Hue, and Saturation), PCA (Principal Component Analysis), MCI (Mineral Composite Index), and NDVI (Normalized Difference Vegetation Index) for visual interpretation. These techniques were used to differentiate moisture characteristics and reduce noise levels (Upadhyay et al., 2021).

According to Upadhyay et al. (2021), among the image processing techniques, Principal Component Analysis (PCA) is an easier process to improve spectral signatures, as described by Ciampalini et al. (2013).

2.3.3.3 Application of GIS or, Geographical Information System

The application of GIS (Geographical Information System) is also a valuable tool for palaeochannel delineation and mapping, as described by Chaudhary and Aggarwal (2009) and Wang, Guo, Wu, Zhu, and He (2012). In their work, they used GIS to identify the source of groundwater by mapping palaeochannels. Hou and Mauger (2005) also applied GIS techniques by overlaying Landsat images on a Digital Elevation Model (DEM). This approach allowed them to locate palaeochannels and associated geomorphic features, although they noted that further investigation through borehole drilling and core analysis was required (Upadhyay et al., 2021).

2.3.3.4 GPR or, Ground penetrating Radar

As described by Neal (2004), GPR (Ground Penetrating Radar) is a non-invasive radar technology used to obtain information about subsurface structural differences by measuring the time it takes for high-frequency electromagnetic pulses to travel through the subsurface layers and reflect back to the machine. GPR can detect differences in subsurface strata up to 50 meters below the ground (Neal, 2004). Since GPR is a non-invasive, non-excavational process, it assists in future planning for excavation work (Hambly, 2015).

GPR is also an important tool in reconstructing past depositional environments through sedimentological studies. Slowik (2011) and Denith et al. (2010) describe how GPR can visually differentiate various subsurface strata based on moisture, porosity, and lithological properties. Due to its non-invasive nature, GPR is an ideal technique for investigating palaeochannels and core drilling sites (Hambly, 2015; Mallinson et al., 2010; Barnhardt & Sherrod, 2006; Timmons et al., 2010).

2.3.3.5 Terrain Elevation information from Digital Elevation Model or, DEM

Another useful technique in spatial science is the Digital Elevation Model (DEM), which helps produce elevation information of terrain through remote sensing, specifically using laser pulses or sound. According to Deng (2007), DEM not only provides elevation information but also offers insights into the shape of the terrain, its topographic position, and its topographic context. Eisank et al. (2014) mention that parameters such as slope and curvature, which differentiate one terrain from another, can also be derived from DEM. According to Jones et al. (2007), DEM is created by measuring elevation through the calculation of distance and time between the aircraft (or laser pulse source) emitting laser to the target terrain and the reflected laser signals from the terrain. DEM is a 3D point cloud-based dataset containing recorded points from emitted and received laser pulses (Straatsma & Middelkoop, 2006).

Aerial Laser Survey (ALS), Light Detection and Ranging (LiDAR), and other modern techniques produce highly accurate DEMs (Srivastava et al., 2016). According to Srivastava et al. (2016), DEM can be a useful tool to identify various geomorphometric parameters related to the distribution of palaeochannels. Hambly (2015), Challis et al. (2011), Chiverrell et al. (2008), Budja & Mlekuz (2010), and Hohenthal et al. (2011) all used LiDAR-derived DEM data for palaeochannel identification in smooth, level, sparsely vegetated fluvial and alluvial floodplains.

2.3.3.6 Palaeochannel Identification through NDWI and PCA Analysis

Identifying the sequence of channel shifts or palaeochannels is crucial for understanding the stratigraphic history of civilization in the Lower Bengal Delta Plain. The Normalized Difference Water Index (NDWI) and Principal Component Analysis (PCA) are used to identify the course of ancient rivers that supplied water for trade and livelihood. NDWI is conducted to eliminate non-water features, which is essential for palaeochannel identification. The lower intensity of backscattering from the Near Infrared (NIR) band in areas with higher soil moisture may help in detecting palaeochannels or hidden palaeochannels, especially when combined with Digital Elevation Model (DEM) or elevation data, as stated by Challis (2011) and Upadhyay et al. (2021).

For calculating NDWI, a multispectral image from the Sentinel-2A satellite with a 10m spatial resolution was used. In this study, NDWI was calculated by using the spectral response from the visible green band, divided by the NIR band, following McFeeters (1996). These two bands were selected to maximize the reflectance of green light to detect water features, minimize the low reflectance of NIR, and enhance the high reflectance of NIR from terrestrial and soil features. Following this approach, the same bands were chosen in this study to highlight water bodies and soil with moisture content, which may help identify palaeochannels. Soil and terrestrial features have zero or negative NDWI values due to their higher NIR reflectance compared to green light, whereas water features have positive NDWI values because of their low NIR reflectance (McFeeters, 1996). In this study, after calculating NDWI, the negative values were eliminated using Erdas Imagine 2014 software to highlight only the water bodies.

Principal Component Analysis (PCA) is a spectral enhancement technique that reduces the redundancy of the dataset (Eklundh and Singh, 1993). This technique compresses the multispectral variance of separate layers into three or more component images, which also helps improve spectral resolution (Mehdi et al., 2015). According to Munyati (2008), PCA is a mathematical technique that reduces the dimensionality of a dataset. In this study, high-resolution Sentinel-2A data with a 10m spatial resolution were used for PCA, which helped highlight palaeochannels more prominently.

2.3.3.7 Secondary data sources and analysis

Secondary data for mapping of Archaeological sites and stylistically analysis of excavated ancient elements in Lower Bengal Delta plain have been done from data published by Ms. Sharmi Chakraborty in her theses has also been used in this present report. Quaternary Geological Map by RK & Chattopadhyay G. S. 1997, has also used for the present report.

2.4 Applied methodology for Palaeochannel Identification

2.4.1 Data used SENTINEL 2

The data provided by SENTINEL 2 is a European wide- swath, high resolution, multi- spectral imaging mission which provide continuity of SPOT and LANDSAT type image for land management, agriculture, forestry, risk mapping and security concerns. The images have high resolution with 13 spectral band within which 4 bands at 10 m, 6 bands at 20 m and 3 bands at 60 m spectral resolution. The SENTINEL- 2 data is able to avoid the contamination of atmospheric constituent like water vapour which influence the spectral accuracy and also sensitive to soil iron oxide content. (Sentinel- 2 User Handbook, 2015). Beside of this SENTINEL- 2 product which distributed by European Space Agency have a more extensive swath of around 280 km ^{2} than Landsat (swath 185 km ^{2}) and SPOT (swath 60km ^{2}). (Sola, I. et al., 2018). Over this the revisiting time or, temporal resolution which is 5 days combining with Sentinel- 2A and Sentinel- 2B, higher than Landsat which is 16 days. Due to these multi-facilities provided by SENTINEL- 2, in this present study data from SENTINEL- 2 considered as most acceptable for palaeochannel identification and mapping. According to Sola, I. et al., 2018, several authors like Gascon et al., 2017; Zanter, 2015 they also considered SENTINEL-2 as more useful than Landsat and SPOT data.

SENTINEL- 2 is satellite images are very helpful to monitor land cover which provide data for land cover mapping that became operational from 2012. To get spatial information and to identify palaeochannel, satellite data of SENTINEL 2 were downloaded from Copernicus Service Element (GSEs). For palaeochannel mapping in this study, SENTINEL- 2 data have been downloaded for N 24 Pgs. and S 24 pgs. Separately dated of 3rd February, 2023.

2.4.2 Image processing techniques

The downloaded data was originally in JPEG format, but it required conversion to an image or TIFF format for further analysis. This conversion was performed using ERDAS IMAGINE 2014 software. After the conversion, the processed images were layer-stacked to create a false-colour composite image of the study area. A total of 9 bands were used, including 4 bands with a 10m spatial resolution (bands 2, 3, 4, and 8) and 5 bands with a 20m spatial resolution (bands 5, 6, 7, 11, and 12).

Before proceeding with further data analysis of the satellite images, noise reduction and atmospheric correction are essential preprocessing steps. However, since the European Space Agency provides SENTINEL Level 2A products, which are processed by SEN2COR to obtain Bottom of Atmosphere (BOA) reflectance, atmospheric correction was not performed in this study. SEN2COR is a processor that generates SENTINEL Level 2A data through cloud detection, scene classification, and the conversion of Top of Atmosphere (TOA) reflectance to BOA reflectance (Sola et al., 2018).

2.4.3 Application of NDWI

Challis (2011) observed lower backscattering intensity of NIR from palaeochannels or areas with higher soil moisture during a LiDAR survey. This characteristic of NIR reflection can assist in identifying palaeochannels or hidden palaeochannels when combined with Digital Elevation Model (DEM) or elevation data (Upadhyay et al., 2021). Generally, vegetation and soil features exhibit higher NIR reflectance due to the lower absorbance of NIR compared to water surfaces, which have very low NIR reflectance. For this reason, eliminating non-water features is crucial, and this can be achieved using the Normalized Difference Water Index (NDWI).

The distribution pattern of palaeochannels and elevation is shown in Figures 5.6, 5.7, 5.9 and 5.10. An attempt has been made to correlate the distribution of palaeochannels with elevation. The palaeochannels shown in Figure 5.9 are distributed in a north-south direction, likely formed by an east-west flowing river, which may conceptualize the river Jamuna. The sequence of these palaeochannels is identified in Figure 5.10, which will be discussed later. The presence of several palaeochannels indicates that the river has shifted its course multiple times.

To calculate NDWI, a multispectral image from SENTINEL-2A with 10m spatial resolution was used. In this study, NDWI was calculated using the spectral response of the green band, divided by the NIR band (Boland, 1976; McFeeters, 1996). The NDWI formula used in this study is based on the principle outlined by McFeeters (1996):

$$\text{NDWI} = (\text{Green} - \text{NIR})/(\text{Green} + \text{NIR}) \qquad (1)$$

McFeeters (1996) selected the green and NIR wavelengths for NDWI calculation to maximize the reflectance of green light for detecting water features, while minimizing the high reflectance of NIR from terrestrial and soil features. In this study, the same bands were used to highlight water and soil with moisture content, which may help identify palaeochannels. Soil and terrestrial features generally have zero or negative NDWI values due to their higher reflectance of NIR compared to green light, whereas water features exhibit positive NDWI values because of their low NIR reflectance (McFeeters, 1996). After calculating the NDWI, negative values were eliminated using ERDAS IMAGINE 2014 software to highlight only the water bodies.

The study area includes three major rivers: the Ganga, Bidyadhari, and Adi Ganga. The primary objective of this study was to identify palaeochannels, and NDWI analysis successfully fulfilled this goal. The sequence of palaeochannels was also marked. From the NDWI images, the main palaeochannel patches near Chandraketugarh, shown in Figure 5.7 were identified. These palaeochannels run in the opposite direction of the current river flow, situated between the Bidyadhari and Icchamati rivers. Additional palaeochannel patches of the river Hugli were identified near Kalyani, existing as Jhil or relict patches of water, such as Mathura Jhil and Gayshpur Kulia Jhil. Furthermore, small palaeochannel patches of the Adi Ganga were identified on the western side of Sarberia.

2.4.4 Application of PCA

Principal Component Analysis (PCA) is a spectral enhancement technique that reduces redundancy in datasets (Eklundh and Singh, 1993). This technique compresses the multispectral variance of separate layers into three or more component images, which helps improve spectral resolution (Mehdi et al., 2015). PCA is a mathematical technique that aids in reducing the dimensionality of a dataset (Manyati, 2008). In this study, high-resolution SENTINEL-2A data with 10m spatial resolution were used, and PCA further highlighted the palaeochannels more prominently.

The area near Chandraketugarh in North 24 Parganas, which is within the main palaeochannel-covered region, was analysed. After applying NDWI, palaeochannels of the Ganga and Adi

Ganga rivers, as well as those near Chandraketugarh, were identified. However, PCA helped identify additional palaeochannels, particularly near Chandraketugarh in North 24 Parganas. Figure 5.6 shows an enlarged portion of the palaeochannel, where the location of the important ancient port of Chandraketugarh, dating back to 300 B.C. to 500 A.D., can be observed. Another significant river in this area is the Adi Ganga, a medieval outlet of the Bhagirathi River, which originated from the Hugli River at Dahighat and flowed through Kalighat, Garia, Baruipur, and Jaynagar (Rudra, K., 2014). According to Rudra (2014), the river might have continued to the sea through the Saptamukhi or Thakuran estuary. Palaeochannels along this river course are also highlighted in Figure 5.21. Additionally, some parallel stretches of river channel courses have been identified to the east of the river, located near the northern part of Chandraketugarh. The palaeochannels along the river course of Bidyadhari are discussed in Figures 5.9, 5.10, and 5.11.

Chapter 3 Study Area and Geological setting

3.1 Geological Evolution of Ganges – Brahmaputra lower Delta Plain

Shoreline accretion and aggradation from riverine sediment are common characteristics of the Ganga-Brahmaputra Delta, as depicted by Allison and Kepple (2001). It is known that the increased sediment supply during the late Quaternary period was a primary factor in the development of the Bengal Basin (Goodbred et al., 2003). The tectonically active lower delta basin plain of the Ganga-Brahmaputra-Meghna (G-B-M) river system was shaped under energetic marine conditions.

3.2 Subsidence within Bengal Basin:

The Ganga-Brahmaputra Delta has been significantly affected by tectonic activity, as it is located close to the Indo-Burman collision zone in the east and near the Himalayan thrust in the north (Morgan and McIntire, 1959). In addition, the eastern and northern regions of the delta have been influenced by intra-basinal faulting, resulting in the uplift, tilting, and subsidence of fault blocks during the Quaternary period. According to Goodbred et al. (2003), changes in the river course, river avulsion, and sediment dispersal in the Bengal delta are directly linked to tectonic activities such as faulting and earthquakes, revealing the unstable conditions of the delta.

Studies by Galloway (1975) and Stanley and Warne (1994) also support the concept of tectonic control on the fluvial system of the Bengal delta. They agree that any deformation or change in sediment load in the Bengal delta has been influenced by active tectonic activities, with continental controls also playing a role. Goodbred et al. (2003) demonstrated from borehole data that the Ganga-Brahmaputra Delta has experienced massive changes in sediment discharge and tectonic activity during the Late Quaternary period.

Goodbred and Kuehl (2000) identified two tectonic processes that influenced the G-B Delta:

1. The overall tectonic setting of South Asia exerts a general control on deltaic processes.
2. Overthrusting and compression within the Bengal Basin, associated with faulting, have caused the uplift of floodplain terraces in several regions (e.g., Barind Tract, Modhupur Terraces, Comilla Terraces), leading to river avulsion in different parts of the delta system.

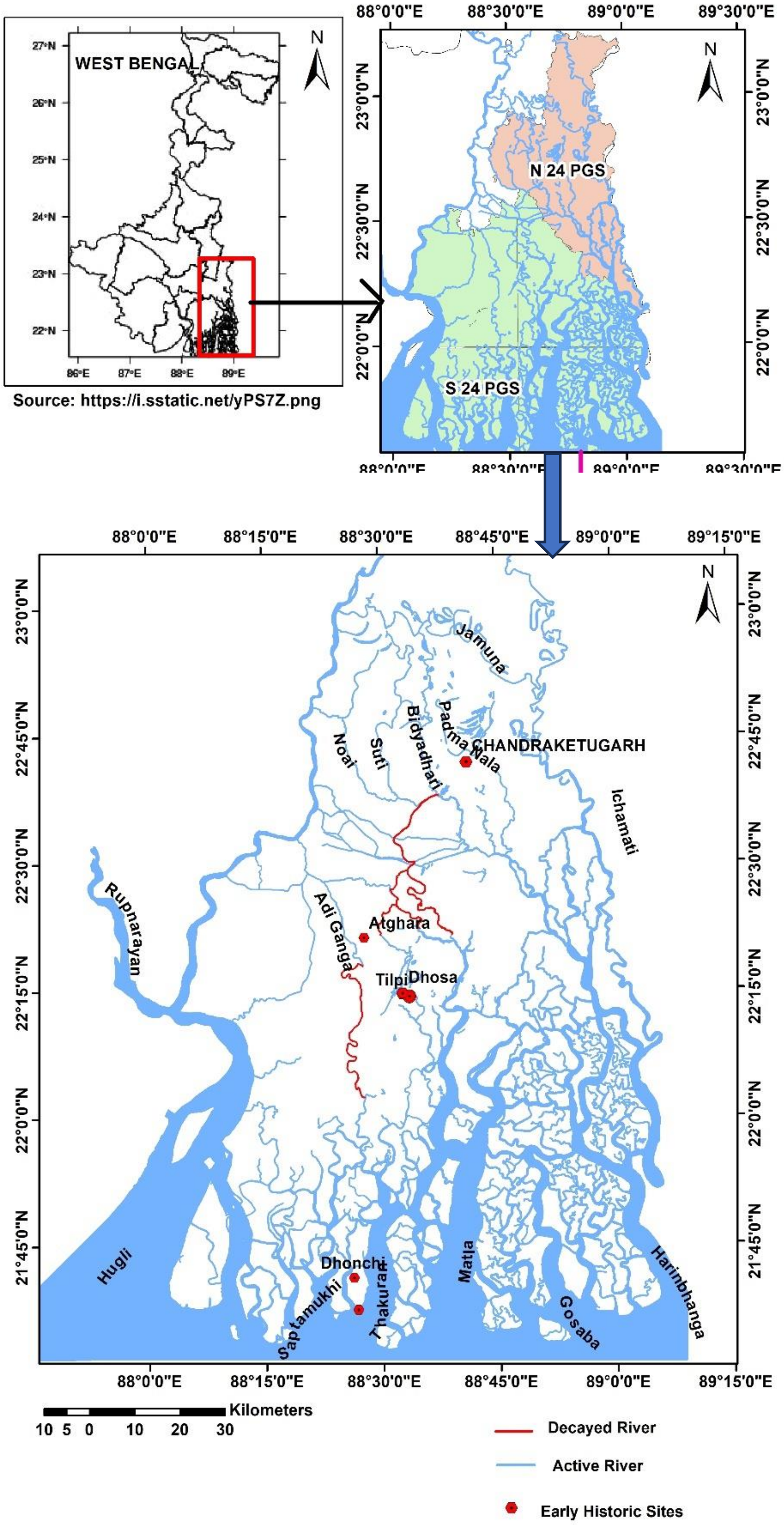


Fig. 3.1 Showing the study area includes the Indian part of Lower Bengal Delta, covering N and S 24 Pgs.

3.3 Some tectonic features in Bengal Basin

In the northeast, flexural loading from the overthrust of the Shillong Massif has caused a downwarp in the adjacent Sylhet sub-basin. Shear and compression in the northern and central parts of the Bengal Basin have resulted in the uplift of the Madhupur Terrace, as well as the recent uplift of the Comilla Terrace, which is associated with the Pleistocene uplift process (Goodbred S.L. et al., 2003). Similarly, the northern Bengal Basin is divided into several sub-basins by the Mymensingh Terrace. Additionally, the presence of vertically displaced fault blocks, formed due to tectonic movements, may influence the flow behaviour of the Ganga-Brahmaputra River (Goodbred S.L. et al., 2003).

According to Brammer (1996) and Fergusson (1863), a severe earthquake in the Sylhet region in 1782 caused significant vertical displacement near Mymensingh. This event contributed to the avulsion of the Brahmaputra River from its old course east of the Madhupur Terrace to its modern channel. Such course changes of the Brahmaputra River between its western and eastern paths have occurred relatively frequently throughout the Holocene.

Goodbred S.L. et al. (2003) also noted that, in contrast to the tectonically complex eastern Bengal Basin, the southwestern delta is located along a trailing-edge margin that is far less influenced by tectonic activity. As a result, after entering the Bengal Basin through a narrow corridor between the Rajmahal Hills and the Barind Tract, the Ganga River experiences largely unrestricted migration across several hundred kilometers of the lower floodplain and delta plain. Although recent stratigraphic studies suggest the absence of tectonic features such as terraces or sub-basins (Goodbred & Kuehl, 2000), Sesoren (1984) and Stanley & Hait (2000) identified numerous subtle lineaments from aerial and satellite imagery. These features suggest the presence of underlying tectonic structures and movements that may influence the long-term positioning of the Ganges River and delta development.

Another perspective suggests that the eastward migration of the Ganges River during the Holocene is a result of loading-induced flexure along the northeast-trending hinge line (Alam, 1996; Stanley & Hait, 2000). An alternative interpretation by Stanley et al. (2003) proposes that the Ganges River is being diverted eastward due to downwarping caused by compression along the Indo-Burman Fold Belt. Goodbred & Kuehl (2000) analysed both new and existing chronostratigraphic data and observed that sediment deposited a few meters above sea level shows an offset. They suggested that this offset reflects relative movement and can be used to reconstruct past subsidence, with paleo-elevation calculations indicating a subsidence rate of 2–4 mm per year.

Several geophysical and aerial studies of the region have noted an apparent fault system trending northeast along the Swatch of No Ground, extending toward the modern Meghna River course (Khandoker, 1987; Agarwal & Mitra, 1991; Khan, 1991).

3.4 Sediment supply and late Quaternary delta evolution process

Several studies have identified a variety of stratigraphic patterns within the Ganga-Brahmaputra (G-B) system, revealing distinct modes of delta development under different tectonic influences (Goodbred & Kuehl, 2000; Stanley & Hait, 2000). Research by Banerjee & Sen (1988), Umitsu (1993), and Vishnu-Mittre & Gupta (1972) indicates that the initial formation of the G-B delta began around 11,000 years ago (11 ka). During this time, rising sea levels led to back-flooding of the lowstand surface, trapping riverine sediments and transitioning from the clean alluvial deposits of the Pleistocene to overlying muds or marine shells. This transition occurred when the mean sea level rise exceeded 1 cm per year, leading to a rapid eustatic rise that deposited a 20–30 m thick muddy sequence.

Notably, between 11–7 ka, the sediment discharge into the G-B delta was at least 2.3 times higher than present levels (Goodbred & Kuehl, 2003). Oceanographic evidence suggests that while river discharge was significantly reduced due to the dominance of the dry northeast monsoon (Cullen, 1981; Wiedicke et al., 1999), sediment discharge increased due to continued climatic warming and ice sheet melting in the early Holocene. The increased surface runoff, driven by the strengthening of the southwest Indian monsoon, contributed to this phenomenon. This period of high sediment discharge, coinciding with rapid sea level rise during deglaciation, allowed for the accumulation of a 50 m thick sedimentary unit (Goodbred & Kuehl, 2000).

According to Steven et al. (2003), model simulations indicate that the timing of high sediment flux played a crucial role in delta evolution. A later peak in sediment flux led to extensive marine transgression, followed by late-stage progradation of the delta. Conversely, an earlier peak in high sediment discharge resulted in significant sediment bypass to the deep sea, causing delayed and less extensive marine transgression. A similar scenario occurred during the early Holocene when the high Ganga-Brahmaputra sediment discharge was sufficient to halt transgression and promote delta progradation (Goodbred S.L. et al., 2003).

3.5 Stages of delta development

3.5.1 Early development: 18000 – 7000 Cal yr. BP

During the last sea-level lowstand, river discharge was very low and perhaps negligible compared to modern output (Cullen, 1981; Milliman, 2000). Starting around 15,000 cal yr BP, sediment input to the upper Bengal Fan increased, indicating climatic warming and enhanced precipitation in the Himalayas (Weber et al., 1997). By 115,000 cal yr BP, the intensity of the humid southwest monsoon had strengthened beyond its present levels (Gasse et al., 1991), leading to a significant increase in river sediment discharge, reaching 2.5 × 10^9 t/year (Goodbred and Kuehl, 2000).

3.5.2 Transition time (10000 – 11000 Cal Yr. BP)

By 10,000 – 11,000 cal yr BP, a major transition occurred in the southern Bengal Basin when fine-grained mud from the lower delta was widely deposited over the lowstand oxidized and alluvial sand units (Goodbred and Kuehl, 2000). Studies on the Pleistocene to Holocene transition in the Bengal Basin (Umitsu, 1987, 1993; Goodbred and Kuehl, 2000) have shown that the enormous early Holocene sediment discharge from the Ganga-Brahmaputra river system led to the formation of deltaic silt deposits, up to 60 m thick, over the oxidized lowstand surface, beginning around 10,000 – 11,000 cal yr BP (Allison et al., 2003).

According to several studies (Fairbanks, 1989; Blanchon and Shaw, 1995), during this time, eustatic sea levels had risen by 45 m, causing extensive back flooding, sediment trapping, and the initial establishment of the G-B delta system. Stanley and Warne (1994) described the development of 36 deltas in the early Holocene as a result of decelerating post-glacial sea level rise, but they noted that this viewpoint differs somewhat for the G-B delta. Data from the delta sequence suggest that the maximum transgression and the subsequent onset of rapid progradation were responsible for the initial formation of the delta (Goodbred and Kuehl, 2000). The transition from transgressive sand to muddy, organic-rich deltaic sediments clearly marks the initiation of G-B delta growth (Goodbred and Kuehl, 2000).

Several studies (Banerjee and Sen, 1988; Umitsu, 1993; Goodbred and Kuehl, 2000) suggest that the maximum transgression was reached about 100 km inland from the present shoreline, including the Sundarbans, around 7,000 cal years BP, followed by the progradation of the delta plain (Allison et al., 2003).

The intense summer monsoon, characterized by an estimated rise in precipitation of 20 – 100 percent in the Northern Hemisphere, is a general feature of the early Holocene (Singh, I., 1996). In the Ganga Plain, only the topmost few meters of sediment deposits represent the geomorphic surface of the Holocene age. This area extends from the Aravalli-Delhi Ridge in the west to the Rajmahal Hills in the east, and from the Himalayan foothills (i.e., the Siwalik Hills) in the north to the Bundelkhand-Vindhyan Plateau and the Hazaribagh Plateau in the south (Singh, I., 1996).

Singh (1996) summarized several important incidents in the Ganga Plain, including the activation and formation of river channels due to the drop in sea level and increased water availability from the melting of Himalayan glaciers in the early Holocene (12 – 8 Ka). This period also saw the formation of many large linear lakes and channel abandonment due to sea level rise between 8 – 6 Ka. Between 4 – 2 Ka, the shrinking of lakes, increased siltation, deposition of organic matter, and a higher rate of sediment supply were observed. This period is further linked with anthropogenic interference, as humans began agriculture in the Ganga Plain around 3 – 2 Ka (Singh, I., 1996).

3.5.3 Year between 7400- 2500 (Late Holocene Period)

Based on radiocarbon evidence provided by Allison M.A. et al. (2000), it can be explained that the lower delta plain advanced from west to east, with subsidence and the inclination of the delta surface (Stanley and Hait, 2000). This period corresponds to the Late Holocene, characterized by the post-glacial slowdown of sea level rise and delta progradation (Stanley and Warne, 1994; Allison M.A. et al., 2000), with maximum sea transgression reaching 100 km inland during 7000 cal years BP.

According to radiocarbon dates and Holocene stratigraphic thickness analysis conducted by Allison M.A. et al. (1994), the formation of the Ganges Delta can be summarized into three phases. The first phase is linked to the formation of the westernmost delta, created by the Ganges distributaries with a prograding nature (Allison M.A. et al., 2002). The second phase involves the formation of the Bangladesh Sundarbans, which were also primarily formed by the Ganges distributaries (Allison M.A., 1998). This section of the delta formed when most distributaries lost their connection to the main channel due to decreased water supply from the Ganges, caused by siltation in the channels (Brammer H., 1996). This condition led to the cessation of delta progradation, resulting in a tide-dominated nature of the distributaries, even during high discharge periods (Allison M.A. et al., 2002). The third phase marks the formation of the eastern part of the delta in the Meghna estuary, shaped by the combined sediment supply from both the Ganges and Brahmaputra rivers (Allison M.A. et al., 2002).

3.5.4 Recent Tectonic activities on G- B Delta

In the 1950s, one of the most significant tectonic events was the magnitude 8.7 earthquake in Assam, which changed the course and morphology of several Brahmaputra tributaries and introduced a large volume of sediment (Goodbred, S.L. et al., 2003). This event led to rapid progradation of the Ganges-Brahmaputra Delta for several years following the earthquake.

From the above discussion, it is clear that the late Quaternary Ganges-Brahmaputra Delta was heavily influenced by eustatic sea level rise, tectonic processes, and variable sediment supply. The Ganges-Brahmaputra delta drainage basin is associated with tectonic and climatic influences, which have caused regional vertical movements, uplift, and downthrown sedimentary blocks. These have partitioned the delta into various sub-basins, altering the drainage morphology and position.

Neotectonic displacement and differential land subsidence are major controlling factors in the Late Quaternary depositional patterns in the western Ganges-Brahmaputra Delta. This is conceptualized from litho- and chronostratigraphic analysis of the regional distribution of Holocene and Pleistocene deposits (Stanley, D.J. & Hait, A.K., 2000).

The Ganges-Brahmaputra Delta, influenced by low-lying plains due to subsidence, has been indicated by preliminary radiometric and palaeobiological data mentioned in previous studies by Umitsu (1993). According to Umitsu, two-thirds of the Ganges-Brahmaputra Delta is composed of Late Quaternary deposits, as shown by the study of drill cores along a north-south axis in the Bangladesh portion of the delta. Petrological analysis and radiometric dating of Holocene and Late Pleistocene subsurface units in parts of the delta reveal that subsurface Holocene deposits are related to neotectonic structures in the western and Sundarban delta (Stanley & Hait, 2000). Limited radiocarbon dates of Pleistocene and Holocene subsurface exposures and core facies analysis, including 14C in selected western delta cores, suggest that the Holocene deltaic section ranges from 6,500 to 8,500 years BP.

An unconformity has also been identified in the upper part of the Late Pleistocene and lower part of the Holocene layer, known as the transgressive units (Stanley and Chen, 1993; Stanley and Warne, 1993), dating back more than 10,000 years. Increased sediment accumulation during the Early Holocene (around 7,500 years ago) was influenced by enhanced subsidence along a NE-SW trend, which provided accommodation space for sedimentation (Stanley & Hait, 2000). This NE-SW hinge zone extends from the Bay of Bengal to beneath the delta proper (from Mahanadi offshore in India to Mymensingh in Bangladesh) and has been identified through deep drilling and geophysical surveys for hydrocarbon exploration (Roybarman, 1983, 1992; Lindsay et al., 1991; Alam, 1996; Mukherjee and Hazra, 1997). Geological events, such as isostatic adjustment, the rise of the Himalayas, and sediment loading on the lower Bengal delta, continued from the Tertiary period and are related to this hinge zone, which dates back to the Eocene period. This hinge zone plays a major role as the boundary between two separate blocks (Stanley & Hait, 2000).

According to Sanyal (1990), Chaudhuri and Choudhury (1994), and Blasco et al. (1996), eastward tilting of the delta is related to the eastward progradation of the delta during late Quaternary tectonic displacement, which altered the Ganges-Brahmaputra River course. The eastward shifting of the delta is also evident in the progressive shift of the hinge line towards the southeast and in the contour lines, which are not parallel to the coastline (Stanley & Hait, 2000). This eastward tilting resulted in a reduced freshwater supply, decreased delta progradation, and an increase in saltwater encroachment, leading to increased erosion in the southwest part of the delta (Allison, 1998; Stanley & Hait, 2000).

Radiocarbon dating of cores by Stanley and Hait (2000) indicates a decrease in the rate of sediment accumulation from the Early to Late Holocene, explaining the reworking of deposited sediment in the delta. The distribution of peat layers rich in mangroves and other organic matter indicates that there was relatively low subsidence in the central and north-western parts of the delta during the Holocene, which decreases towards the southern and south-central parts. These areas reveal deeper water conditions or higher sea levels in the early to mid-Holocene (Stanley & Hait, 2000), reflecting a high rate of subsidence with a high sea level (Chandra & Hait, 1996). The presence of mangroves, influenced by sea level, and specific intertidal conditions may help to infer sea level conditions. From palaeobiological studies and palynological analysis, rapid sea level rise with high land subsidence was identified during the early to mid-Holocene when mangrove growth was limited to 80 to 120 km north of the present coastline, stabilizing the environment (Stanley & Hait, 2000). After the mid-Holocene, mangrove growth continued to spread southward until the 1800s due to a balance between increasing sediment accumulation from high freshwater influx and decreasing sea level rise (Stanley & Hait, 2000).

Table 1. Correlation among Geological Evolution of Lower Ganga Delta Plain with Holocene Climatic events.

GEOLOGICAL TIME SCALE	GEOLOGICAL EVENTS IN GANGA- BRAHMAPUTRA DELTA	CLIMATIC EVENTS	REFERENCES
10000 – 11000 cal yr BP	An enormous sediment discharge by the Ganga- Brahmaputra, led to formation of deltaic silt deposits up to 60 m thick over the oxidised low stand surface.		Allison et al, 2003
11 ka	The initial formation of the G- B delta occurred around.	Banerjee and Sen, 1988; Umitsu, 1993; Vishnu- Mittre and Gupta, 1972	
11 – 7 Ka	Enormous sediment discharge to the G –B delta was at least 2.3×higher than present.		Goodbred and Kuehl, 03
Early Holocene	River discharge was greatly reduced but sediment discharge was increased.	dominance of the dry northeast monsoon, continued climatic warming and through occurrence of ice sheet melting related with surface runoff was increased with strengthening southwest Indian Monsoon.	Cullen,1981; Wiedicke et al, 1999, Goodbred and Kuehl, 2000.
	High sediment discharge was sufficient to halt transgression and resulted progradation of the Ganga- Brahmaputra delta.	The intense summer monsoon with an estimated rise in precipitation of 20 –	Steven et al, 2003, Singh. I.1996

		100 percent in the Northern Hemisphere	
	Maximum transgression was reached at 100 km inland of present shoreline including Sundarban and was followed by delta plain progradation.		Banerjee and Sen, 1988; Umitsu, 1993; Goodbred and Kuehl, 2000, Allison et al, 2003.
	The increased sediment accumulation was influenced by enhanced subsidence along NE-SW trend which is a hinge zone provide accommodation space for sedimentation.		Stanley and Hait, 2000
Mid Holocene	Relatively low subsidence in central and north-western delta, which decreases towards south- and south-central part of delta reveals deeper water condition or, high sea level.		Stanley and Hait, 2000
	Rapid sea level with high land subsidence has been identified.		
5000 cal years BP	Delta progradation was undertake in the Sundarban part.		Allison, M.A et al., 2000
2500 cal Years BP	Delta formation was finished		Allison, M.A et al., 2000

Late Holocene	A balance between increasing rate of sediment accumulation by high fresh water influx with decreased sea level rise.		Stanley and Hait, 2000
	A decreased rate of sediment accumulation		Stanley and Hait, 2000

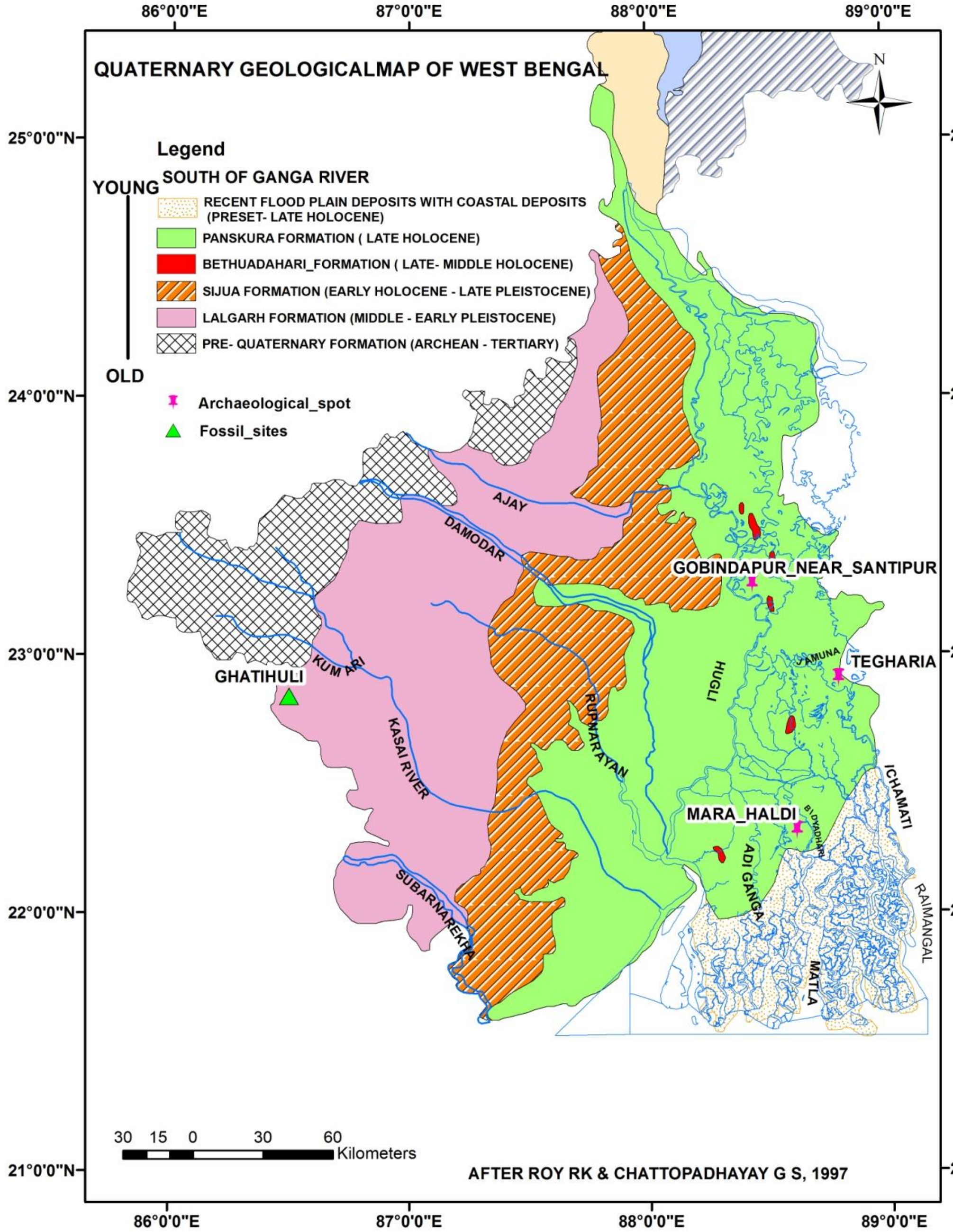


Fig 3.2 Showing the Quaternary Geological Map of West Bengal.

3.6 Spatial division of Quaternary depositional set up in Bengal Basin

Figure 3.2 shows the Quaternary Geological Map of West Bengal, based on the work of Roy R.K. & Chattopadhyay G.S. (1997). This geological map is a vectorized version of the original map, created using ArcGIS 10.8 GIS Mapping and Data Analysis Software. The map illustrates that the entire area of West Bengal, particularly the Lower Ganga Delta Plain, is divided into six geological formations:

1. Pre-Quaternary Formation
2. Lalgarh Formation
3. Sijua Formation
4. Bethuadahari Formation
5. Panskura Formation
6. Recent Floodplain Deposits with Coastal Deposits

From the geological map, it can be interpreted that the western part of the region is geologically older, with Pre-Quaternary deposits, while the eastern part and coastal regions are progressively younger.

- The Pre-Quaternary deposits cover the entire portion of Purulia district, along with parts of Birbhum and Bardhaman districts.
- The Lalgarh Formation (Middle to Early Pleistocene Epoch) spans parts of Paschim Medinipur, Bankura, Bardhaman, and Birbhum districts.
- The Sijua Formation (Late Pleistocene to Early Holocene Epoch) is found in the eastern part of Paschim Medinipur district, the eastern part of Bardhaman, the western part of Murshidabad, and the western part of Hooghly district.
- The Panskura Formation (Late Holocene) is present in Purba Medinipur, Howrah, Hooghly, Nadia, Murshidabad, the northern part of North 24 Parganas, and Malda districts.
- The extreme southeastern part, i.e., South 24 Parganas district, is composed of recent floodplain deposits and coastal deposits from the Late Holocene to the present time.

In summary, the Lower Bengal Delta Plain is primarily covered by a combination of Early to Late Holocene deposits, consisting of the Sijua Formation, Panskura Formation, and Recent Coastal Deposits.

In the realm of Bengal Basin, the depositional set up of the Quaternaries may be divided into 3 morphogenetic domains: 1). Domain of the peninsular rivers on the shelf margin, 2). the foredeep belt or, the domain of the Himalayan River and, 3). Ganga delta

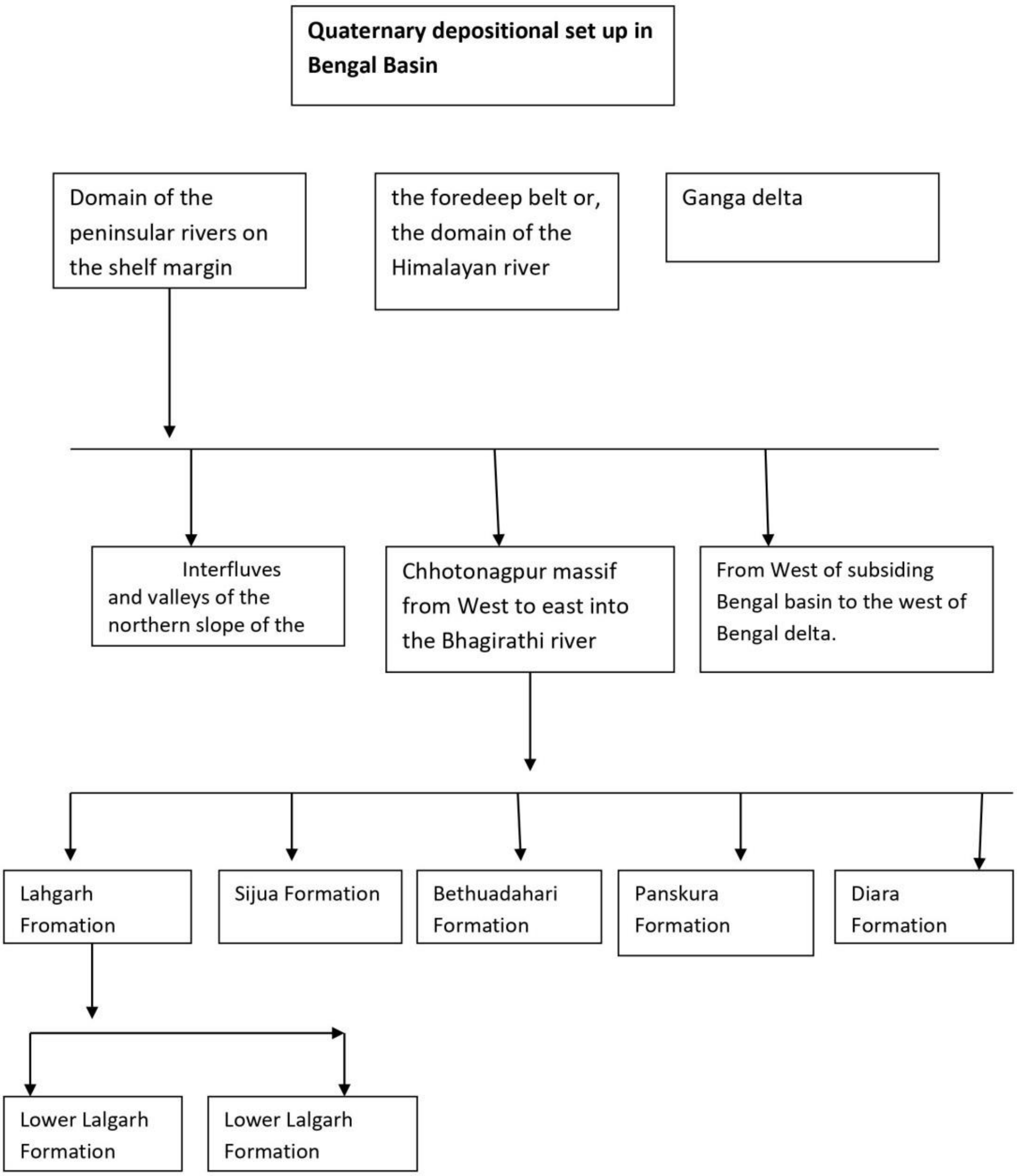


Fig 3.3 Flow chart showing Quaternary depositional set up in Bengal basin.

3.6.1. Lalgarh Formation

Area coverage and nature: The Lalgarh Formation, the oldest among the Quaternary deposits, is characterized by a coarsely dissected upland surface with a persistent laterite cover. This upland is distinguished by dendritic to sub-dendritic drainage patterns, well-incised channels, and badland topography. The outcrop area of this formation ranges from 140 m to 42 m above mean sea level (m.s.l.). It can be traced along the margin of the Chotonagpur massif and in the interfluves of the peninsular rivers draining the western shelf area of the Bengal Basin. The name Lalgarh Formation was proposed because the contact with the underlying Neogene sediment is clearly exposed in the Lalgarh area.

Lithology:

1. **Lower Lalgarh Formation:** This level consists of boulder-pebble conglomerate in the cis-Damodar area and pebble conglomerate in the Trans-Damodar area. The entire Lower Lalgarh Formation is predominantly covered by laterite, with well-developed ferricrete, lithomarge, and saprolite profiles.
2. **Upper Lalgarh Formation:** This formation is composed of finer clastics and sand, with occasional pebbles and granules. At the top, there is a layer of nodular detrital laterite, which is underlain by a more compact latosol layer.

3.6.2 Sijua Formation

Area Coverage and Nature: This is the highest and oldest alluvial terrace, consisting of floodplain deposits, valley fills, and delta fans over the eroded surface of the Lalgarh Formation. This formation covers parts of Medinipur, Bardhaman, Bankura, and Birbhum districts, as well as the Kasai and Ajay basins.

• **Lithology**: The formation is characterized by a nodular and compact calcrete pedocalcic soil horizon. The nodules, ranging from 0.5 cm to 2.0 cm in diameter, are found 0.5 to 1.6 meters below the surface. The thickness of the calcic horizon varies from 0.2 to 12 meters. Late Pleistocene and Early Holocene fluvial and fluvio-aeolian deposits are common features of this layer.

The surficial cover of this formation can be divided into three sequences:

- 0.0m to 0.9m: Gray Silty Loam
- 0.9m to 9.0m: Silty Clay with thin lenses of very fine greyish sand
- 9.0m to 26.0m: Fine to Coarse Sand Layer

3.6.3 Bethuadahari Formation

- **Area** Coverage and Nature: This area represents the older meander belt deposits on the elevated upland, which has been extensively eroded by the younger meander belt over the floodplain.
- **Lithology**: The primary lithological characteristics include yellow and pale brown very fine sand, silt with soft iron nodules, and detrital caliche nodules. The silty loam ranges in color from yellow to brown, while the presence of red soil indicates a more mature soil profile compared to the newer floodplain. The iron-rich nature of this formation suggests a post-depositional humid climate.

3.6.4 Panskura Formation

- **Area Coverage and Nature**: This formation is primarily characterized by aggraded floodplain, meander belt, and delta fan deposits. These present-day river deposits lie over the eroded surface of the Lalgarh Formation in the upper reach and over the Sijua Formation in the lower reach.
- **Lithology:** The formation consists of a varied sequence of silt, clay, and sand of different sizes. The sediments are predominantly unoxidized, with thickness ranging from 1.0 m to 10.0-15.0 m in the Hugli River domain. The silt-clay deposits gradually change into silt-clay and fine sand in the delta fan area, with the sediment wedge thickness increasing from west to east towards the Hugli River. The recovered carbonaceous material suggests that the age of this formation ranges from 4810 ± 120 years B.P. to as young as 780 ± 120 years B.P.

3.6.5 Recent Flood Plain and Channel Deposits

- **Area Coverage and Nature:** This formation is named *Diara* due to the presence of numerous mid-channel bars, point bars, and cut-off meander deposits. It is characterized by active channels, channel bars, active meander belts, and floodplain deposits within the active river channel, influenced by a dynamic hydraulic regime. These deposits are laid over the eroded surface of the Panskura Formation. This formation is known by different names in various regions: *Bhagirathi Formation* in the

Ganga River unit, *Ajay Formation* in the Ajay River, and *Kasai Formation* in the Kasai River.

- **Lithology:** The formation consists of silty and clayey deposits in the floodplain and sandy deposits in the channel regions. As this regime is shaped by each flood cycle, the overbank deposits vary from finer grain sizes to silt and clay.

3.7 The channel networks of Lower Ganga Delta Plain

3.7.1 Bhagirathi Hugli River system

The non-tidal regime of the Bhagirathi River, between Jangipur and Nabadwip, is highly dynamic, oscillating continuously within its meander belt (Rudra, K., 2014). Hirst (1915) described the complex and abnormal nature of tributaries such as the Bhairab-Jalangi, the Mathabhanga-Churni, and the Icchamati rivers. The floodplain of the Bhagirathi is characterized by numerous wetlands and abandoned meander loops. This river is an offshoot of the Ganga-Padma, which has degenerated over the last few centuries (Rudra, K., 2015).

The largest delta in the world, the Bengal or Ganges Delta, is bordered by the Bhagirathi-Hugli in the west, the Ganga or Padma in the north, and the combined flow of the Ganga, Padma, and Brahmaputra in the east. However, these boundaries are not fixed due to the changing nature of rivers caused by avulsion and erosion-accretion along the southern part (Rudra, K., 2015). According to Rudra (2015), the distributaries that originated from the Ganga-Padma system in India and Bangladesh are in a state of rapid decay, with the Bhagirathi-Hugli considered the oldest channel of the Ganga.

Several vulnerable stretches of the Bhagirathi River have seen habitual course changes. Important events that produced meander loops were described by Rudra (2014). A meander cutoff occurred just upstream of Nabadwip in 1990 after the Farakka Barrage was commissioned. In 1994, near Shantipur, the river changed course, reducing its length by 10 km. In September 2000, another disastrous event occurred when the river avulsed into the Gobra River (Chapman and Rudra, 2007). The lower part of the Bhagirathi River, in the tidal regime, is less dynamic because the banks are composed of fine silt and clay, which prevents oscillation (Rudra, K., 2014).

According to Rudra (2014), several oxbow lakes and cutoffs along the Bhagirathi-Hugli, such as those near Bhabta, Nabadwip, and Shantipur, formed after 1975 due to increased discharge through the channel. However, Bandyopadhyay et al. (2015) disagreed, stating that two oxbow lakes near Bhabta actually formed between 1949-51 and 1967, a cutoff near Nabadwip occurred in 1989, and an oxbow lake near Shantipur formed between 1967 and 1972. Bandyopadhyay et al. (2015) also mentioned that the channel cutoffs of the Bhagirathi-Hugli River are mainly confined to its upper 314 km. Between 1975 and 1994, four cutoffs formed at an average rate of one every 9.8 years, and five oxbow lakes formed at an average rate of one every 10.6 years. Furthermore, Bandyopadhyay et al. (2015) highlighted the decay of the Bhagirathi-Hugli by illustrating an increasing sinuosity index from 1.73 in 1849-55 to 1.96 in 1947.

According to Majumder (1942) and Morgan and McIntire (1959), the easterly tilting of the delta during the Holocene and the continuous diversion of the main flow of the Ganga through the Padma are major causes of the decay of the Bhagirathi-Hugli River (Rudra, K., 2014). As stated by Rudra (2014), the thalweg of the Ganga-Padma River has become deeper than that of its distributaries, such as the Bhagirathi, Bhairab-Jalangi, and Mathabhanga-Churni. This is one of the leading reasons for the decay of these distributaries. Additionally, the water level of the Padma is much lower than the height of the off-takes during the lean months, contributing to the decay.

Rudra (2014) referred to an unpublished map by the Nadia River Division, which shows the changing position of the Bhagirathi off-take between 1824 and 1852. In 1824, the Bhagirathi was about 22 km upstream of Suti, near Farakka, and shifted 11 km southeast due to the course change of the Ganga in 1825. Between 1825 and 1830, the Bhagirathi off-take shifted 5 km downstream. During the flood of 1871, another connection opened between the Ganga and the Bhagirathi about 10 km southeast of Suti. Rudra (2014) states that the Bhagirathi was connected with the Ganga at three locations: Dhulian, Suti, and Giria, as shown in the topographical sheets (no. 72P/13, 14, and 72D/2,3) from 1917.

Decaying of different distributaries have been explained by Rudra. K, 2014 and Bandyopadhyay, 1996, 2014.

3.7.2 Decaying distributaries of the river Bhagirathi- Hugli and Padma

3.7.2.1 Shifting and decaying course of Adi Ganga

The river Adi Ganga was a medieval outlet of the Bhagirathi River, originating from the Hugli River at Dahighat. It flowed through Kalighat, Garia, Baruipur, and Jaynagar (Rudra, K., 2014), eventually discharging into the sea through the Saptamukhi or Thakuran estuary (Rudra, K., 2014). According to Mandal (2018), as described by Babu (1976) and Das et al. (1985), the 5 km wide and 50 km long levee zone to the south of Kolkata marks the course of the Adi Ganga. South of Khari, the Adi Ganga flows to the sea through the Saptamukhi estuary along the Gobadiya creek, as described in the Chaitanya Bhagabat or Chaitanyamangal (Rudra, 1981, 1986, 1987).

Rudra (2014) notes that the lower course of the river has now become a series of small pools of stagnant water due to sedimentation, human intervention, and the interruption of roads at various points, particularly after Garia. However, this river was an important navigational route during medieval times, as reflected in Bengali literature, including the Mangalkavya and Chaitanyabhagabat (Rudra, K., 2014).

The Adi Ganga is a paleochannel, once a medieval outlet of the Bhagirathi-Hugli River, which now carries wastewater from southern Kolkata (Bandyopadhyay et al., 2015). According to Bandyopadhyay et al. (2015), the Adi Ganga can be traced up to 80 km downstream of its off-take from the Bhagirathi-Hugli. The upper 13 km of this course was excavated between 1775 and 1777 to form a navigational canal connecting Kolkata port to the Bidyadhari River, which was directly connected to the Matla River. The Matla River was a major estuary and waterway in eastern Bengal through the Sundarbans (Bandyopadhyay et al., 2015). The lower part of the Adi Ganga, which is now traceable as a series of elongated pools of stagnant water, is further identifiable only by relics of its levee (Bandyopadhyay et al., 2015).

Once, this river flowed into multiple channels south of Basantapur, south of Surjyapur, including the Baratala, Saptamukhi, and Thakuran rivers. Today, the river is still traceable as a water body in Baruipur, Dakshin Barasat, Jaynagar, and Diamond Harbour. Additionally, some tanks excavated along the course of the Adi Ganga are still found in Joynagar and Vishnupur, and are referred to as the "Ganga" by local people (Mandal, A., 2018).

3.7.2.2 The Moni River

The river Moni is a distributary of the Adi Ganga, originating from the main flow of the Adi Ganga at Mirzapur, located to the northeast of Chatrabhog. Along its course, it is known by different names. From the source up to approximately 2 km, it is referred to as Patnighata Khal. Further downstream, it is called Nalua Gang or Nalua River. After this, the river divides into two branches. The southwest-flowing distributary is known as Raydighi Gang or Raydighi River, while the southeast branch flows as the Moni River, which ultimately meets the river Thakuran (Naskar, D., 1993).

3.7.2.3 Shifting and decaying course of Jalangi and the Mathabhanga- Churni

The Bhairab-Jalangi and Mathabhanga-Churni are offshoots of the river Padma, flowing southwestward. In contrast, all other distributaries of the Bhagirathi-Hugli flow south to southeast, connecting the Padma with the Bhagirathi (Rudra, 2014). The orientation of these flows is explained by subsidence, as described by Hirst (1915). It is also noted that the river Bhairab now flows through the course of the Jalangi. Sometime in the late eighteenth century, the Bhairab-Jalangi and Mathabhanga-Churni rivers changed to their present course due to subsidence, as stated by Hirst (1915). Meander migration, avulsion, and multiplication have been suggested as reasons for the course change of the Mathabhanga-Churni River, as stated by Rudra (2014), although this notion is denied by Bandyopadhyay et al. (2015).

The river Jalangi, which joins the Bhagirathi near Nabadwip, has been changing its course through meander migration. Similarly, the Mathabhanga and Churni rivers, which also join the Bhagirathi at Kalinarayanpur, are changing their course due to meander migration. However, both rivers are now detached from the main flow of the Padma. In the early 20th century, the Jalangi, Mathabhanga, and Churni rivers were disconnected from the Padma and are now flowing in highly sinuous conditions, with many abandoned loops. The Jalangi River, now detached from the Padma, receives water from the Bhairab and some flow from Gobra, which is a paleochannel of the Bhagirathi. The Mathabhanga, which formerly off-took from the Padma, has bifurcated into two rivers: the Icchamati and the Churni (Rudra, K., 2014).

3.7.2.4 Changing course of the Saraswati

Below Nabadwip, the stretch of the Bhagirathi is known as the Hugli, with Tribeni being an important location from where three channels branched off: the Saraswati in the west, the Hugli in the middle, and the Jamuna in the east (Rudra, K. 2014). According to Rudra (2014), the Saraswati River is a moribund distributary of the Bhagirathi-Hugli, which took off near Tribeni and flowed southward. After 77 km, it rejoined the Bhagirathi-Hugli River near Sankrail. Tamralipta, now known as Tamluk, was another important location where archaeological ruins were excavated on the right bank of the Rupnarayan River (Rudra, 2014).

Rudra (2014) mentions that by the 14th and 15th centuries, the Saraswati River had already begun to decay, making navigation difficult and causing the port of Satgaon to suffer. According to Mukherjee (1938), during the Bengal Survey conducted by Rennell (1764-1777), the Saraswati was reduced to a small creek, with a depth of only 2.29 m near Tribeni during high tide.

The Saraswati River, once an important outlet of the Bhagirathi-Hugli during the medieval period, is greatly degraded today. Although its channel is still active, it remains dry during the lean period, from May to August (Bandyopadhyay et al., 2015). Satgaon, the principal port city on the Saraswati River, was a major trading city from the 15th to the late 16th centuries (Bandyopadhyay et al., 2015; Hunter, 1876, p. 262; Crawford, 1903, p. 2; Mukerjee, 1938, p. 111). According to Rennell's book, published in 1788, Satgaon was a large trading city in 1566, when small vessels could still pass through the Saraswati River.

Bandyopadhyay et al. (2015) mention that after Satgaon, the river's course continued through Adaumpour (now untraceable), Omptah (present-day Amta), Tamlook, and the Old Ganga. The Old Ganga is a paleochannel of the Saraswati River, as stated by Bandyopadhyay et al. (2015), and was referred to by Gastrell in the navigational chart of lower Bhagirathi-Hugli.

3.7.2.5 Decaying curse of Jamuna and Icchamati

The Jamuna River, another offshoot of the Bhagirathi, delineates the northern limit of the Southern Delta region in West Bengal. The tidal waters along the active rivers Saraswati and Bidyadhari, which meet at Tribeni, resulted in extensive sediment deposition and the formation of a channel bar at Tribeni. This channel bar forced the Hugli River to open a new path, the Jamuna, which likely formed after the decay of the Bidyadhari (Rudra, K. 2014). Currently, the course of the Jamuna is disconnected from the main flow near Kalyani and meets the Icchamati River near Charghat in North 24 Parganas, flowing through a 66 km extremely sinuous path.

According to Rudra (2014), the Jamuna was a navigable channel until the late 19th century, as described in various literary and historical records. Bipradas Pipilai, in 1495 A.D. in Manasamangla, referred to the Jamuna as a "Bishal" or mighty river, indicating that in the 15th century, the Jamuna was a very active river. Another description by Hunter in 1875 called the Jamuna a deep river, navigable by larger trading boats throughout the year. However, in 1780, Rennell mapped the Jamuna as a feeble or weak channel (Rudra, K. 2014).

3.7.2.6 Decay of the river Icchamati

The Icchamati River is an offshoot of the Mathabhanga River at Majhdia, east of Krishnanagar, and it receives the Jamuna River at Charghat in North 24 Parganas. The river flows southward along a sinuous course through Bongaon, Charghat, and the Indo-Bangladesh border (Rudra, K. 2014). Its 240 km long course discharges water into the sea through the Harinbhanga estuary.

The Icchamati River was navigable year-round in 1795 A.D. (Garrett, 1910), but it has decayed due to reduced water supply from the Mathabhanga River (Rudra, K. 2014). Currently, the upper portion of the Icchamati has degenerated in many places, while the lower portion remains active as tidal water flows up to Charghat (Rudra, K. 2014).

3.7.2.7 Decaying distributary: The river Bidyadhari, Sunti and Noai

The Bidyadhari River is another ancient distributary of the Bhagirathi River, originating from a meander cut-off of the Bhagirathi known as Mathura Bill, near Kalyani, which is an abandoned meander loop. The course from Kalyani to Guma is known as Nona Gang (creek) and is very sinuous. From Guma to Haroa, the river is called Bidyadhari. Other names for this river mentioned by Mitra (1995) include Sealdah Gang and Harua Gang (Rudra, K. 2014). Near Tehatta, the river bifurcates into two branches. The western branch flowed into the Matla Estuary until the first half of the 20th century, while the eastern branch flowed into the Harinbhanga Estuary, known as Kulti Gang (Rudra, K. 2014).

As described by Rudra (1981), the present-day Bidyadhari used to flow to the sea through the ancient Mega, one of the five distributaries of the Ganga identified by the famous Greek geographer Claudius Ptolemy in the 2nd century A.D. This is now known as the Harinbhanga Estuary. The important ancient port of Chandraketugarh, which facilitated maritime trade between India and Rome from 300 B.C. to 500 A.D., stood on the bank of the Bidyadhari River (Rudra, K. 2014; Ray, 1979).

After 500 A.D., the water supply to the upper part of the Bidyadhari started to decrease due to the westward shifting of the Bhagirathi near Kalyani (Rudra, K. 2014). Through the western branch of the old Bidyadhari, tidal water flowed into the East Calcutta Wetlands in the early 20th century. However, this process ceased after the disconnection from the Matla River (Rudra, K. 2014).

3.7.2.8 Beheaded River: Sunti and Noai

The rivers Sunti and Noai are other beheaded rivers that flow through the interfluves between the Hugli and Bidyadhari. These rivers have been interrupted by human activity multiple times. The human interference in the flow of the Sunti and Noai rivers has led to the formation of many small pools, which are only waterlogged spots during the monsoon season, as stated by Rudra, K. (2014).

3.7.2.9 Decay River Piyali

The river Piyali is a tidal river that deviates from the river Bidyadhari near Pratapnagar in South 24 Parganas. It flows about 45 km south and eventually joins the Matla River (Das, G.K., 2015). According to Naskar, K. (1993), the river Piyali, which bifurcates from the Bidyadhari about 14 km north of Bamanghata, has become a narrow channel due to siltation, resulting in low, cultivated land. Rudra, K. (2014) notes that the river Piyali was active until the 19th century and served as a connector between the Adi Ganga and Bidyadhari rivers, a point also mentioned by Hunter, W.W. (1875) in the Statistical Account of Bengal. However, this view is disputed by Bandyopadhyay, S. et al. (2015), who assert that the river Piyali actually connected the Bidyadhari and Matla rivers.

The river exists today as a narrow canal near the Uttar Bhag pumping station, and then flows through Dhosa-Amtala (where the Suryapur Khal meets the Piyali river) and Herobhang before falling into the Matla River near Rendho Khali (Naskar, K., 1993). Several instances of human interference along the Piyali's course have been described by Das, G.K. (2015), such as the construction of a pumping station near Uttarbhag Ghat to drain water from Garia, Sonarpur, and Baruipur. Additionally, a large rainwater dam near Ambikanagar has blocked the southern part of the river. According to Mondal, B. (2015), the main issues facing the Piyali today due to human intervention include loss of water flow, narrowing of the river course, increased siltation, water pollution, and the presence of brick industries along the riverbank. Extensive cultivation in areas such as Kothabati, Mahishmari, Dhosa, and Dhankhola since the 20th century has also contributed to these problems.

3.7.2.10 The River Matla

The river Matla is formed by the combined flow of the Kartoa, Atharobaki, and Bidyadhari rivers. It sometimes flows through narrow channels and at other times spreads out in wider paths, with varying flow speeds as it meets the sea (Naskar, K. 1993). Currently, near Canning, its width is only 1 km, expanding to 3 km near Herobhanga jungle and 13 km near the mouth. In 1853, the Governor General Lord Dalhousie built the Canning port along the bank of the Matla River, recognizing its wide course and substantial water flow. The main distributaries of the river Matla include the Hogla, Piyali, Herobhanga, Kakalmari, Ajmalmari, and Mayadeep rivers (Naskar, K.1993). This tidal river was once widely used as a maritime trade route connecting eastern districts to Calcutta by water, though it has become a narrow, moribund flow in the present day (Naskar, K.1993).

According to Seto (2011), Syvitski & Saito (2007), and Szabo et al. (2016), deltas have significant socioeconomic, agricultural, and environmental value, with dense populations relying on them. In the Bengal Delta, more than 150 million people depend on groundwater as a primary source of drinking water due to its availability and lower risk of microbial contamination. However, 27.5 million people drink groundwater with high levels of geogenic arsenic, and approximately 20 million people consume salted groundwater (Bangladesh Bureau of Statistics, 2011; Xu et al., 2023). As pointed out by Guo et al. (2018), Triantafilis & Buchanan (2009), and Karmokar et al. (2021), palaeochannels serve as crucial aquifers, and identifying these channels is important for groundwater management.

Karmokar et al. (2021) emphasize the importance of identifying and mapping palaeochannels in the Gangetic Delta due to the dynamic nature of the Ganga River. These channels, often created by river cut-offs, result in abandoned rivers that act as palaeochannels, significantly impacting groundwater recharge, local ecology, economy, and social life, particularly in districts like Murshidabad and Nadia. The Bhagirathi River's dynamic nature leads to the formation of many palaeochannels in the Gangetic Delta Plain.

Karmokar et al. (2021) also provide insights into previous work on palaeochannel identification, noting an increase in the use of remote sensing for palaeochannel mapping since the 1950s. Their work references studies by various authors, such as Bridge, Kalick, Wi et al., Xu et al., Lawrie et al., and others. For instance, Hou and Mauger identified palaeochannels using Digital Elevation Models (DEM) and sedimentological analysis in the Harris Greenstone Belt of South Australia. They also mention studies conducted in India, including works by Khan, Rajawat et al., Rathore et al., and others. In parts of Punjab, Haryana, and Rajasthan, Landsat Multispectral Scanner (MSS) or Thematic Mapper data were used to delineate palaeochannels of the Saraswati and Drishavadi rivers. Upadhyay et al. (2021) employed remote sensing, geophysical, and sedimentological techniques for palaeochannel delineation and mapping. Bandyopadhyay et al. (2015) identified some palaeochannels of the Bhagirathi River system, while Mohammed M.A. & Balasubramanian A. (2001) used remote sensing data for palaeochannel identification around the Cauvery River near Talakad in Karnataka. Additionally, Re G.L. et al. (2018) used high-resolution maps for mapping palaeochannels in the Manawatu River in southern North Island, New Zealand.

Based on these previous studies, the present research aims to identify and map palaeochannels in the Lower Ganga Delta Plain in the North and South 24 Parganas districts of West Bengal.

Chapter 4 Nature of ancient Terracotta Art and Figurines of the study site and time lines derived from Artistic Style

4.1 Chronological Evolution of Civilization under different dynasties

The evidence of various stone tools confirms the presence of human beings in the Old Stone Age and the Middle Stone Age in different parts of India. Although they were nomads, they were divided into small groups. However, a new chapter in human history began during the New Stone Age. The time period of the New Stone Age is around 9000 BCE globally, while the oldest settlement in India was found in Southeast Asia around 7000 BCE. Some settlements in the Vindhya Mountains date back to 5000 BCE. However, there is no evidence of human settlement in southern India before 1000 BCE.

Simultaneously, the use of metal, especially copper, instead of stone marked the emergence of the Copper Age at the end of the Stone Age, around 3000 BCE. Around 2000 BCE, the decline of city life in the Harappan civilization occurred, coinciding with the arrival of the Aryan community in the western part of India. The Vedic period lasted from 1500 BCE to 600 BCE, during which black metal, painted grey ware, glass bracelets, and other archaeological artifacts have been excavated.

After the Vedic period, the Maurya Empire emerged as the dominant ruling power across most of India. The Shunga Empire (200 BCE to 300 CE) succeeded the Maurya's, ruling over the entire Gangetic plain, including Pataliputra in Bihar, Vidisha in Madhya Pradesh, and Ayodhya in Uttar Pradesh. The presence of gold coins and inscriptions from the Kushan period indicates that their empire not only controlled the northwestern part of India and the Sindhu region but also dominated most of the Gangetic plains.

All these dynasties expanded their territories across India, except for the eastern Gangetic delta plain. The focus of this study is to investigate the evolution of civilization in the Lower Ganga delta plain under different dynasties and to analyse the relationship between the spread and retreat of ancient civilizations over the last 3000 years in relation to coastal evolution.

4.2 The Legendary Period in Bengal

The history of both legendary and social-political life in Bengal begins in 326 BCE, during the influence of the Aryan population as they started expanding into the region. The earliest inhabitants of Bengal belonged to diverse cultural and ethnic backgrounds. There are various perspectives regarding the origin and characteristics of ancient Bengal's people. However, one important and interesting aspect is that the earliest people of Bengal had a strong connection with the ocean.

4.2.1 Early History from 326B.C. to 320 A.D.

The early historic people of Bengal emerged during the latter half of the 4th century BCE, and the population of this specific time period was known as the Gangaridai, as mentioned by Greek and Latin writers. However, there are various viewpoints regarding the spatial distribution of the Gangaridai population. Some writers placed Gangaridai to the west of the Ganges, while another view suggests that it was located along the easternmost branch of the river, separating India from Indo-China—an area where Alexander the Great did not venture. A similar description can be found in the writings of Diodorus.

Pliny described Gangaridai as the land through which the final course of the Ganges flows, whereas Ptolemy stated that the mouth of the Ganges was inhabited by the Gangaridai. According to Ptolemy, the city of Pataliputra was located far from the Ganges, including regions such as Tamralipti, while Gangaridai was even farther from this territory.

4.2.2 Maurya Period

After the withdrawal of Alexander, the Maurya period became renowned for its efficient governance. Several punch-marked coins from this period have been excavated in Bengal. In the mid-3rd century CE, Vikramapura, the capital of Vanga, was replaced by a settlement known as the "Gold Village." Excavations from this village have uncovered gold coins depicting a standing, bearded figure of Kanishka.

4.2.3 Samatata

Samatata was a new kingdom that emerged in Eastern Bengal. The Kingdom of Pushkarana, located in the Bankura district, was ruled by Sivhavarman during the late 3rd and early 4th century CE.

4.2.4 Rise of Gauda and Vanga during 320 A.D. – 650 A.D.

The Gupta Empire flourished at the beginning of the 4th century CE. The Gupta imperial authority was strong over Gauda (Northern Bengal) and extended its sovereignty over almost all of Bengal, except for the Samatata kingdom, which roughly corresponded to Eastern Bengal.

From the Damodarpur copper plates of Budhagupta, we learn that by the late 5th century CE, Northern Bengal was an integral part of the Gupta Empire. However, at the beginning of the 6th century CE, clear signs of the empire's decline began to appear. After the fall of Gupta power, several independent states emerged in Northern India. Some of the notable ones included the Pushyabhutis of Sthanvisvara (Thanesar), the Later Guptas of Magadha, and the rulers of Malwa. During this period, Bengal was under different political powers, two of the most significant being Vanga and Gauda, both of which were established in the 6th century CE.

4.2.5 The rise of Vanga

The provinces of Vardhamana-bhukti and Navyavakasika were the first independent provinces to emerge after the fall of the Gupta Empire, corresponding to Western and Southern Bengal. Gopachandra, Dharmaditya, and Samacharadeva were the three known rulers of this kingdom, as identified from inscriptions discovered near Kotalipada in the Faridpur district and another in the Burdwan district.

A large number of gold coins have been found in different parts of Eastern Bengal, including Sabhar (in the Dhaka district) and Kotalipada. These coins were likely issued by Samacharadeva and date back to the 6th–7th century CE, based on their resemblance to Gupta coins. In Vanga, many gold coins have been discovered without any inscriptions identifying the rulers who issued them. Undoubtedly, Bengal during this time was under a strong and independent administration led by powerful kings. However, the Chalukya king Kirtivarman is known to have conquered Anga, Vanga, Kalinga, and Magadha, as recorded in the Mahakuta inscription.

4.2.6 Rise of Gauda and suzerainty of Sasanka

Gauda and Vanga were the two major political divisions of West Bengal throughout the Hindu period. The northern and western parts of Bengal were under Gauda, while southern and eastern Bengal were under Vanga.

During the 6th century, Northern Bengal was under the control of the Later Guptas. However, by the end of the 6th century, King Sasanka became the first independent ruler of Gauda, establishing his capital at Karnasuvarna, which included Rangamati, located about six miles southwest of Berhampur in the Murshidabad district. Sasanka's sovereignty extended over Northern and Western Bengal, including Magadha, and reached as far south as Chilka Lake in Odisha. After Sasanka's death, political power came under Buddhist influence.

4.2.7 Period from 650 A.D. to 750 A.D.

This period was marked by political disturbances, disruptions, and the invasion of Chinese forces in Eastern Bengal. In 702 CE, the Tibetan invasion played a role in Indian politics, although it was for a short duration.

The reestablishment of power by the Later Guptas was another significant event in the latter half of the 7th century and the beginning of the 8th century.

4.2.8 The Palas in the mid of 8^{th} century

The middle of the 8th century marked a new era in the history of Bengal with the establishment of the Pala Dynasty. The history of this dynasty can be divided into six stages. The foundation of the Pala Dynasty was driven by the long-term political disintegration in Bengal. The key figure behind the establishment of a strong, centralized authority was Gopala, who was elected by the people.

In 770 CE, Dharmapala succeeded Gopala, expanding the Pala Dynasty's supremacy westward despite a challenging political situation. His influence also extended into Northern India. Dharmapala was a great patron of Buddhism and founded the famous Vikramashila Monastery in Magadha on a hilltop along the banks of the Ganges.

After Dharmapala, Devapala ascended the throne in 810 CE and expanded the Pala Empire across Northern India. He ruled for 35 years, from 810 to 850 CE, a period considered the golden age of the Pala Dynasty.

After Devapala's death, the prestige of the Pala Dynasty began to decline. However, in 988 CE, Mahipala restored its former glory. He extended his dominion over North and South Bihar, reaching as far as Benares by 1026 CE. Mahipala's contributions included the restoration of Nalanda's monuments and the construction of two temples at Bodh Gaya, as documented in two inscriptions.

Despite these efforts, Eastern Bengal slipped from Pala control as they were continuously engaged in struggles with the Kalachuri kings. As a result, Vanga (Eastern Bengal) came under the rule of the Chandra Dynasty. Under the reigns of Kumarapala, Gopala III, and Madanapala, the Pala Dynasty gradually collapsed between 1120 and 1155 CE.

4.2.9 The Chandra Dynasty (6th to 8th century A.D)

The Tibetan historian Lama Taranatha, in his book *History of Buddhism*, mentioned the presence of the Chandra Dynasty in Eastern Bengal. Layahachandradeva's kingdom encompassed the territory of present-day Comilla.

Interestingly, the alphabets used by Layahachandra have been dated to the latter half of the 10th century CE, supporting the theory that his reign lasted between 900 and 1000 CE. This dynasty was a follower of Buddhism, as evidenced by their copper plate inscriptions.

4.2.10 The Sena Dynasty

There are several controversies regarding the origin of the Sena Dynasty. According to the Deopara inscription, the dynasty originated in Karnata, which corresponds to present-day Mysore and Hyderabad. Another perspective, derived from Pala inscriptions, suggests that during the Pala era, frequent foreign invasions occurred, making it unlikely that the Senas were among them. Samantasena was the first king of the dynasty to establish his kingdom on the banks of the Ganga in his later years.

In the early days of the dynasty, their power was concentrated in Radha. However, over time, they expanded their territory, integrating Vanga and conquering Kalinga under the rule of Vijayasena. Vijayasena restored peace and prosperity in Bengal, a legacy that was maintained by his successor, Vallalasena.

During Vallalasena's reign, his dominion included five regions: Vanga, Varendra, Radha (which comprised Bengal), Bagdi (a portion of Bengal that likely included the Sundarbans), and Mithila (North Bihar). The Sena period also marked significant developments in Sanskrit literature in Bengal. The major capitals of the Sena Dynasty were Vikramapura (near present-day Dhaka in East Bengal), Gauda, and Nadiya.

4.2.11 Invasion of Muslim and extinction of Sena power over Bengal

After Vallalasena, Lakshmanasena ruled for 27 years, up until 1205 CE. His successor, Visvarupasena, ruled over Eastern and Southern Bengal. According to Tabaqat-i-Nasari, a historical work by Maulana Minhaj-ud-din Abu-Umar-i-Usman, the territory of Lakhnawati—spanning both sides of the Ganga, including Radha, Barind, and Banga (covering Western, Eastern, and Southern Bengal)—fell under Muslim rule, while Eastern and Southern Bengal remained under Lakshmanasena. This account suggests that the final downfall of the Sena

Dynasty was closely linked to the Muslim invasion, as they conquered Western and Northern Bengal from Sena control.

4.3 Nature of ancient Terracotta Art and Figurines of Bengal

Muhammad Bakhtiyar Khalji, after his successful attack on the monastery in the city of Bihar, launched a swift and surprise attack on Nadiya, marking the beginning of Muslim rule in the Sena kingdom. As Bengal faced continuous disturbances due to Turkish invasions for about a year, most of the inhabitants of the city fled. The excavated terracotta artifacts from different parts of West Bengal belong to various time periods. In the southwestern districts, mainly Purulia, Bankura, Bardhaman, Birbhum, and Purba and Paschim Medinipur, several Paleolithic sites have been reported. Similarly, Mesolithic sites have been identified in the districts of Purulia, Bankura, Birbhum, Paschim Medinipur, and Bardhaman.

According to Chattopadhyaya et al. (2005), Birbhanpur in the Bardhaman district is the only significant site where microlithic artifacts have been excavated. Neolithic artifacts have mostly been found in the western part of the region and in the foothills of the Himalayas. The districts of Bankura, Bardhaman, and Birbhum are important Chalcolithic sites, where Black and Red Ware culture, which began around the 2nd millennium BCE, is predominant.

The Early Historic period in West Bengal spans from the 1st millennium BCE to 500 CE. Excavations from this period have yielded significant artifacts, including Northern Black Polished Ware, Black Slipped Ware, Rouletted Ware, bone and ivory objects, terracotta seals and sealings, beads made of semi-precious stones, as well as copper and iron objects. Terracotta figurines and plaques are also notable findings from this era. However, stone sculptures are absent during this period. Terracotta art from the medieval period has also been discovered in Bengal, further showcasing the region’s rich artistic and cultural heritage. The abundance of riverine clay and its easy moldability are the primary reasons behind the rich terracotta culture in Bengal compared to other parts of the country. Some of the most significant terracotta-rich sites include Chandraketugarh, Bangarh, Tamluk, Mangalkot, Rajbaridanga, and Pandu Rajar Dhipi.

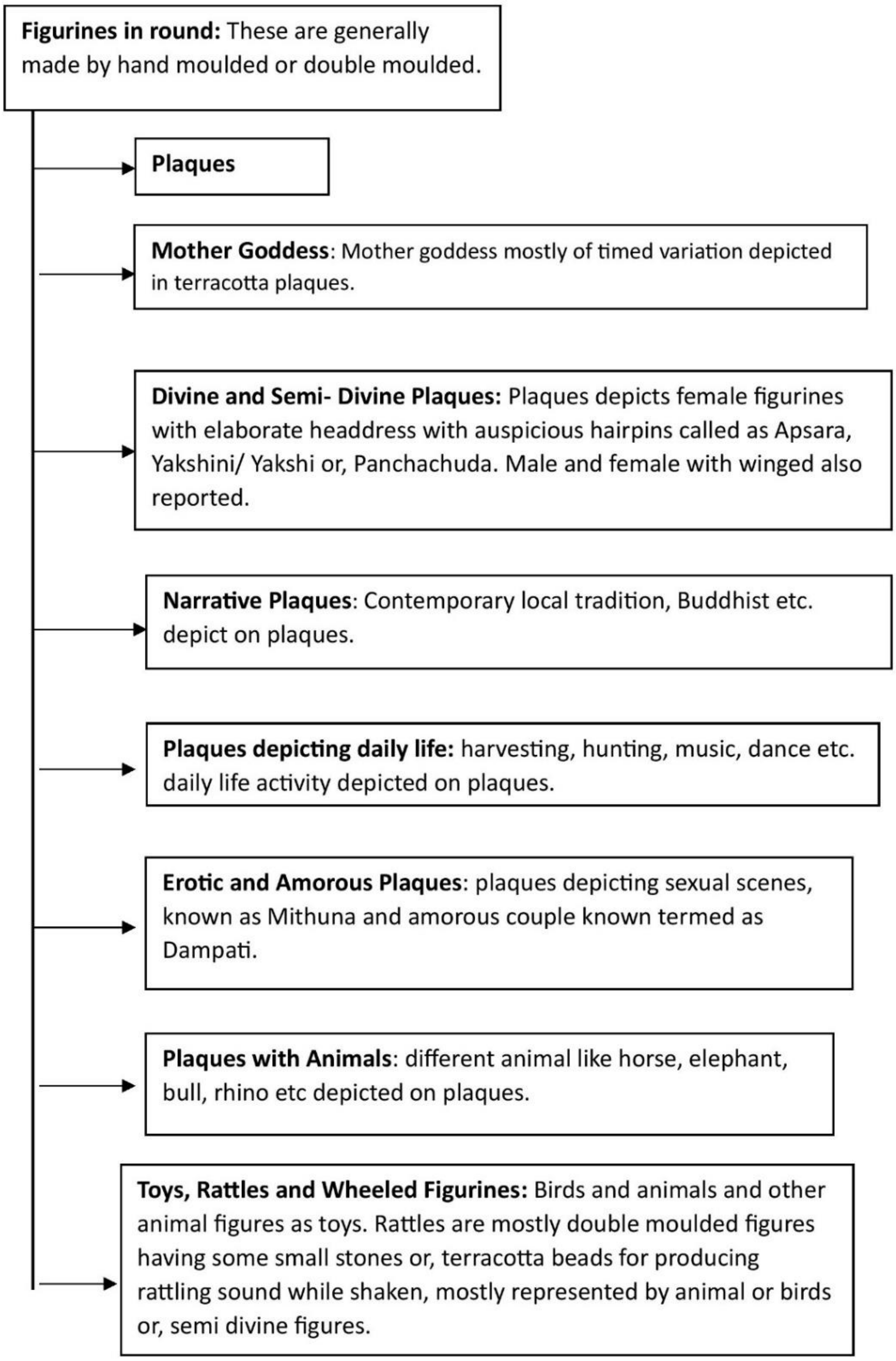


Fig 4.1 Flow Chart showing Nature of ancient Terracotta Art and Figurines of Bengal

4.3.1 Terracotta art forms

4.3.1.1 Terracotta Plaques

Terracotta objects are made of baked earth or clay and have been crafted by humans since ancient times for household use, rituals, aesthetic purposes, and sculptures (Thakur, M., 2022). In ancient times, these terracotta sculptures were shaped from clay, dried under direct sunlight, and then hardened at high temperatures. Finely crafted terracotta art from the Early Historic period has been discovered in various parts of Bengal, particularly in Chandraketugarh, Tamluk, Mangalkot, and Pandu Rajar Dhipi, as noted by Thakur (2022). Other Early Historic sites such as Tilpi, Dhosa, Harinarayanpur, and Boral have also yielded terracotta plaques, as documented by Chakraborty (2016). Additionally, terracotta plaques from the Early Medieval and Post-Gupta periods have been found in Dhonchi, located in the Pathar Pratima block (Chakraborty, S., 2016). According to Thakur (2022), the abundance of clay from the Ganges region was a key factor in the flourishing terracotta art tradition in Bengal.

Terracotta art can generally be divided into two broad forms: figurines in the round and terracotta plaques. Mold-made terracotta plaques were the most common in Early Historic Bengal and were produced on a large scale (Thakur, M., 2022). Some terracotta plaques discovered at Chandraketugarh, Tilpi, and Dhosa depict female figures and floral motifs. Molds used to create these plaques, particularly those featuring female figures, have also been found at Chandraketugarh. Additionally, some plaques from Chandraketugarh depict scenes of contemporary social life, providing valuable insights into the culture of that period.

4.3.1.2 Terracotta Figures

Among terracotta objects, figurines in the round form are another significant type found in West Bengal. These terracotta figures generally include male and female figures, as well as depictions of animals. Among the female figures, the most common representation is that of the Mother Goddess, often depicted holding a child.

Mother Goddess figurines from the Early Historic period have been discovered in Chandraketugarh and Tilpi. Another significant female figure found in West Bengal is known as Yakshi, Panchachuda, or Apsara, typically depicted as a lady adorned with auspicious hairpins. Such Yakshi figurines have been excavated from Chandraketugarh. Additionally, a terracotta head was discovered at Dabu, an Early Historic site located in the Canning block, as mentioned by Chakraborty (2017).

4.3.1.3 Potteries: Fine ware and black ware

Pottery, including Fine Ware, Rouletted Ware, and Black Ware, is among the most significant archaeological findings in the Lower Bengal Delta. Fine pottery, made of refined clay and dating from approximately 400 BCE to 300 CE (the Early Historic period), has been discovered in eastern India, southeastern coastal India, and Bangladesh (Das K. S. et al., 2017). There are ongoing debates regarding the primary site of origin for Fine and Rouletted Ware. As noted by Das K. S. et al. (2017), previous studies by Wheeler et al. (1946), Begley (1983, 1988), Krishnan and Coningham (1997), and Ford et al. (2005) have presented differing views on this subject. According to Salles and Allios (2005), the Gangetic alluvium was the main source of Fine Ware and Black Slipped Ware production, a tradition dating back to 800 BCE. They based this conclusion on the widespread presence of fine pottery across the upper, middle, and lower Gangetic Valley (Das K. S. et al., 2017).

Selvakumar (2008) suggested that since the Ganga Valley was a major source of clay, Fine Ware was likely imported from the Gangetic Delta region to South India. However, contradicting this view, Das K. S. et al. (2017) conducted a geochemical analysis of pottery and found that the origin of Fine Ware was closer to Arikamedu, Tamil Nadu, from where it was exported to Chandraketugarh and Tamluk. Their analysis revealed that pottery recovered from Chandraketugarh, Tamluk, and Arikamedu contained materials derived from the weathering of felsic to intermediate rocks—materials that are absent in the Gangetic alluvium but abundantly available in Tamil Nadu.

4.3.1.4 Coins

Early Indian coins were primarily found in the form of punch-marked coins, mainly made of silver. These coins were small, thin, and roughly square, rectangular, or round in shape, bearing specific symbols created using a weight punch. According to Ghosh, A. (1990), early punch-marked coins in India date back to 600–500 BCE, preceding Alexander’s invasion. Excavations suggest that punch-marked coins can be placed within the same time frame as Northern Black Polished Ware. The extensive use of punch-marked coins occurred during the Mauryan period, spreading to the Deccan and South India (Ghosh, A., 1990). According to Ghosh, silver punch-marked coins featuring wheel or sun-like stamped designs, discovered in Taxila, date from the late 600s BCE to the mid-400s BCE, coinciding with the Persian Empire's influence.

In addition to punch-marked coins, early Indian coinage also included cast coins, both inscribed and uninscribed. Uninscribed cast coins, primarily made of copper as a supplement to silver currency, were most commonly found from the Mauryan period, dating from the 4th to the 2nd century BCE. The introduction of inscribed cast coins in northern India began in the 2nd century BCE (Ghosh, A., 1990). However, the process of making cast coins was time-consuming and geographically limited. Another category of early Indian coins includes uninscribed die-struck coins, featuring a lion stamped on the obverse (head) and an elephant on the reverse side. These coins, dating back to around 400 BCE, have been found in regions such as Gandhara, Kausambi, and Mathura.

4.3.1.5 Seals and Sealings

A seal is a stamped device, and when its impression is made on a material, it is called a sealing, both of which are associated with their owner (Ghosh, A. 1990). Seals are significant as they provide valuable information about kingdoms, chronology, titles, and trade relationships. In early India, seals and sealings were primarily used for trade purposes. Seals and sealings have been discovered at several sites in India, including the Indus Valley Civilization, Mesopotamia, and Harappa, with the Indus site yielding the earliest examples. The primary method of making seals involved pressing a moist lump of clay over a knotted string, which was then hardened either by direct sunlight or fire.

In the Lower Bengal Delta, seals and sealings have been excavated from Chandraketugarh. These artifacts are preserved at the State Archaeological Museum of West Bengal in Behala and the Chandraketugarh Museum.

Chapter 5 Results

5.1 Mapping of early historic sites connection with palaeochannel and palaeo levee

In this chapter the locational pattern of archaeological sites related to river in Lower Bengal Delta plain in different historical time period (Early Historic time to Early Medieval time period) have been discussed. As we know the river were the first attractive and suitable locations for the growth of ancient civilization because of multi-opportunity nature of river that made the life easy for ancient people. Several example of ancient river centric livelihood also we can see from the location maps of archaeological site in lower Bengal Delta Plain along Bidyadhari and Adi Ganga. This study also has emphasized on the influence of river Adi Ganga on ancient civilization in lower Bengal deltaic region. Here the excavated archaeological site from 600 BC to 1300 AD are plotted on River layers of lower Bengal Delta plain to delineate fluvio-archaeological interrelation in the past time.

5.1.1 Map showing archaeological sites dates back to Early Historic Period (400 BC-500AD BC) in Lower Bengal Delta Plain.

Distribution of archaeological sites have been shown in Fig 5.1 those are belonging to Early Historic time period fall under 600 to 400 BC. The sites have denoted by red triangle point on the river map of lower Bengal delta plain prepared by Bhadra, T. in 2014. The river Bidyadhari, Matla is the main channel along through ancient elements has been found dates back to Early Historic period. Chandraketugarh, Harishpur, Dabu, Madhabpur, Boral, Deulpota, Harinarayanpur, Dhanchi Thakuran, Dhonchi III and Gobardhanpur are the main sites from where different types of ancient remnants such as structural mound, potteries of early to late historic time on top and early historic potteries, Terracotta head and medallion, Terracotta plaques, Pottery, Terracotta tiles, ancient coins, bishnu idols (900 AD), Dam Dama dhipi, copper coins, sealing's (400- 300 BC), hop scotch, net sinker, terracotta beads, black colour jar, Hubble bubble, Pottery including Rouletted Ware, semi- precious bead, Terracotta plaques, semiprecious stone beads, Pottery, owls with flat base, featureless rims, handles of frying pan etc. have been excavated from these sites. If we see the distributional pattern of archaeological sites, most of the Early historic element has found along the river channel as a linear pattern where at the mouth of the Thakuran archaeological sites have located in a small patch. The Chandraketugarh in which structural remains 400 BC found over which medieval structure known as Khana Mihirer Dhipi, main sites Harishpur and Dabu located along the river Matla from where low mound, potteries of late historic time on top and early historic potteries have

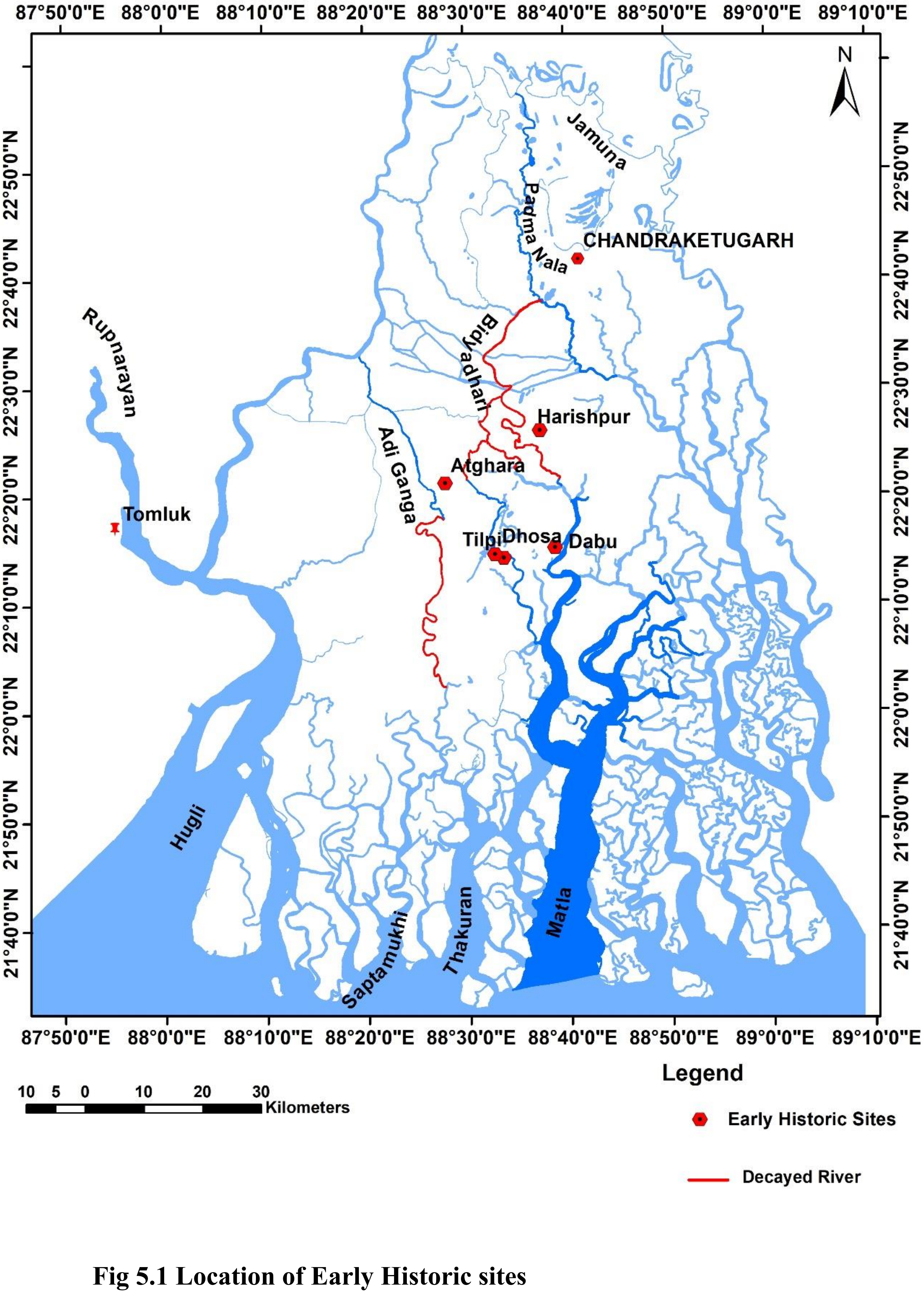


Fig 5.1 Location of Early Historic sites

been found where Madhabpur, Boral are site located along the river Adi Ganga from where some Terracotta plaques, Pottery, Terracotta tiles, ancient coins, Vishnu idols (900 AD), Dam Dama dhipi, copper coins, sealing's (400- 300 BC), hop scotch, net sinker, terracotta beads, black colour jar, Hubble bubble etc. have been excavated. Dhanchi Thakuran, Dhanchi and Gobardhanpur are some places in Dhanchi island where some Pottery, owls with flat base, featureless rims, handles of frying pan, Semiprecious stone beads etc have found. In this map we can see the main distributional nature of early historic element along the Bidyadhari River, although they have been found along the Adi Ganga in Baruipur block and Sonarpur block, one place in Jaynagar II block and three places in Patharpratima block at the mouth of river Adi Ganga. This linear distribution of elements dates back to 600 BC to 400 BC along river Bidyadhari, we can assume that the river Bidyadhari was an active river channel which was suitable for ancient livelihood or, river-based civilization in early historic time.

5.1.2 Mapping of Chandraketugarh, Tilpi Dhosa, Atghara

The Chandraketugarh, Tilpi and Dhosa are some of the early historic sies located along the course of river Bidyadhari. Here, figure 5.2 and 5.3 showing the elevation and contour maps of Chandraketugarh area. Figure 5.2 showing the contour map of surrounding area of Chandraketugarh including Khana Mihirer dhipi, Chandraketugarh fort, hadipur etc located south of Padma nala. From the contour map which prepared from Coastal Dem showing that the elevated part belongs to 6 m to 7 m covering the fort area and from elevation map shows in figure 5.2, implies the khana Mihirer dhipi, hadipur etc located 8 m to 9 m elevation. The elevation of fort wall belongs to near 5 m which following a 'L' shaped.

The contour map showing existence of a number of palaeo levee on the norther part of Chandraketugarh. Here we can find a number of sequences of levee zone covering 8m to 9 m elevation located along east west direction following the river flow of Jamuna. From this pattern of levee we can assume that river has shifted for several time or we can also say that northern part of Chandraketugarh has experienced river shifting incidence for many times in this portion in during past.

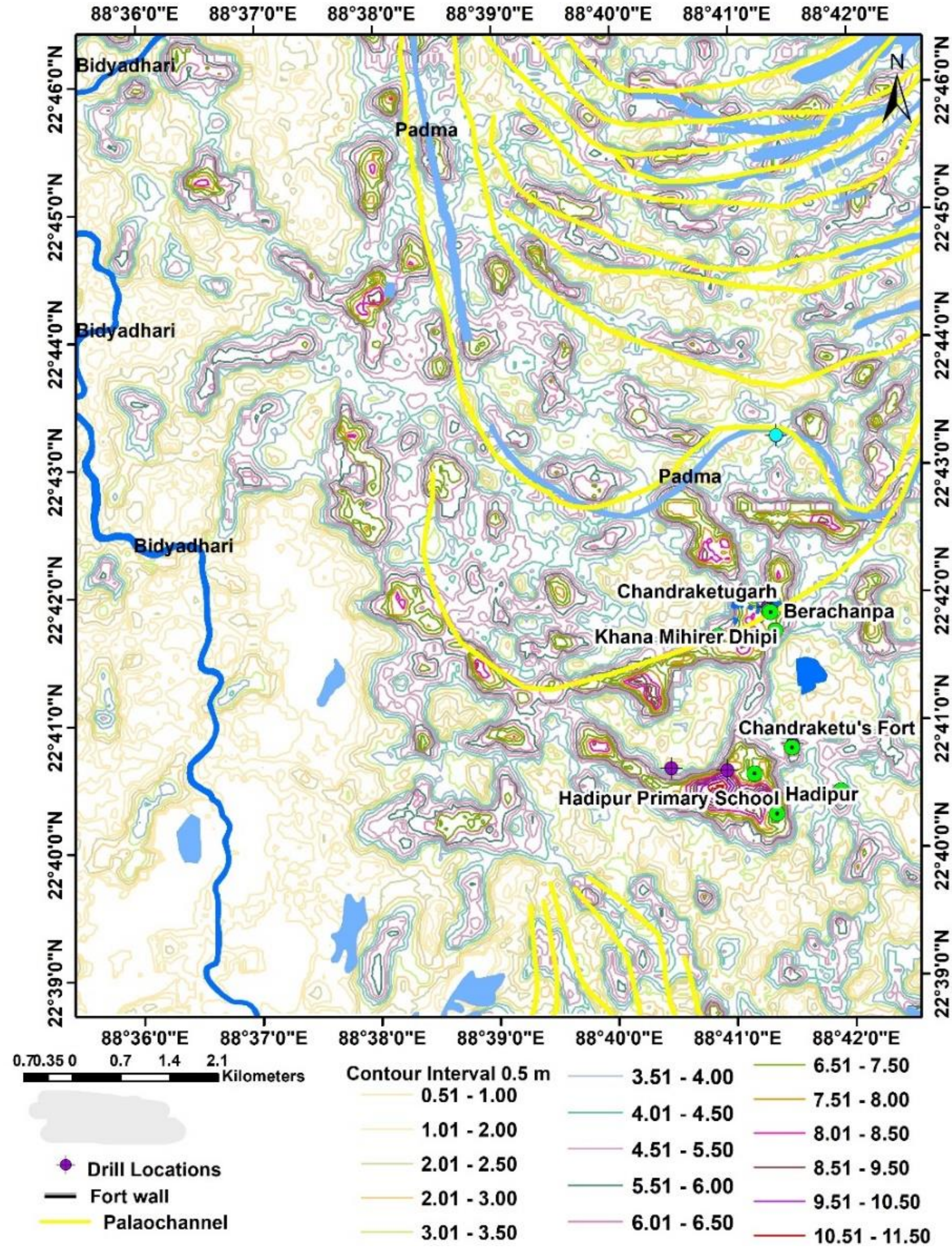


Fig 5.2 Contour map, Palaeochannels and Palaeo- levees along and around river Bidyadhari

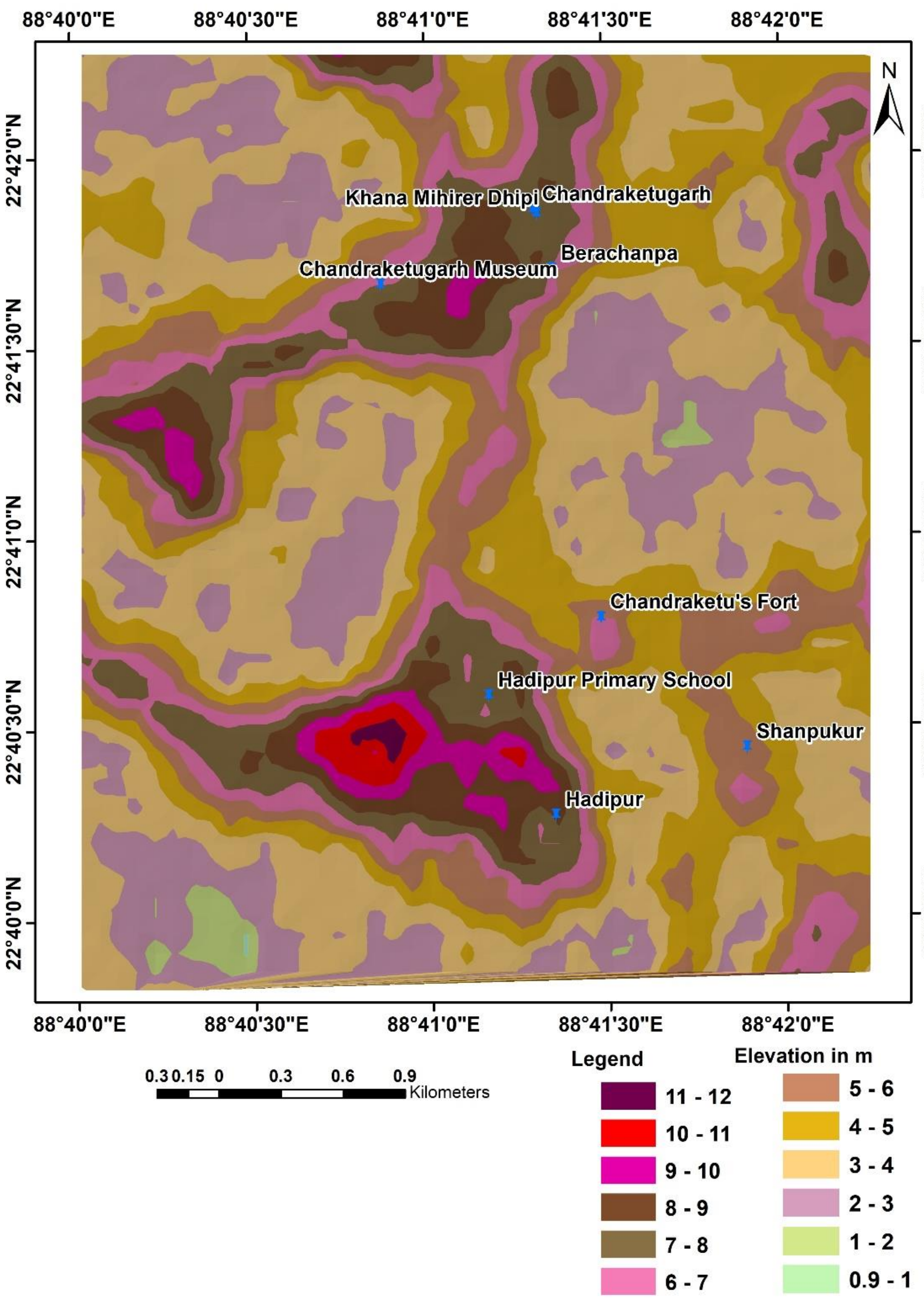


Fig 5.3. Elevation map around Chandraketugarh

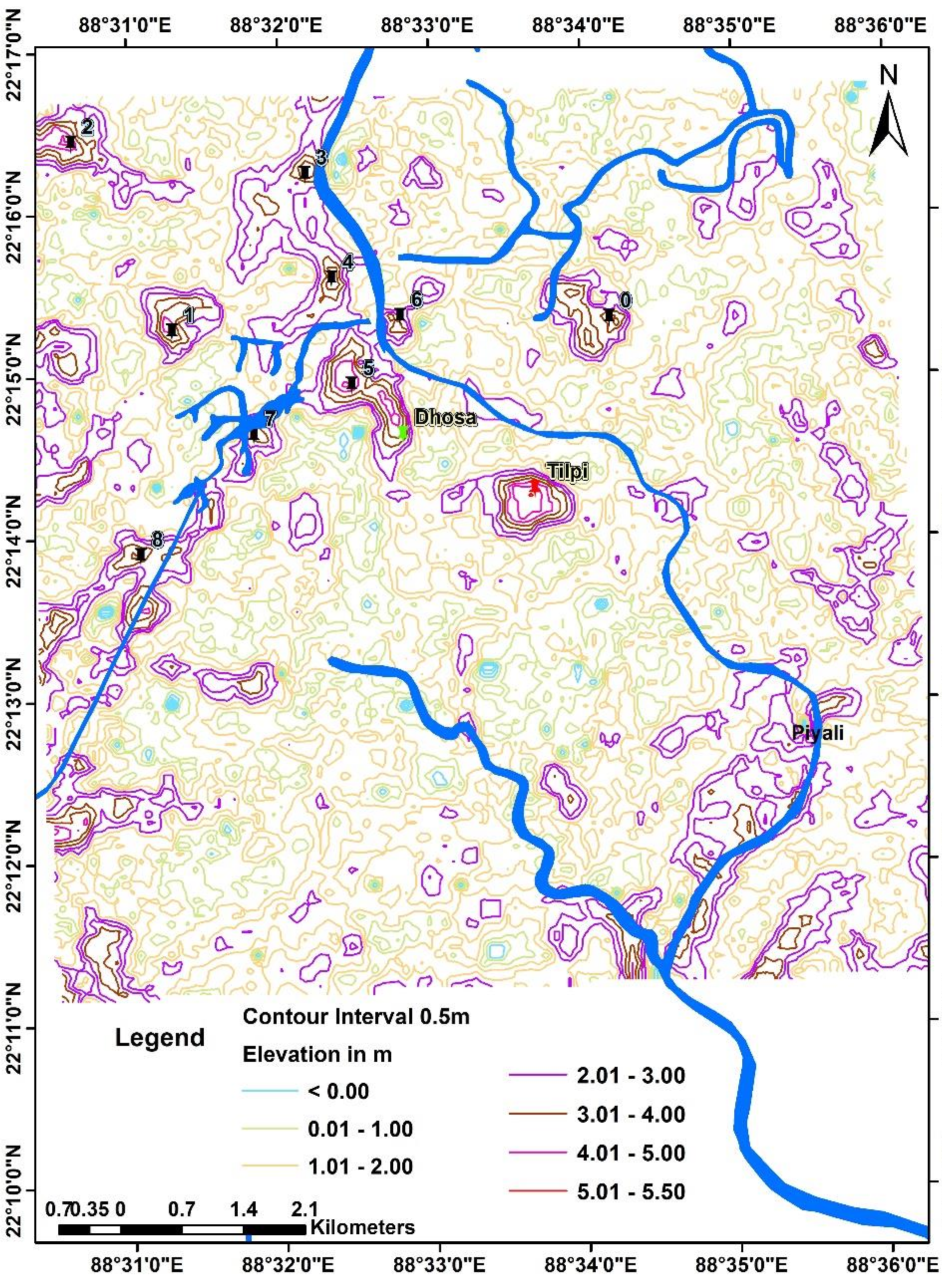


Fig 5.4 Archaeological sites along the palaeo- levee trends in an around Tilpi and Dhosa

Figure 5.4 showing the contour map in an around Tilpi Dhosa, another early historic site located on the bank of river Piyali. As shown in map these two sites are located in between two rivers as river Piyali connect river Bidyadhari with river Matla. From the contour map it has shown that Tilpi and Dhosa are located along elevation of 5 m or mor than 5 m. several other elevated patches has also been found shrouding of Tilpi and Dhosa.

Existence of diverse religious culture of Hinduism, Jainism, and Buddhism and indication of Port activities mentioned has been assumed from the presence of thin brick temples, extensive house foundations, and numerous dug wells. 3 cultural phases have been delineated like -

- Period I belongs to 2^{nd} century BC to 1^{st} century AD of Sunga- Kushana phase,
- Period II Kushana phase belongs to 1^{st} century AD to 2^{nd} century AD
- Period III of the Gupta phase
- At Dhosa terracotta and other remains of 1^{st} century CE to 5^{th} Century have been reported
- The overall area of the known archaeological clusters around 16 sq km.

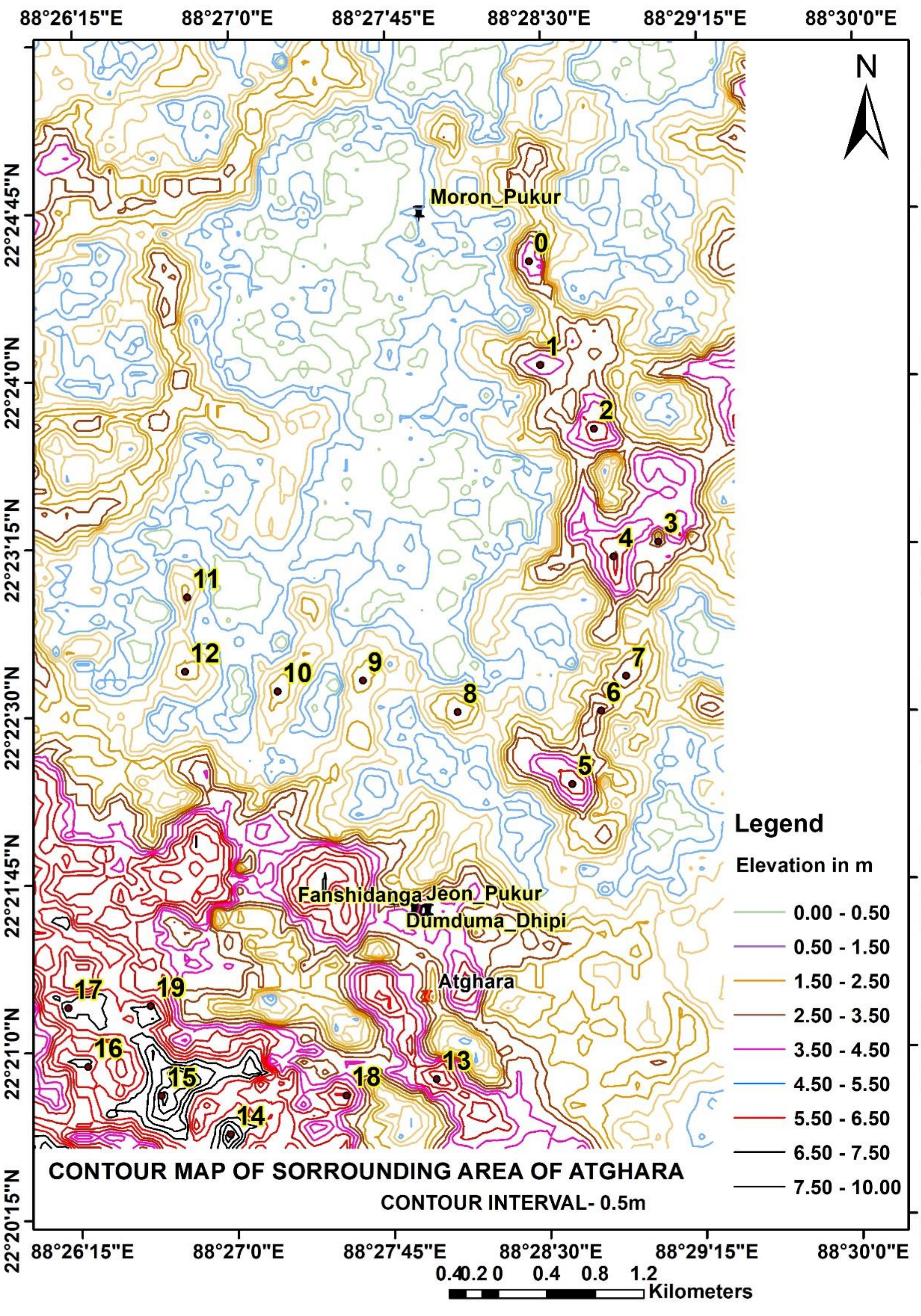


Fig 5.5 Palaeo- levees around Atghara

Atghara lies in the interfluve of river Bidyadhari and Adi Ganga. Some elevated places / levees with mound (Damdama Dibi) have been found. Figure 5.5 showing the contour map of in an around Atghara where we can find that that some elevated patches having 4 to 4.5 m at Atghara and surrounding area of Atghara.

5.1.3 Palaeochannel near Chandraketugarh

Sequence of palaeochannel describe the process to make a sequence of development of river course from an older stretch to recent course of a river which is flowing through a dynamic river course. The sequence of palaeochannel may help to find out the nature of ancient environment as well as the types of agents that was forced the river to shift its course. It is also possible to understand that how many time river has changed its course by the studying of palaeochannel sequences.

Identification and mapping of palaeochannel is the most important pre work to read out the sequence of palaeochannel. Here in this present study the identification of palaeochannel has

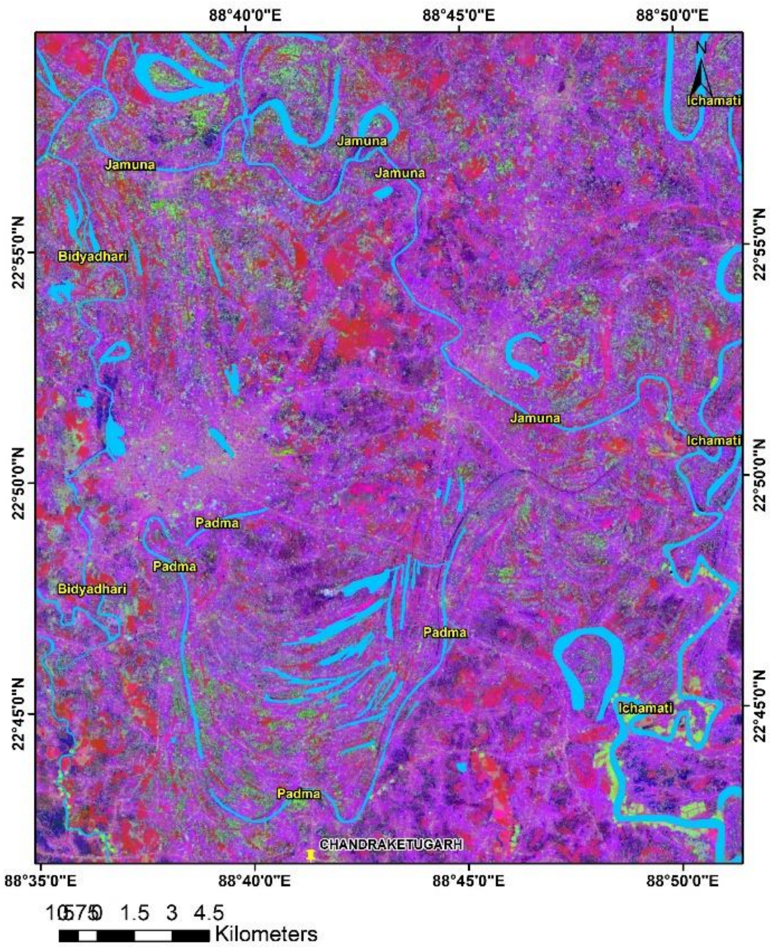


Fig 5.6 PCA analysis showing Palaeochannels of river Bidyadhari near Chandraketugarh

been done by applying some image processing techniques like Normalized Difference Water Index or, NDWI and Principal Component Analysis or, PCA.

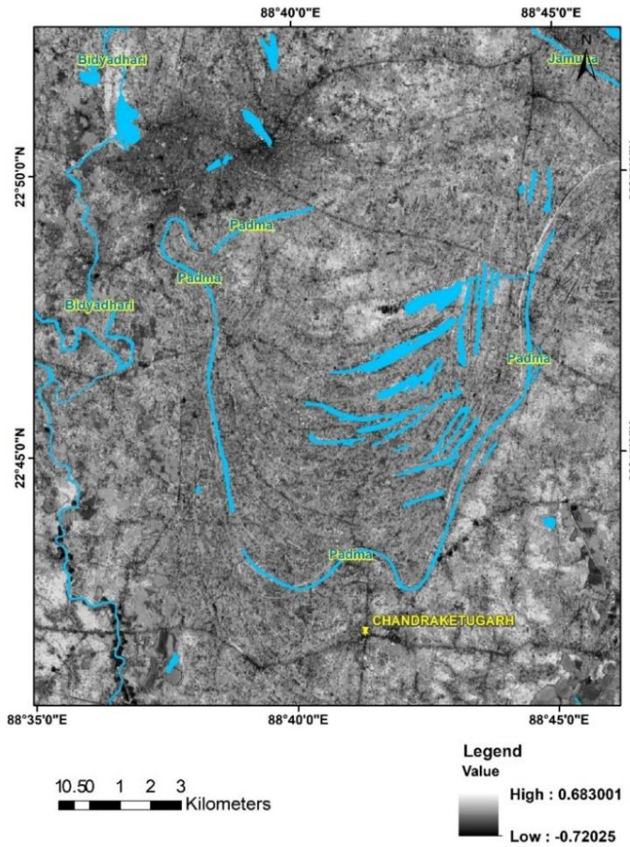


Fig 5.7 NDWI analysis showing Palaeochannels of river Bidyadhari near Chandraketugarh

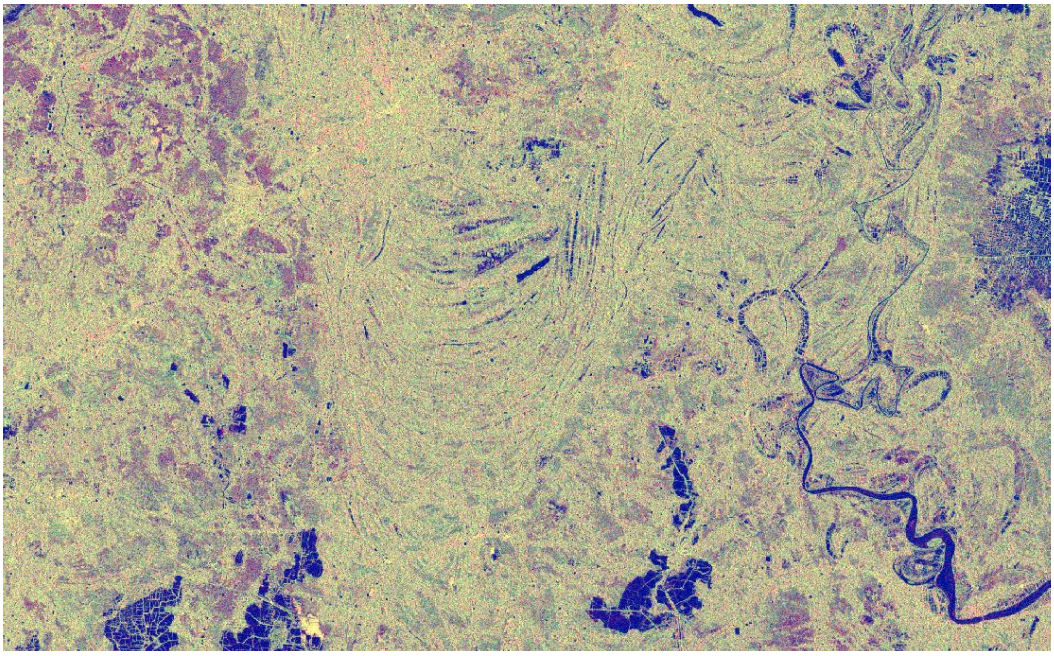


Fig 5.8 distribution of palaeochannel of River Jamuna on Sentinel 1A SAR GRD data near Chandraketugarh

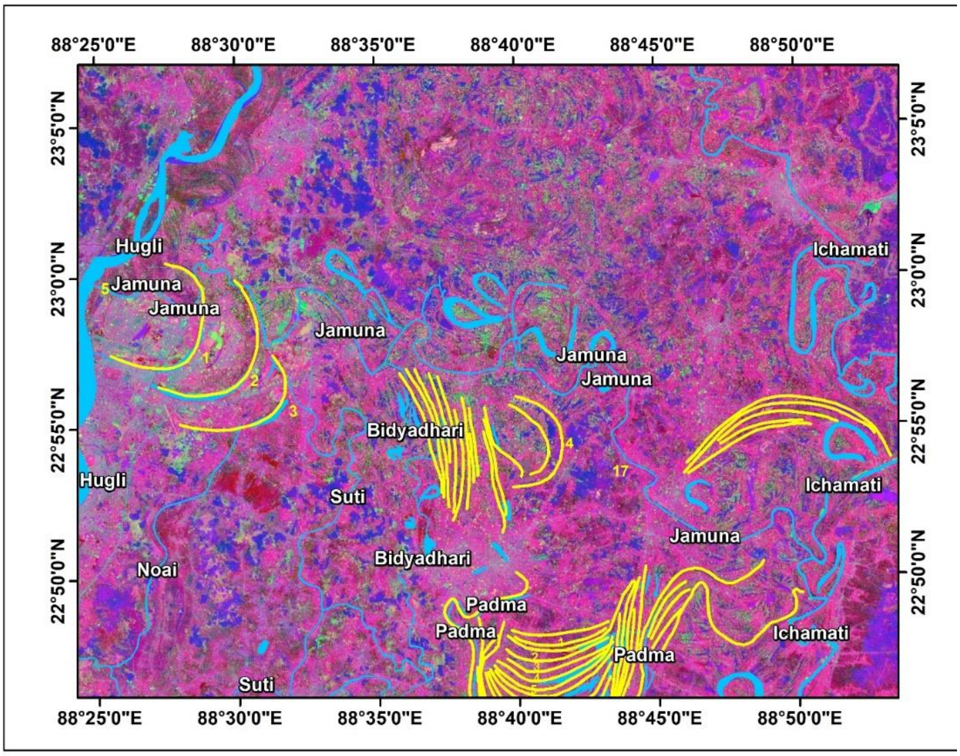


Fig 5.9 Sequence of Palaeochannel of river Bidyadhari near Bidyadhari Jamuna confluence.

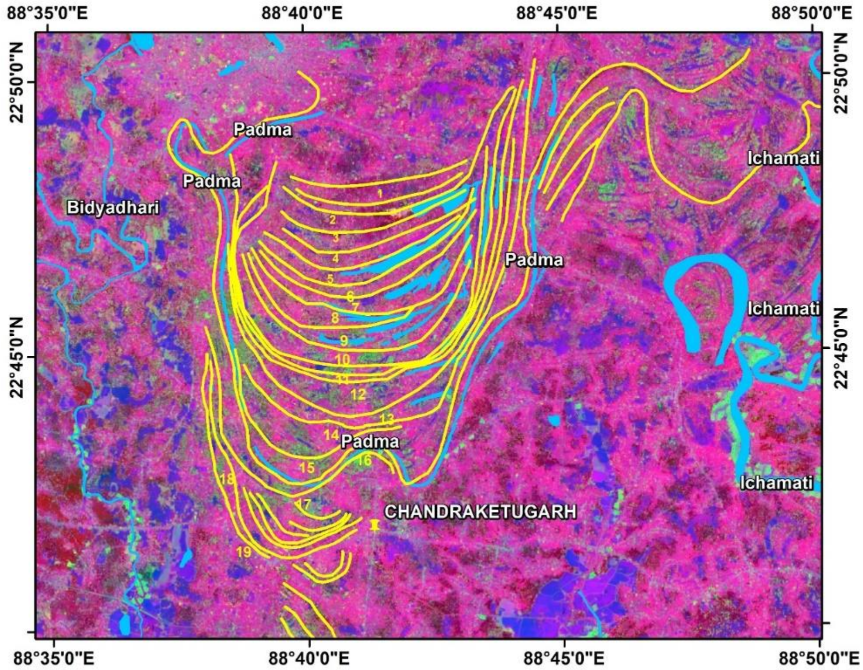


Fig 5.10 Sequence of Palaeochannel in the north of Chandraketugarh

Chandraketugarh located in an area which is broadly meandering bounded by the river Padma in the north exist as derelict meander belt, an east-west flowing river Jamuna and north south flowing river Bidyadhari in the west. According to Chakraborty, C et all 2007, location of Chandraketugarh is in a transition zone of Bengal Delta where upper part is river dominated and lower part is tide dominated. The area around Chandraketugarh is generally covered by proto meander belt of Proto-Padma, Bidyadhari and Jamuna, where Bhagirathi and Padma meander belt are made up of three and five belts. Among these meander belts, the Proto- Padma meander belts are the oldest which has been cut by meander belts of river Bhagirathi and Padma. (Chakraborty, C et all 2007). Beside of this, specifically the Chandraketugarh is also located on the oldest meander belt which known as Proto-Padma Meander belt. Dominance of river activity in this area has been proved from the stratigraphic information as a succession of 180 m thick unconsolidated coarse clastic sediments of Late Quaternary time by valley aggradation by a north south flowing river over Miocene deposition. (Chakraborty, C et all 2007). Chakraborty, C et all 2007, the development of meander belt chronologically divided into 5 stages (PPM.1 to PPM.5) on the basis of visual interpretation of satellite images and pattern of river cross cutting. Among them PPM.2 is the oldest meander belt which cover the far northern part and western part of Chandraketugarh. This part of meander comprises channel remnants filled with alluvial deposits associated with large levees formed by lateral accretion, palaeo-flood deposits with 8 to 9 m elevation. This meander belt which was of a southward flowing river (PPM. 2) gradually dried up and this belt were cut off by a newly formed eastward flowing river known as river Padma formed PPM.3 meander belt. (Chakraborty, C et all 2007). The Chandraketugarh is located in between these two-meander belts PPM.2 which is oldest and PPM.3 which formed by cutting a straight flowing channel give place to a vigorously meandering channel with largely meander loops possibly due to ground uplift or tilting. (Chakraborty, C et all 2007). The settlement in the Chandraketugarh was developed due to several facilities provided by the north-south flowing river which denoted as PPM.2 by Chakraborty, C et all 2007 like profuse fresh water supply, adjoining flood plain which was suitable for agriculture, low threat of storm as located far from sea etc. With time complete exsiccation of south flowing river subsequent largely meandering channel which provide an access to the Bhagirathi and Icchamati. But the worst situation was created by the emerge of new east ward flowing river from Bhagirathi near Kalyani named as the river Jamuna, which ceased the water supply to the settlement. (Chakraborty, C et all 2007).

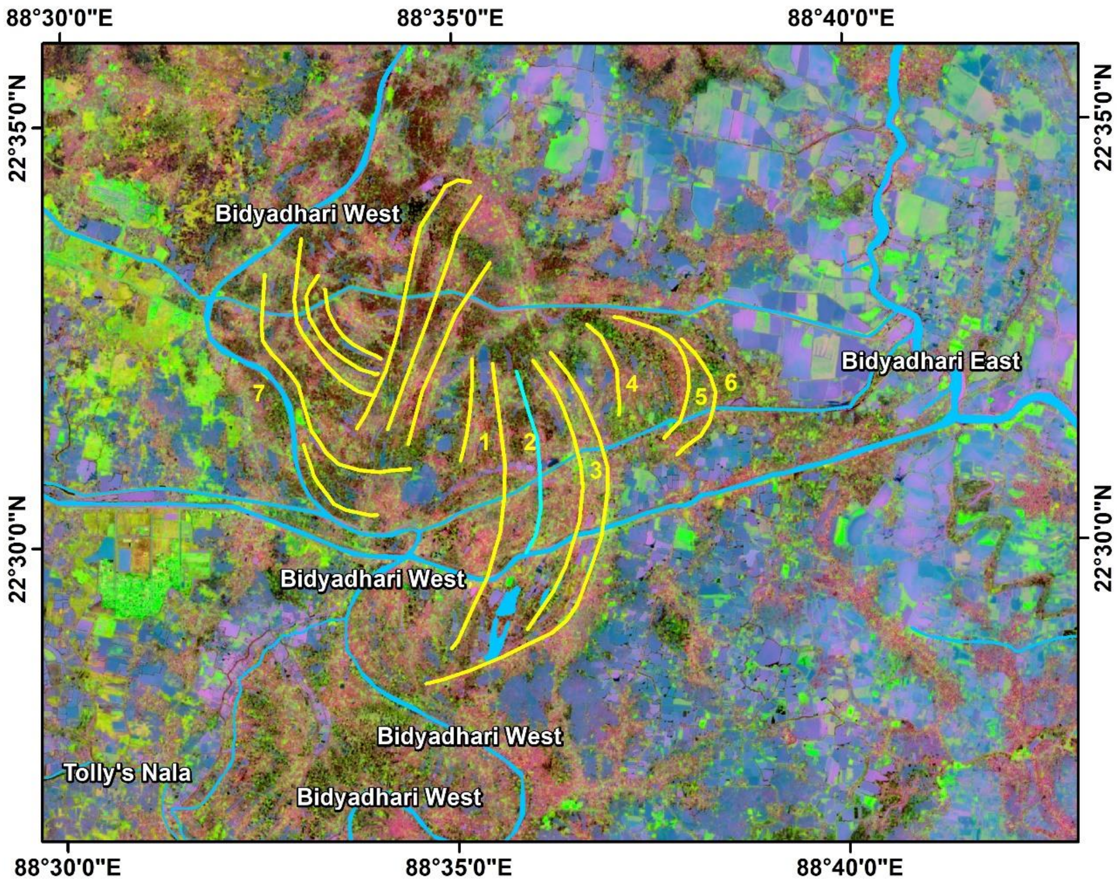


Fig 5.11 Sequence of Palaeochannel of river Bidyadhari in the south of Chandraketugarh

The river basin of the river Bidyadhari is another important basin in the Lower Ganga delta plain. It's complicated pattern of palaeochannels throughout its course makes it a more interesting to investigate.

The paleochannels in the northern part of this river basin has been shown in figure 5.9 and 5.10. Here showing the palaeochannel in the northern part of river Bidyadhari where river has originated near Tribeni. In Figure 5.10 we can also find several palaeochannel of an east west flowing river which might be palaeochannel of river Jamuna. This palaeochannels of east to west flowing Jamuna River has shown in figure 5.10 which is located northern part of Chandraketugarh where we can find the sequence of palaeochannel near Berachampa. Chandraketugarh, an ancient port city of 300 B. C. to 500 A. D. time period. The cluster sequence of this palaeochannel where western part is bordered by the river Bidyadhari, the river Icchamati is in the east and in the northern part bordered by the river Jamuna which is flowing west to east. Here the river Jamuna is another off- take of the river Bhagirathi which flowing towards west to east and meet with the river Icchamati. From the sequence of these palaeochannels it has been shown that the river course within this segment has changed at least 17 to 18 times, in which the last segment is known as the river Padma Nala. It is clear from the direction of palaeochannel that the river Padma might be ancient branch of river Jamuna, which is the off- take the river Bhagirathi formed after decaying of the river Bidyadhari. The figure 5.10 also showing some abnormality in normal flow of river Bidyadhari near Chandraketugarh.

From the pattern of palaeochannel on the north of Chandraketugarh, it can be said that this port city was might resulted abundant due to loss of water connectivity.

The southern part of this river Bidyadhari having also complicated palaeochannel pattern just before it falls into the rivet Matla has shown in figure 5.11. In this segment we can find 5 to 6 times of shifting of meander bend. This meander cut within this stretch reflects some possibilities of obstruction that was faced by river Bidyadhari in past.

5.1.4 Connectivity of Chandraketugarh with Atghara

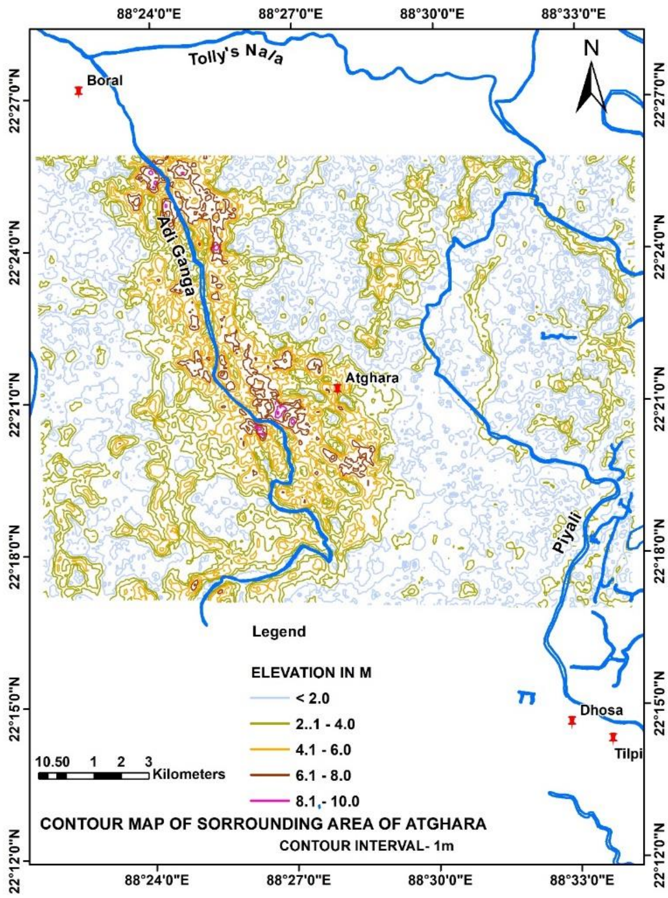


Fig 5.12 Levee mapping near Atghara

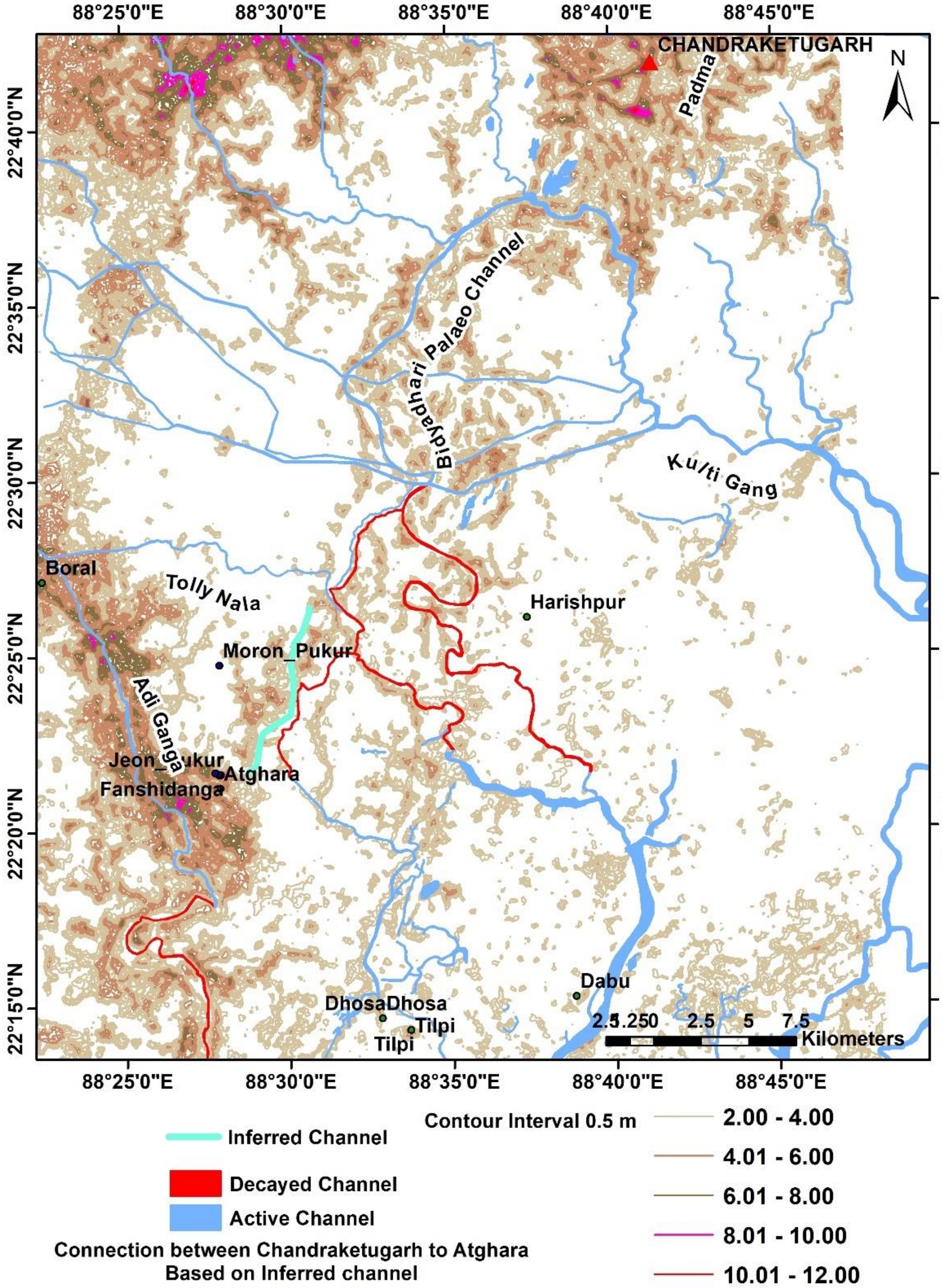


Fig 5.13 Inferred channel between Chandraketugarh and Atghara

Chandraketugarh and Atghara are both Early Historic sites located on different river side. Few archaeological remains of early historic period are found at Atghara below where Pir Darga of late medieval times (Chakraborty, 2016) is now located. No present-day connectivity between Chandraketugarh and Atghara are found. Hoever, there appears to be a need of water connectivity between the from levee mapping and existence of number of water bodies/ palaeochannels indicate connectivity between these two site Chandraketugarh and Atghara which has shown in figure 5.13. Atghara might be a forward base of Chandraketugarh after 400 AD when the dominant inhabitants shifted their base when the establishment on Bidyadhari started showing instability due to frequent meandering and channel shifting causing insecurity of repeated flooding, Atghara and Tilpi Dhosa could continue their marine trade along the Matla and Thakuran estuary.

5.1.5 Archaeological Artifacts of Chandraketugarh, Tilpi and Dhosa, Atghara

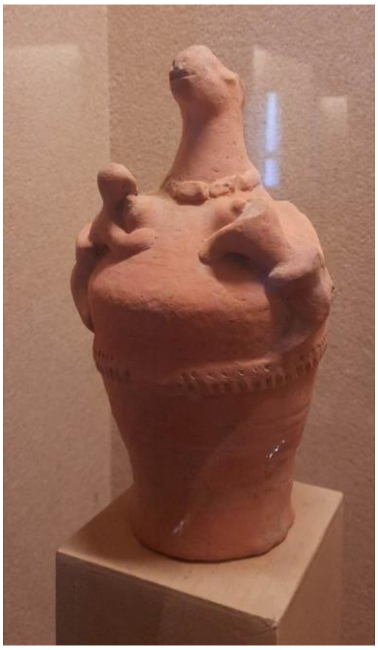
The locational pattern of archaeological sites related to river in Lower Bengal Delta plain in different historical time period (Early Historic time to Early Medieval) have been discussed in this section. As we know the river were the first attractive and suitable locations for the growth of ancient civilization because of multi-opportunity nature of river that made the life easy for ancient people. Several example of ancient river centric livelihood also we can see from the location maps of archaeological site in lower Bengal Delta Plain along river Adi Ganga, Bidyadhari and the Rupnarayan. This study also has emphasized on the influence of river Adi Ganga on ancient civilization in lower Bengal deltaic region. Here the excavated archaeological site from 600 BC to 600 CE are plotted on River layers of lower Bengal Delta plain to delineate fluvio-archaeological interrelation in the past time.

5.1.5.1 Tilpi (22°14′17.4″ N and 88°33′40.80” E) is an Early historic Site located on bank of river Piyali in Baruipur sub- division of South 24 Pgs. As per excavation conducted by the Directorate of Archaeology and Museum, Government of West Bengal, 3 cultural phases have been delineated like Period I belongs to 2nd century BC to 1st century AD of Sunga- Kushana phase, later Kushana phase belongs to 1st century AD to 2nd century AD identified as Period II and the Gupta phase delineated as Period III. Several antiquities like terracotta plaques, bangle, wheel, some cast copper coins and sealings, beads of semiprecious stone, iron nail, earing of copper etc. According to Basak, B 2014 no structural remains have been found in Tilpi but habitational deposits have been found. Sign of industrial activity have also been found from Several hearths excavated from a series of mud floors those were associated with ashes, charcoal, iron slag. (Basak, B). According to Chakraborty. S, Terracotta plaques, pottery, uninscribed cast- copper coin, semiprecious stone beads etc. have been excavated from Tilpi.

5.1.5.2 Dhosa

Dhosa is also located in Baruipur sub-division located at 22°14'37.90" N and 88°32'48.69"E at 6m above mean sea level. This place has been found as a structural mound which represent cultural evidences of 1st century to 5th century AD (Basak, B). Chakraborty, S. 2017 has depicted the period of Dhosa estimated as begins of 1st century CE which was excavated by the Directorate of Archaeological Museum. Some Terracotta plaques of Yaksi, ram and elephant figurines have been excavated from this site as described by Chakraborty, S. 2017. Beside of this several ceramics of different colour like grey, dark grey, red, dull red and black etc. have been found as described by Basak, B. some tiled- brick with inscription of Brahmi dates back to second- third century CE have also been found.

Terracotta Plaque, Tilpi Dhosa. Source: State Archaeological Museum, West Bengal. Terracotta objects are made of baked clay, to make of household objects, ritual objects, aesthetic objects and different sculptures.



Ram headed Mother Goddess, Tilpi. Source: State Archaeological Museum, West Bangla. Among the female figure, Mother goddess is mostly common which depicts the mother with child.

Fig 5.14 Archaeological findings from Tilpi and Dhosa

5.1.5.3 Antiquities in Atghara

Atghara is another site of Baruipur block located 22°21'13.6" N and 88°27'54.8" E with 9m elevation above sea level bearing a number of Early Historic and Medieval findings have been excavated which is located along the older channel of Bhagirathi Hugli River. (Dasgupta. S. et. all, 2017). According to Chakraborty, S. 2017, evidence of Early Historic phase has been proved from excavation by the Directorate of Archaeology and Museum, West Bengal. Beside of this, evidence of mound of Early Historic time has been noticed which exist as small mound where Pir Darga presents as recent time. (Chakraborty, S. 2017).

Smack sculpture from Atghara. from personal collection (Registered collector).

Deity with tangrik influence at Sitakund mandir.

Thin wider brick of Gajir than, Atghara.

Fig 5.15 Findings at Atghara

5.1.5.4 Chandraketugarh

Chandraketugarh is another important buried Early Historic structural mound with multi-cultural sequences located on the meander bend of river Bidyadhari. Chandraketugarh located at 22° 41´ N and 88° 42´ E which is 38 km north east of Kolkata cover about 4.5 sq. Km area comprises Berachampa, Deulia, Shinger Ati, Jhikra, Shanpukur, Hadipur, Ghazitola etc. vilagges. (Basak, B). From the report by IAR of different excavation in 1956,57 and 1966-67 identified several cultural sequences in different part from Chandraketugarh. Five occupational sequences identified in Berachampa, six to eight cultural sequences at Khana- Mihirer Dhipi, four- six sequence at Itakhola etc. (Basak, B). Based on excavation evidences of seven to eight cultural period can be summarized. The evidences of 6th- 5th century BC can be identified as period- I which is characterized by Pre- NBPW, Period II belongs to 4th to 2nd century BC in which NBPW, Black Slipped Ware, Grey Ware, Rouletted ware, Red Ware, fragmented piece of ivory and copper antimony rods etc. can be placed. Sunga- Kushana period can be placed in Period- III which belongs to 2nd century BC to 3rd century AD. Gupta and Late Gupta period has been identified as Period- IV which is yielded by seals and sealings, terracotta objects, stamped and moulded potteries. Period- V identified the ruling time of Pala which cover the time 8th to 9th century AD, Post Pala period identified as Period- VI characterized by availability of bone, gaming dice, certain beads and pottery lamps etc. and after this time the cultural sequence were disturbed around 10th century AD from when some small brick temples were found as evidence.

Five successive period has been identified from the excavation by University of Calcutta under Shri K. G. Goswami at the mound of Chandraketugarh. Each period characterized by different types of antiquities like pre-Maurya time categories as Period I where Red Ware are is main findings. Ruling time of Maurya-Sunga demarcated as Period II when appearance of Northern Black polished Ware Black-Slipped ware, Polished and unpolished Grey Ware etc. have been noticed. Period III dominated by post Sunga power marked by appearance of Red Ware, stone beads, cast copper coins etc. and ruling time of Kushan and Gupta identified as Period V and Period V revealed by typical Kushan terracotta figurines and some burnt bricks of Gupta time. (Das, S and Srivastava, T (2019).

5.1.5.5 Excavated findings at khana- Mihirer Dhipi

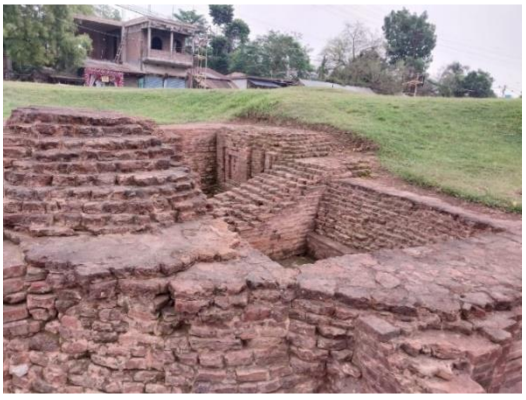
Khana- Mihirer Dhipi is a structural mound of about 5 m located at the north east of the L-shaped rampart wall. (Chakrabarti, C et all. 20070. According to IAR 1957- 58 the structural mound at khana- Mihirer Dhipi which was a planned temple which ascribed to the Gupta period was rebuilt for several time by different type of decorative brick. Several artefacts have been uncovered from this site are diverse pottery including jar, cup and dish, rimless round cup and bowl, carinated and flanged cooking vessel, terracotta plaques depicting Mithuna scenes, cooking pan, jar with high neck, pinched- marked copper coin, terracotta seal depicting foreign affinities, red sandstone sculpture of seated Buddha etc. Among the terracotta figurine, figure of Yakshi and Dampati has been excavated from Khana- Mihirer Dhipi is one of the important findings. Several objects made of steatite, chalcedony, bone, ivory, carnelian etc. also been uncovered from this site. (Das, S and Srivastava, T (2019). The evidence of domestic granaries also assumed from the discovery of paddy husk as reported in IAR 1963-64. Production of lime by burning shell has also been assumed at Khana- Mihirer Dhipi where two furnaces and two troughs have been discovered. (Das, S and Srivastava, T (2019).

5.1.5.6 Excavation at Itakhola

As per report of IAR 1959-60, six occupational period have been demarcated with proper evidence of soil conservation assumed from the discovery of pottery drain in the Maurya time period. Two structural layers of a rampart wall composed of surkhi, brickbats and potsherds were discovered from the excavation by shri D.P. Ghosh and shri C.R. Roychoudhury as reported in IAR 1964- 65. (Das, S and Srivastava, T (2019). Several house complexes made of surki floor, daub walls with heavy wooden pillar at corners, terracotta ring well etc. have been found from excavation at this site.

5.1.5.7 Noongola is nearby site of Khana- Mihirer Dhip where 10 to 15 cm thick layer of flood borne sandy clay which date back to Gupta time has been found which might be reason for discontinuation of settlement in Chandraketugarh. (Das, S and Srivastava, T (2019).

5.1.5.8 Hadipur is another site at Chandraketugarh yielded many antiquities like an elephant rattle, a terracotta plaque depicting Airavata's abhisheka which explain the ride of Puranic legend named as Indra etc. have been excavated from a trial digging reported in IAR 1965-66. (Das, S and Srivastava, T (2019).



Ruins of early historic to early medieval structure of temple at Khana- Mihirer Dhipi.

Semi-precious beads from Chandraketugarh. Source: Chandraketugarh museum.

Fig 5.16 Early Historic findings at Chandraketugarh

Yakshis from Chandraketugarh. Female figure appeared as lady with auspicious hairpins known as Yakshi or, Panchachuda or, Apsara. Source: State Archaeological Museum, West Bnagal.

Terracotta plaque, Chandraketugarh. Source: State Archaeological Museum

Black pottery found from Chandraketugarh. Pottery including Fine ware, Rouletted ware, Black ware etc are the main artifact made of fine clay belongs to 400 BC to 300 AD. Gangetic alluvium was the main source of fine ware and black slipped ware production.

Terracotta moulds, Chandraketugarh. Source: State Archaeological Museum

Fig 5.17 Early Historic findings at Chandraketugarh

5.1.5.9 Findings from Harishpur and Dabu, another Early Historic sites along the river Bidyadhari

Along the river Bidyadhari Harishpur is another early Historic site located in Bhangor block at 22°26′2.3″ N latitude and 88°37′21.4″ E longitude. The Early and Late Historic potteries have been found here on a small dump over a mound as stated by Chakraborty, C et all 2007.

Dabu is another Early Historic site along Bidyadhari river located in Canning block. According to Chakraborty, C et all 2007, this site reported as Early Historic site in IAR 1983-84 where terracotta head and medallion has been found although they are not accountable at present.

5.2 Mapping of Early Medieval sites and palaeochannel and palaeo levee of Adi Ganga

In published article named Adi Gangar Itihas by Kalidas Datta in 1963 mentioned that eight major channels were in the Ganga Delta region those are Raimangal, Harinbhanga, Gosaba, Bidya, Matla, Thakuran or, jamuna, Satamukhi and Baratala. (Chakrabarti. D.K et al, 2010). Datta also mentioned that most name of the Ganga Deltaic channels are recent. The importance of Adi Ganga on ancient livelihood can be traced from description of river Ganga in ancient Bengali literature. The Bengali text of Krittibasa's Ramayana in 15th century, Chaitanya-bhagavata of 16th century described the existence of the Ganga River with hundred mouthed or, Satamukhi and also the religious importance of Ganga River described in text of Raimangal in the 17th century. (Chakrabarti. D.K et al, 2010). This active river existing as a moribund channel in present day that can be traced to northward straight to Kalighat in the southern part of Calcutta. This moribund channel mainly existing as low-lying land those are used for cultivation or used as ditch known as Adi ganga. (Chakrabarti. D.K et al, 2010). Atghara, Boral, Tilpi and Dhosa (in the Piyali river valley), Dhonchi, Gobardhanpur etc are some of those Belongs to Medieval time period are located in the Adi Ganga River valley. Description of archaeological findings from these sites have been discussed below.

Several archaeological sites have been discovered in the different place in the lower Ganga delta plain. Most of the remnants are dates back to 500 CE to 1300 CE. i.e. time period to Medieval history. If we find the location of these early medieval remnant rich sites, most of them are located along any of the river course of Adi Ganga of lower Bengal delta which have become a narrow discontinuous flow at present. The distribution of early medieval sites has been shown in figure 5.18.

The elevation in the river Adi Ganga course area has been shown in figure 5.19. from the distribution of elevation, it has been clear to us that maximum area is low elevated area which is near 2 to 6 m above mean sea level, only the river bank portion is highly elevated than surrounding. The elevation along the river course is 6 m to 8 m, which relies the location of natural levee that may be formed due to sedimentation by flooding in several time.

If we compare this elevation map with the location of archaeological sites, we can see that maximum evidences of ancient civilization have been find along this high elevated portion of Adi Ganga which reflect the presence of livelihood that was gown based on Adi Ganga.

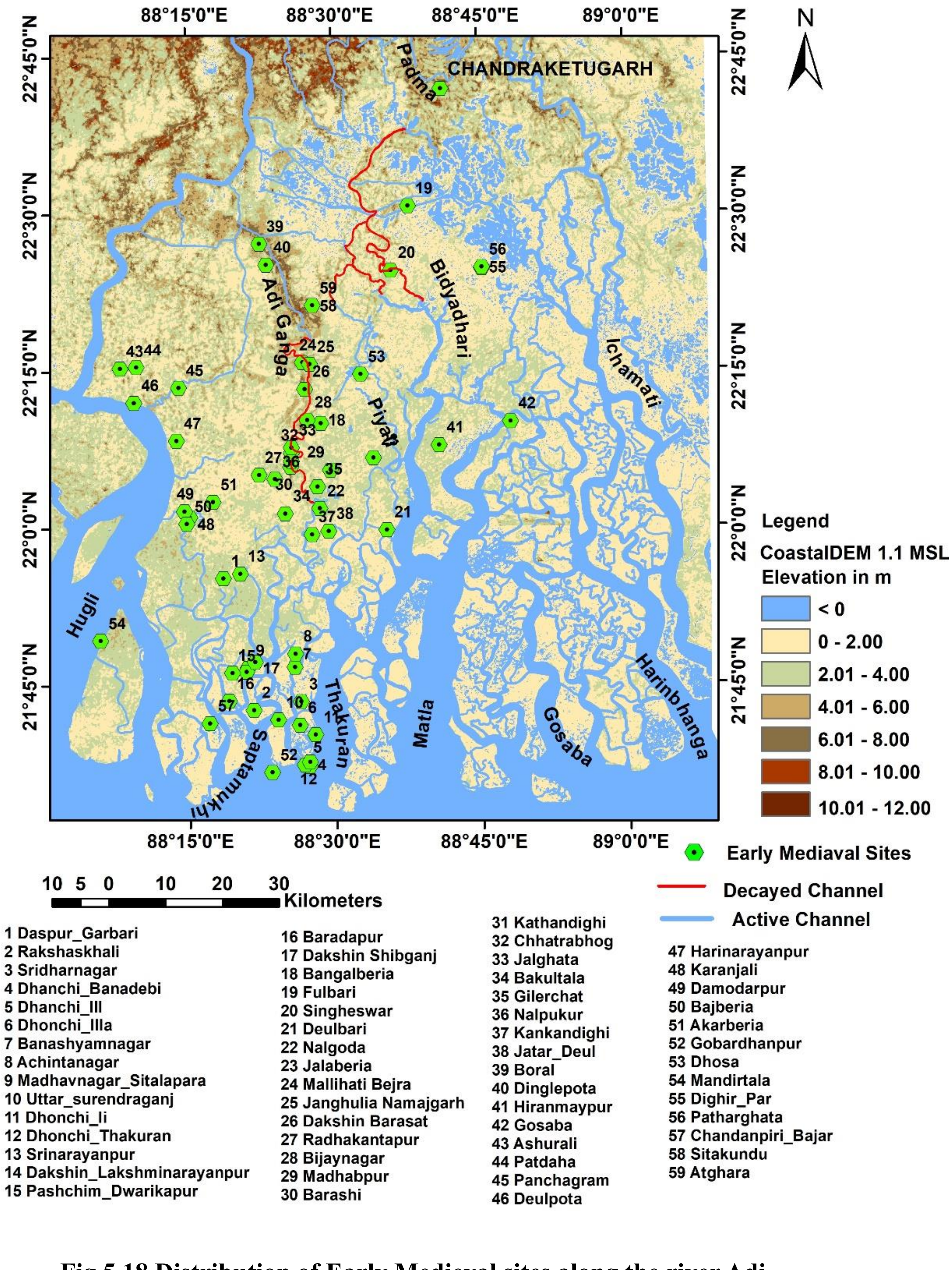


Fig 5.18 Distribution of Early Medieval sites along the river Adi Ganga

In this study area the river Adi Ganga is one of the most ancient rivers of medieval period, outlet of Bhagirathi- Hugli. This river at present only traceable as some number of elongated pool or water bodies and some places it can be identified from remnants of levee. Although, it is known that this river might have continued to the sea through the estuary of Saptamukhi or, the Thakuran river. The river Adi Ganga as it was a major navigational route in the medieval time period as known from the description in ancient Bengali literature like Mangalkabya but currently this route is used as nothing but as waste water canal.

Here in this context find out the fluvio- archaeological influence of the river Adi Ganga is very important that has been find out by Principal Component Analysis which helps to highlight the palaeochannel of Adi Ganga. Figure 5.21 has shown the distribution of palaeochannel near north west position of Sarberia. Here we can see that the river course at this segment have been changes for 3 times.

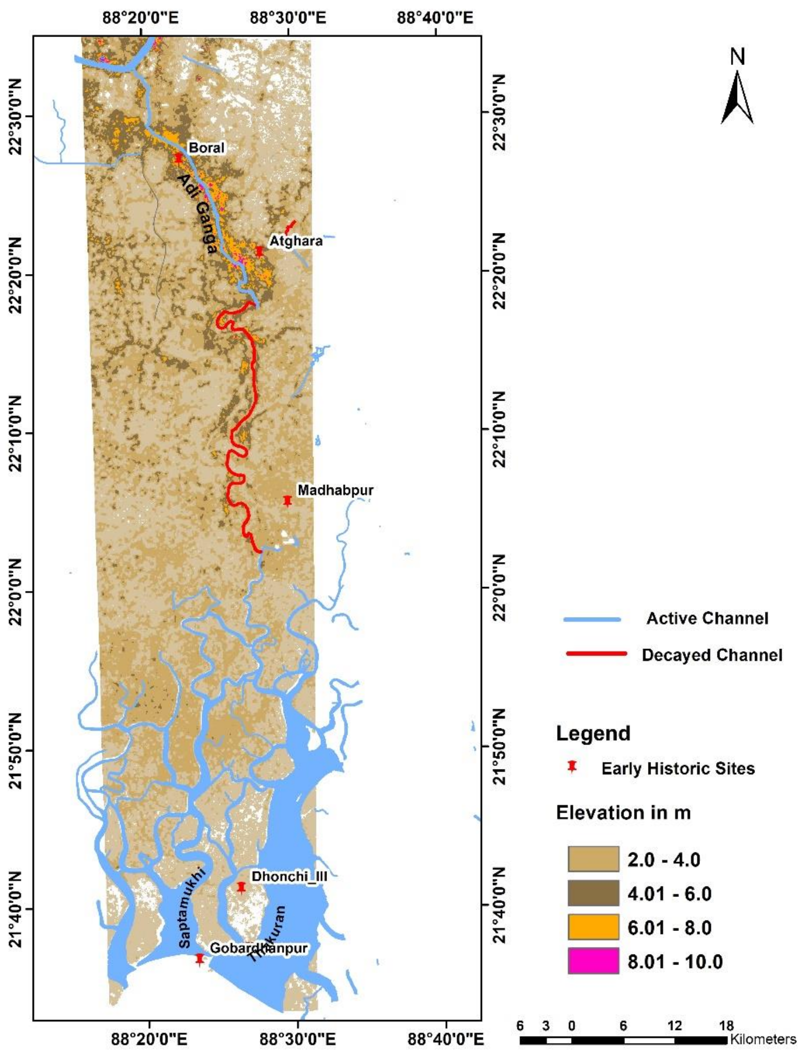


Fig 5.19 Palaeo- levee of river Adi Ganga

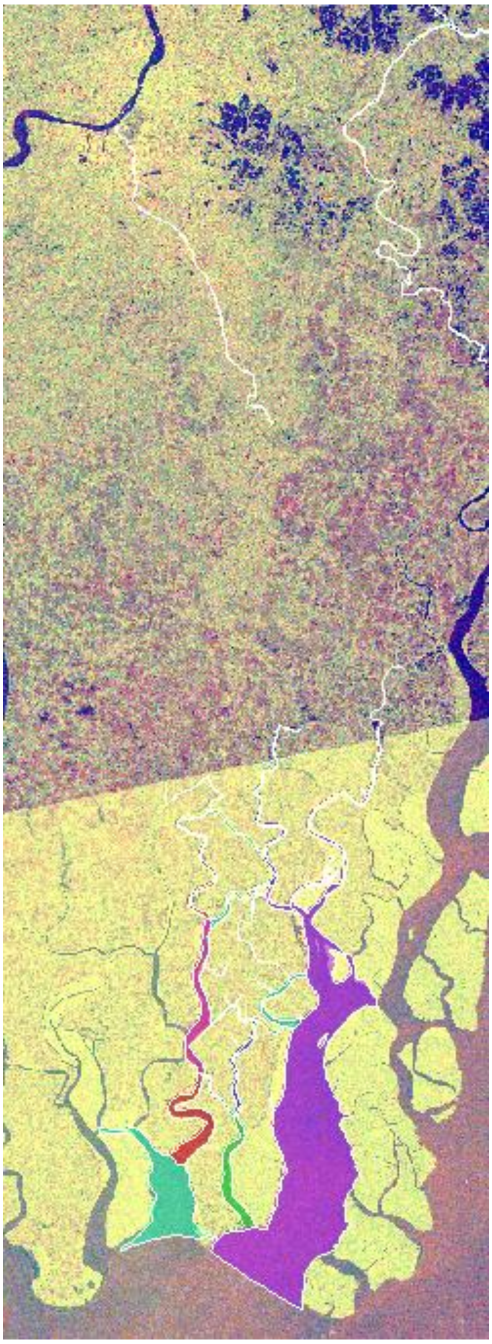


Fig 5.20 Showing the palaeochannel of the river Adi Ganga on Sentinel 1A SAR GRID data. Here band VV has been taken as band VV is useful for identification of water bodies

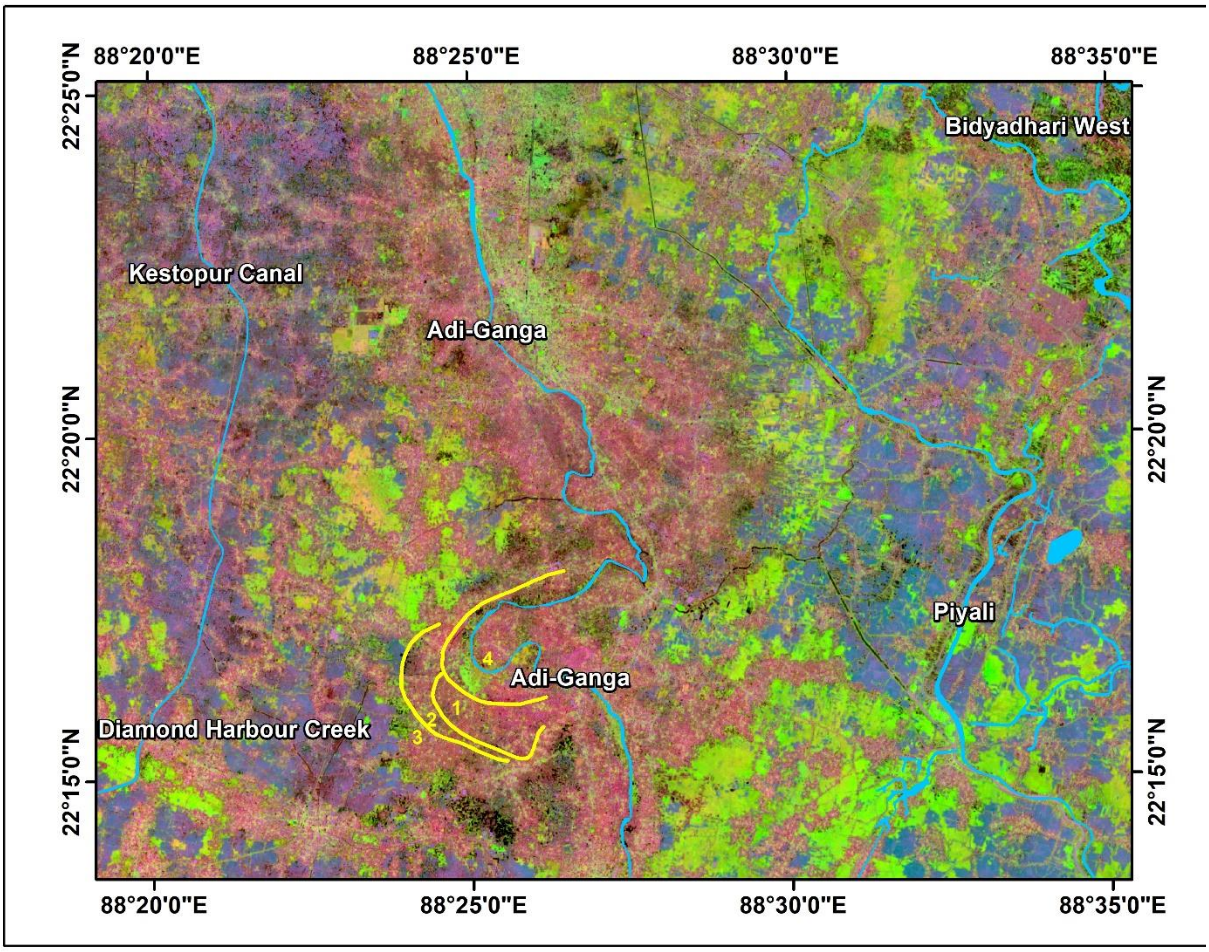


Fig 5.21. Sequence of Palaeochannels of river Adi Ganga.

Showing the sequence of palaeochannel of Adi Ganga course near Sarberia. Sequence mapping has done from PCA analysis. 3 palaeochannel sequences has been identified here that describes at least 3 times of course at this stretch of river.

5.2.1 Mapping Early Medieval sites along Moni River

Nalgoda, Bijynagar, Barashi, Bais hata Kathandighi, Kankandighi, Chhatrabhog, Jalghata, Jatar deul are some of the places along the basin of river Moni, a distributary of Adi Ganga from where archaeological elements of Medieval time period has been excavated. Archaeological remains have been found from Bais hata, Raidighi, Kankan dighi, Monir tat, Nalgoda, which include post Gupta Plaques, broken part of pottery, terracotta figurines, a Vishnu icon of Sena period etc. Long brick walls, thought as flood resistant structure, have been excavated. Brahmin, Buddhist and Jain religious influence on some of the bronze and other metal and stone idols have been mentioned by various researchers (Mukhopadhyay, N 2000). This has been assumed that the ancient settlements in this area started from 6^{th} to 7 th century AD. Moni river basin has an area of approximately 150 Km^2. But the sites elevated paleo- levees with known archaeological find comprise $1/4^{th}$ of the area only, making it one of the largest early medieval clusters in Sundarban.

The ancient finding, existence of tower and structural mounds have been found along 2 sq. km area of Moni River basin. (Basak, B. 2019). Evidence of stylised artifacts of Pala and Sena dynasty of 9^{th} to 10^{th} century have been proposed in this basin area. The Moni River which connected Adi Ganga with river Thakuran which provided the seagoing thoroughfare to the early medieval traders and travellers. It is commonly believed (as written in the historical novel 'Kumudananda' by Nakuleswar Bidyabhusan (Bhattacharya) that during 1001AD, after a massive deluge, the area became water less, and the entire area became covered with forest. The mani river was created from the deluge. This might indicate river avulsion of Adi Ganga during excessive siltation and earthquake, common in this region.

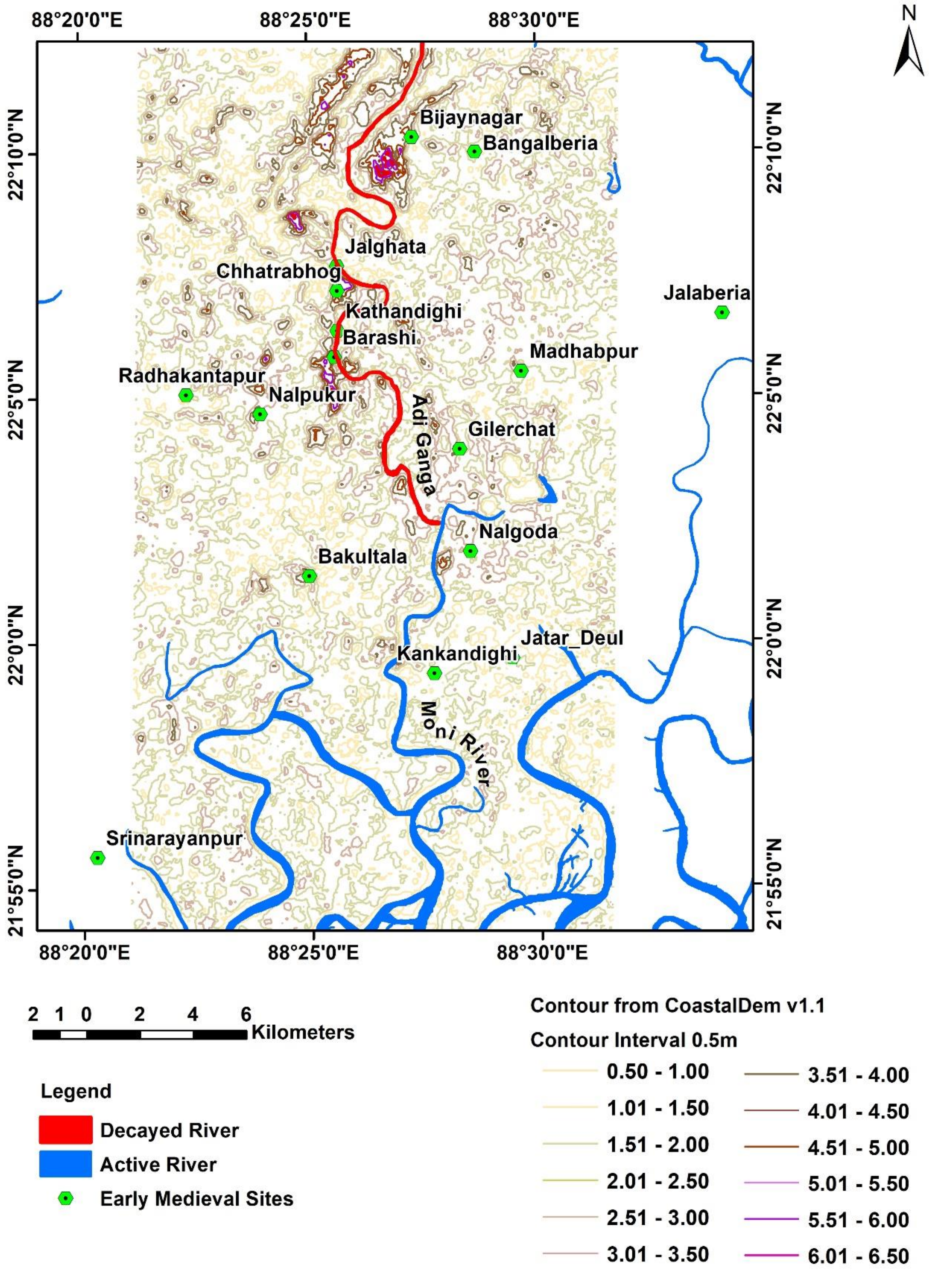


Fig 5.22 Distribution of early medieval sites along the palaeo- levee of Moni River

5.2.1.1 Jatar Deul

The Jatar Deul which is a monument-like structure located in Mathurapur block II on the bank of Moni River is made of brick structure which dates back to 1300 AD (Basak, B. 2019). However, Archaeological survey of India has ascribed a date of 975 AD based on an inscription (not traceable now) of one Raja Jayanta Chandra. This tower is an expression of different religious icon although worship of lord Shiva or dedicated to Mahadev related with the name 'Jatadhari' is the main which proved from available idol inside of this tower. (Basak, B. 2019). Basak, B refereed from Middya 2014 and Mukhopadhyay, 1970 that this deul structure belongs to Orissan architectural style. According to Datta this tower of Jatar Deul having similarity

Fig 5.23 Early medieval site: Jatar Deul

with Ichai Ghosher deul who lived during ruler of Devapala. Devapala was ruler of Pala dynasty which belongs to 8^{th} to 10^{th} century. (Basak, B. 2019).

According to Basak, B 2019, the tower of Jatar Deul is made of thin brick with black cemented layer of a square shaped plan. The floor of deul is located 6 ft below the present level and total interior area is near about 10 feet square.

5.2.1.2 Baish hata

In the 'Bais hata', under Jaynagar police station two architectural mounds have been discovered by people's archaeologist Kalidas Dutta in 1931-32. They are commonly known as Mothbari

Dhibi I and Mothbari Dhibi 2. The conical mound shape indicates existence of buried structure. Collectors have recovered various artifacts of Buddhist and Jain lineage; Existence of a buried brick road was reported between the mounds. A small Visnu idol inscribed on stone, another idol of mixed metal, coins of Gupta period indicate a stylistically imagined date of around 700 A.D for the mounds.

5.2.1.3 Kankandighi

Kankandighi is happens to be one of the very important medieval sites located on the west of Jatar Deul on Moni River presently found at low elevation of 1.5m to 2 m. Numerous small and low mounds, large number of old ponds and rolling mounds were reported from the area. A large building was discovered in 19th century during deforestation and making fields for cultivation in a location called 'Swet rajar dhibi'. The bricks found are large 37.5 cmX30 cmX6 cm (Mukhopadhya, N.2000). There are evidences of city wall in the region.

Apart from the findings of sculptures of four armed Ganapatior laxmi on her owl, four-armed Kamala important sculptures made up of mixed metal related to mahajani Buddhist cult like Jambhal, Shadakshari lokeswar, Astabhuja Mariachi on terracotta plaque has been reported by local collectors. 38 number of terracotta seals with pre-Bengali scripts have been found from Kankandighi.

Fig 5.24 Broken base of a black stone sculpture at near the pond of Pilkhanar Dhibi

Fig 5.25 GPR survey on Pilkhanar Dhibi, Kankandighi

Some findings from these sites have been shown here during field visit From the Pilkhanar Dhibi site of Kankandighi, remains of a broken massive sculpture can be seen in fig 2.24.

5.3 Sites for future exploration

Figures 5.26, 5.27, 5.28, 5.29, 5.30, 5.31, 5.32 and 5.33 illustrate newly identified potential archaeological sites along the Adi Ganga River basin. These maps highlight areas elevated by 3 to 4 meters, which may indicate the presence of ancient remnants. Notably, these elevated sites appear to follow a distinct pattern, forming small patches arranged in a parallel manner.

Figure 5.30 depicts probable archaeological sites on Dhonchi Island, where previous excavations have uncovered pottery, flat-based bowls, featureless rims, frying pan handles, and semi-precious stones dating back to the Early Historic period (600–400 BC).

Figure 5.28 highlights a probable site on a mangrove-covered island, where known archaeological locations such as Banashyamnagar and Sridharnagar already exist.

Similarly, Figures 5.29 and 5.31present potential sites within mangrove-covered areas, though no confirmed archaeological sites have been identified there yet. These areas, elevated between 3 to 3.5 meters, appear to form linear or parallel patterns, suggesting possible ancient human activity.

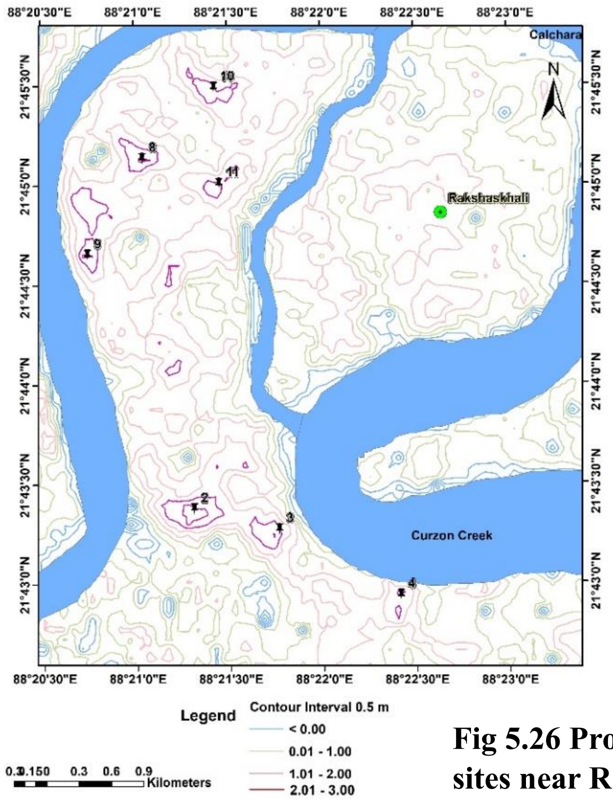


Fig 5.26 Probable archaeological sites near Rakshaskhali

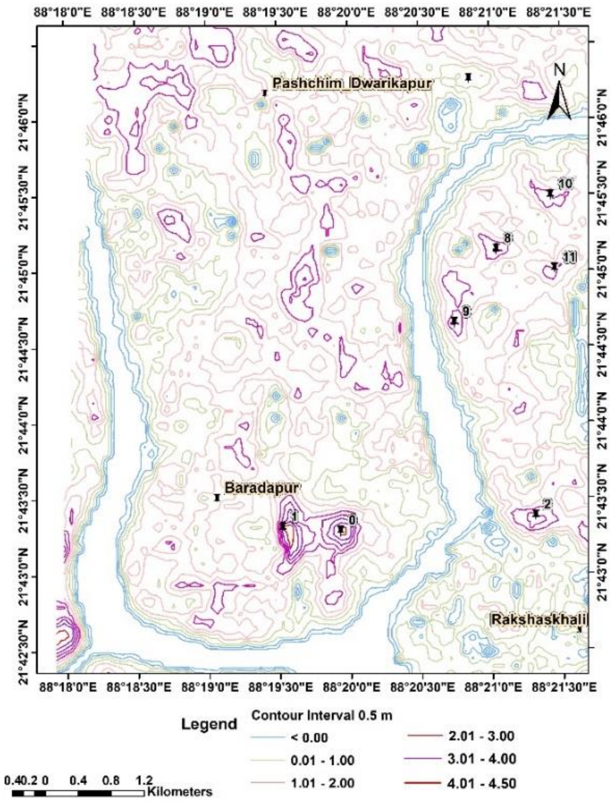


Fig 5.27 Probable archaeological sites near Baradapur and Paschim Dwarikapur

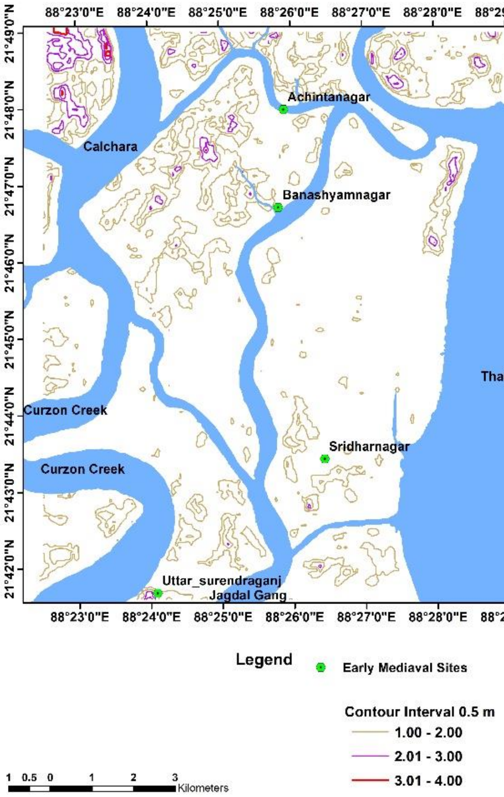


Fig 5.28 Probable archaeological sites near Banashyamnagar

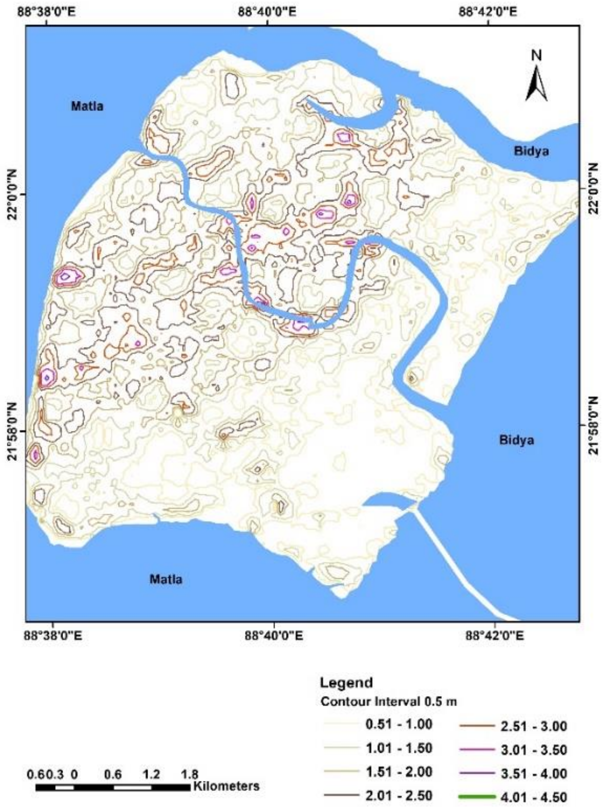


Fig 5.29 Probable archaeological sites in a mangrove island

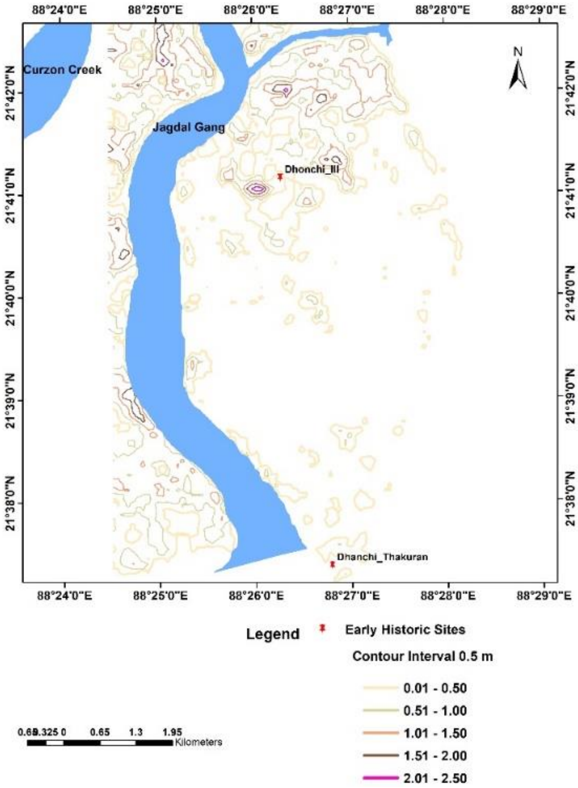


Fig 5.30 Probable archaeological sites near Dhanchi

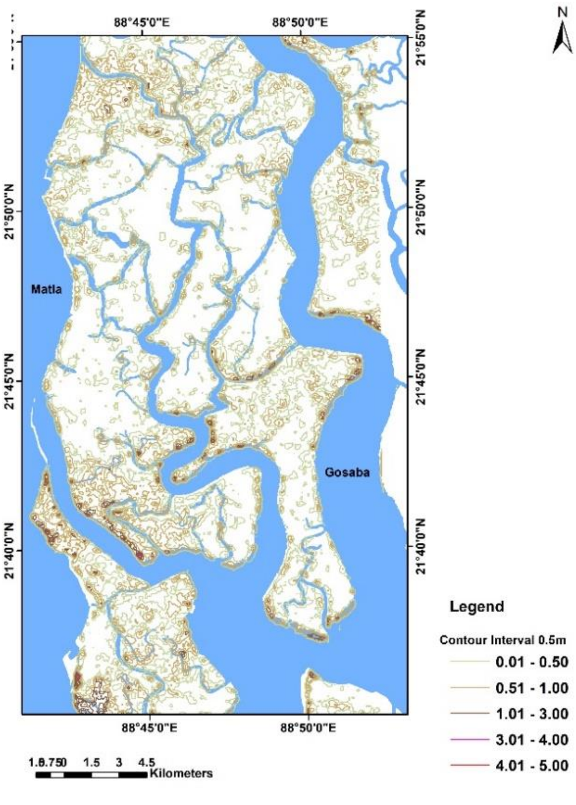


Fig 5.31 Probable archaeological in mangrove cover area of Sundarban delta

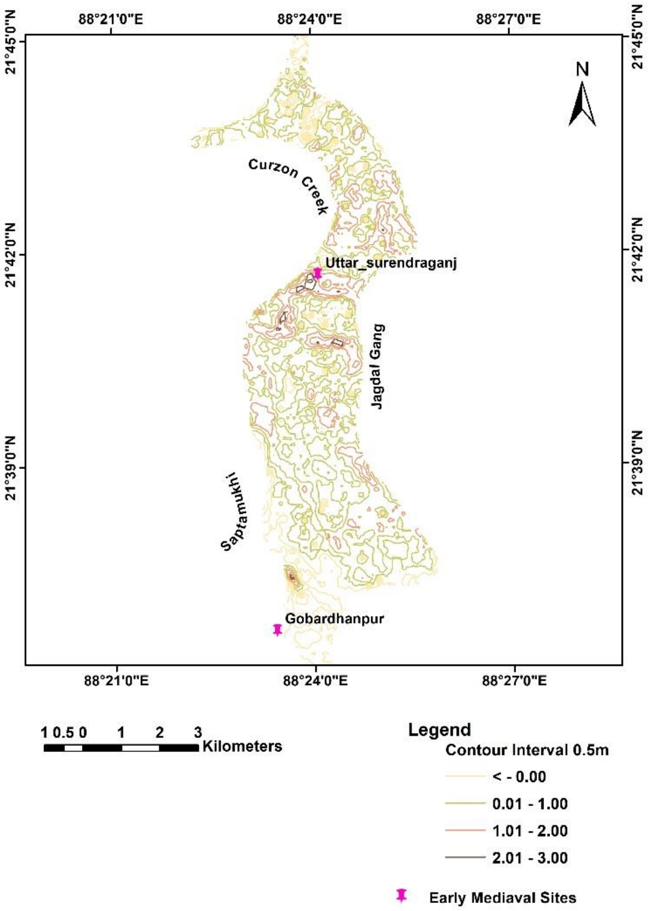


Fig 5.32 Probable archaeological sites near Uttar Surendraganj

Fig 5.33 Artifacts of 900 CE found in Uttar Surendragaunj

Probable sites near Banashyamnagar and Sridharnagar (fig 5.28) located on the bank of river Thakuran. Although these islands are low elevated area belongs to 1 to 2 m above sea level, a linear pattern (transverse ridge) near Uttar Surendragaunj (fig 5.32) on the bank of Saptamukhi of 3 to 4 m elevation has been found which might be new sites for excavation need detail research.

Chapter 6 Discussion

Potential new archaeological sites in the deltaic wetlands can be initially identified by examining three key criteria based on paleochannel courses and the location of natural levees relative to ancient historic and early medieval sites: (a) mound or ridge-like features elevated 2-3 meters above the surrounding terrain, (b) proximity to active or paleo-channels connected to sea-going routes, and (c) reports or findings of ancient artifacts.

Several such sites have been identified, particularly in the younger estuarine and tidally active delta regions, though these need to be confirmed through detailed field surveys, sampling, and subsurface exploration. Numerous archaeological sites from the Early Historic (300 BCE - 500 CE) and Early Medieval (600 CE - 1300 CE) periods have been mapped and analysed. Based on stylistic similarities, most of the archaeological remains excavated at various levels are attributed to historical periods spanning the Maurya, Sunga-Kushana, Gupta, Pala, and Sena dynasties. Further confirmation of these remains requires detailed radiometric dating of both the artifacts and the surrounding late Holocene sedimentary sequences.

The four major ancient occupational clusters—Chandraketugarh, Atghara, Tilpi-Dhosa, and Moni-Kankandighi—show evidence of in situ structures and are located along the paleo-river courses of the Bidyadhari, Adi Ganga, and their distributaries, such as the Piyali River, all of which had marine connectivity. A key contribution of this research is the high-resolution elevation mapping of the deltaic wetland, along with the identification of natural paleo-levees and paleo-channels, and mobility of settlements of the ancient people as a response to the changing climate, geomorphology, and delta dynamics.

6.1 Perspective on changes in Geomorphology and climate in Sundarban delta

The Tectono-Geomorphological map of the lower delta and coastal plain is composed for the present analysis synthesising various secondary data, consultation with scientific literatures and reports by various agencies like ONGC, DST, Kolkata port trust and online sources. Along the Western unit of laterite lies the basin margin fault zone separating the Tertiary shelf from the Cratonic basement further west. The present Ganga delta with the apex near Malda (not shown in the map) developed in the last 11,000 years during the Holocene period. The second important tectonic unit is the Kolkata Maimansingh Hinge zone denoting the shelf -slope break of the Bengal basin formed during Eocene time. The various north -south and east-west lineaments marked in the map have been taken from NRSC Bhuban site (https://bhuvan-app1.nrsc.gov.in/thematic/thematic/index.php) and Agarwal and Mitra, 1991 as their disposition have strong bearing on the river courses and their defection affecting the ancient settlements and sedimentation. The laterites and older alluvium along the Damodar-Ruparayan River upstream are key sites for the early Mesolithic and Chalcolithic civilizations of Bengal. The younger alluvial plains along the coast and the moribund delta, shaped by excess discharge from Peninsular and deltaic rivers, was influenced by the rejuvenated summer monsoon (Gupta et al.2005) after the 4.2 Kyr. B.P. Meghalayan Dry Event.

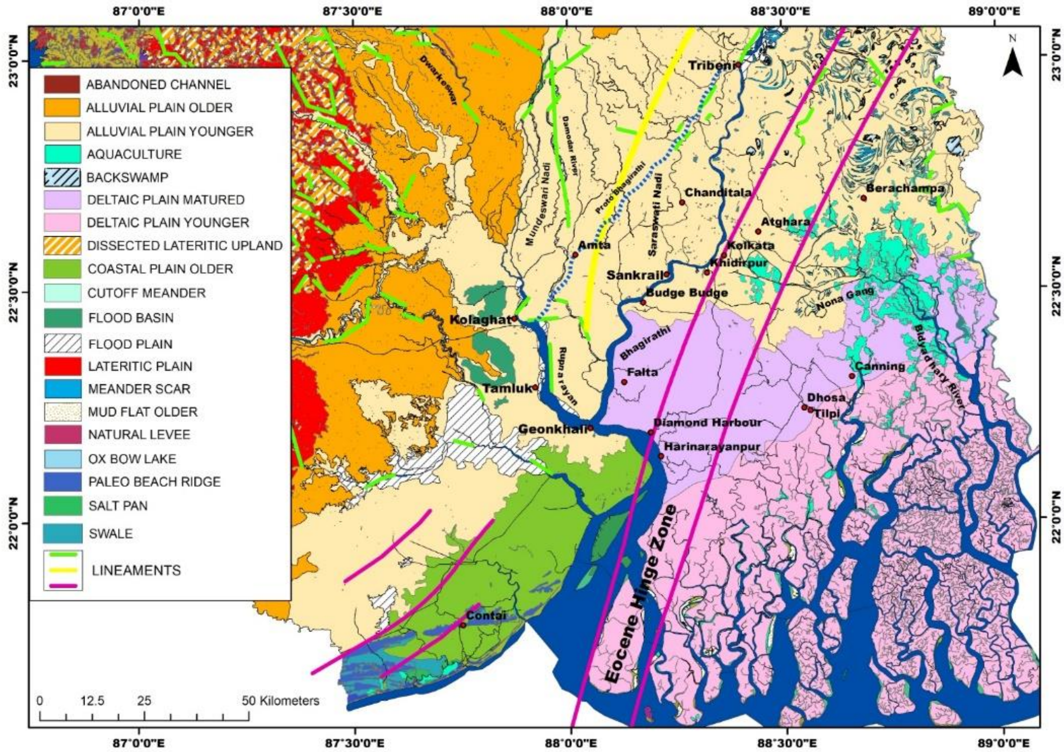


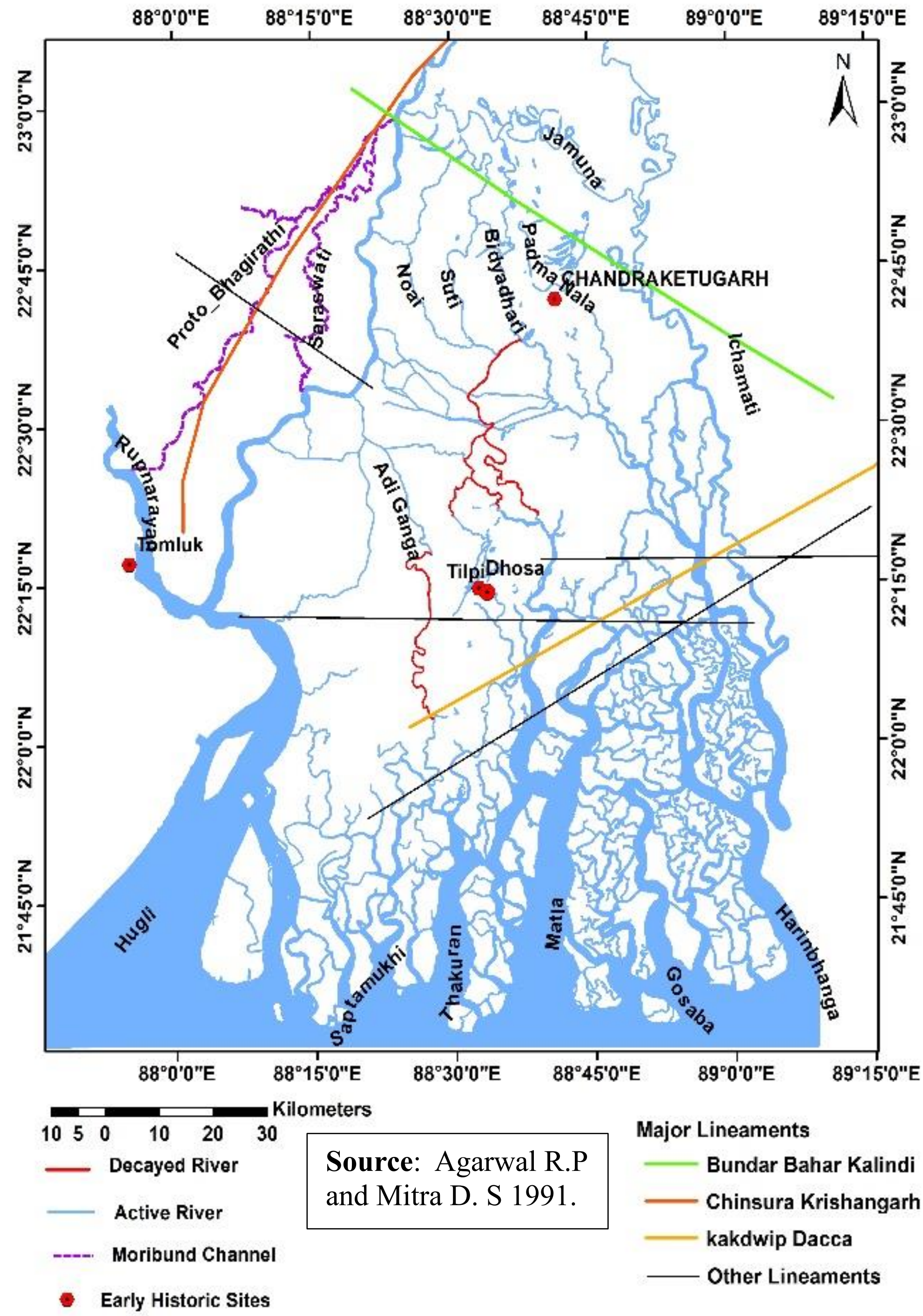
Fig 6.1 Tectono-Geomorphic Setup of the lower Bengal Delta and the coast

These fertile alluvial plains provided an excellent foundation for early societies to settle along rivers, cultivate crops, and establish cities and ports. Notably, Tamralipta on the Rupnarayan River and Berachampa (Chandraketugarh) on the Bidyadhari River in the Mayria-Gupta time period (300BCE to 500AD) flourished as centres of trade and prosperity. The intermediate matured delta plain hosts the subsidiary ancient port sites of Tilpi Dhosa which might have been abandoned before the Gupta period. The moribund delta plain with river borne alluvium is in true sense a riverine delta. The youngest and presently tidally active delta plain, with numerous island active with sea erosion from the south and deposition on the north. These two geomorphic units are site of early Medieval settlements and trade. From palynological analysis of core samples from Kolkata, Dumdum and Kolaghat area Sen and Banerjee, 2016 observed that the environmental situation in Kolaghat (Tamralipta) Kolkata. Dumdum (Chandraketugarh) during 1150 BCE to the present, changed to more fresh water condition with the abundant fresh water supply through a number of important rivers like Ganga/ Bhagirathi and Rupnarayan. Since 3000 ± yr BP to recent the coastline migrated to present position. Recent fresh water dominated locations of Calcutta, Dumdum, Barrackpore, Kolaghat have younger alluvium as the Holocene cover and the subsurface Holocene deposits has Silty clay, Peat, Soft Grey Clay with wood logs, Peat II and Bluish Grey Clay. The southern part has recent geomorphological features of delta top to delta front succession of the basin. 'There is no record of further sea level rise in West Bengal geoprovince after 5000 yr BP'.

6.2 A connection between Tamralipta and Chandraketugarh.

Several researchers (Rennel, 1779/1793, Rudra, 2014, Roy.N.1979) opined that present course of Hugli River was not the ancient course of Bhagirathi, the largest distributary of the Ganga. Rather Rennel 1783 indicated that the now moribund distributary Saraswati flowed through Amta –Chanditala- and joined Rupnarayan at Kolaghat happened to be the ancient and oldest outlet Ganga. This course of Bhagirathi mapped as 'Proto Bhagirathi' (Fig 6.2) suggested by Rudra, 2014, remained active till 700 AD and provided for Tamralipta, the flourishing port city of 300 BC to 700 AD, as reported by Fa Hien in 300 AD, Yuan Chang in 639 AD. The ancient course is drawn following the trend of 'Chinsura -Krishnanagar' lineament of Agrawal and Mitra,1991.

However, corresponding to the onset of the 'Medieval Cold Period' and a reduction in the summer monsoon, (estimated from microfossil from sediment core and other multiproxy analysis, complemented by the Earth System Paleoclimate Simulation (ESPS) model, by the BSIP, DST, GoI , https://pib.gov.in/PressReleasePage ,5.9.2024 accessed on 15.1.2025) the flow in the Proto-Bhagirathi reduced and eventually abandoned. The Bidyadhari River got disconnected in places, and the main seaward route for the Bhagirathi became the Adi Ganga and its various distributaries. During this time, due the dwindling flow along the Jamuna River connecting Tribeni on Bhagirathi with Tilpi on the river Ichamati started to develop series of acute meanders and oxbow lakes.



Source: Agarwal R.P and Mitra D. S 1991.

Fig 6.2 Proto Bhagirathi Connecting Tamralipta with Chandraketugarh

Some of these meander loops of Jamuna and Padma nala later encroached the site Chandraketugarh causing monsoonal flooding and destruction. This shift may have prompted the ancient people to relocate their settlements to the Atghara and Mani basins, continuing trade through the Adi Ganga via the Muri-ganga, Saptamukhi, and Matla estuaries. With the strengthening of the Indian summer monsoon after 900 A.D during the 'Medieval Warm Period' (Sinha etal.,2007), the civilization during the Pala and Sena periods expanded to new areas on the islands of the active delta plain, including in the mangrove forests of the Sundarbans.

6.3 Conclusion

With the growing trend of interdisciplinary studies among Geomorphologists, Geologists, Biologists, Ocean and Climate Scientists, Archaeologists, and Historians, the relationship between ancient climate change and its impact on early historical civilizations is becoming increasingly evident. Researchers are uncovering how these ancient societies responded to climate shifts, including their periods of expansion or decline, at an accelerating pace. This collaborative approach not only enhances our understanding of Paleoclimate and the societal reactions of ancient cultures but also provides valuable insights into how modern societies might respond to future climate challenges.

The integration of systematic interdisciplinary studies focused on the Holocene epoch, along with detailed analyses of early societal responses, in the Sundarban delta is therefore critical. Accurate age dating, paleoenvironmental research, and advanced geoscientific modelling should be prioritized to uncover more precise links between climate change and historical societal development. These efforts will help improve our ability to predict and mitigate future climate impacts on contemporary societies in this vulnerable delta.

References

1. Agarwal, R.P., Mitra, D.S., 1991. Paleogeographic reconstruction of Bengal delta during Quaternary period. In: Vaidyanadhan, R. (Ed.). Quaternary Deltas of India, Memoirs of Geological Society of India, Bangalore, pp. 13–24.
2. Alam, M., 1996. Subsidence of the Ganges- Brahmaputra delta of Bangladesh and associated drainage, sedimentation, and salinity problems. Kulwer Academic Publishing, Dordrecht, Netherlands, pp. 169- 192.
3. Ali, T and A. Mehrabian 2009. A Novel Computational Paradigm for Creating a Triangular Irregular Network (TIN) from LIDAR Data, Nonlinear Analysis Theory Methods and Applications Volume 71: 624-629.
4. Allison, M.A., 1998. Historical changes in the Ganges-Brahmaputra delta front. Journal of Coastal Research, 14, 1269-1275.
5. Allison, M.A., Kepple, E.B., 2000. Modern sediment supply to the lower delta plain of the Ganges- Brahmaputra River in Bangladesh. Geo-Marine Letters 21, 66 – 74.
6. Allison, M.A., Khan, S.R., Goodbred, S.L., Kuehl, S.A., 2002, Stratigraphic evolution of the late Holocene Ganges- Brahmaputra lower delta plain, Sedimentary Geology 155, 317- 342
7. Allison, M.A., Kuehl, S.A., Martin, T.C., Hassan, A., 1998. The importance of floodplain sedimentation for river sediment budgets and terrigenous input to the oceans: insights from the Brahmaputra – Jamuna River. Geology 26 (2), 175 – 178.
8. Assine, M.L., Corradini, F.A., Pupim, F. do N. & McGlue, M.M. (2014) Channel arrangements and depositional styles in the São Lourenço fluvial mega fan, Brazilian Pantanal wetland. Sedimentary Geology, 301, pp.172–184.
9. Babu PVLP (1975). Study of cyclic erosion surfaces and sedimentary unconformities in the Cauvery Basin-South India, J. Geol. Soc. India., 16(3): 349-359.
10. Bandyopadhyay, S. 1996. Location of The Adi Ganga Palaeochannel, South 24-Parganas, West Bengal: A Review, Geographical Review of India Vol 58: ISSN 0375-6386.
11. Bandyopadhyay. S, 2007. "Evolution of the Ganga- Brahmaputra delta: A review". Geographical review of India.
12. Bandyopadhyay. S, Das. S, Kar. N. S, 2015. 'Discussion, Changing River course in the western part of the Ganga- Brahmaputra delta by Kalyan Rudra (2014),

Geomorphology, 227, 87-100’. Geomorphology doi: 10.1016/j.geomorph.2015.02.037

13. Banerjee, M., Sen, P.K., 1988. Paleobiology and environment of deposition of Holocene sediments of the Bengal basin, India. The Palaeoenvironment of East Asia from the mid- Tertiary, Proceeding of the 2nd Conference. Centre of Asian Studies, University of Hong Kong, Hong Kong, pp. 703-731.
14. Barnhardt, W.A. & Sherrod, B.L. (2006) Evolution of a Holocene delta driven by episodic sediment delivery and coseismic deformation, Puget Sound, Washington, USA. *Sedimentology*, 53 (6), pp.1211–1228.
15. Basak, B 2019. The Dynamics of Heritage-Making at an Archaeological Site in South 24
16. Basak, B. (2014). Interpreting historical archaeology of coastal Bengal: possibilities and limitations. In: D. N. Jha, ed. The complex heritage of early India. New Delhi: Manohar Publishers & Distributors.
17. Begley, V. 1983. Arikamedu Reconsidered, American Journal of Archaeology 87: 461-81.
18. Begley, V. 1988. Rouletted Ware at Arikamedu: A New Approach, American Journal of Archaeology 92: 427- 40.
19. Blanchon, P.,Shaw, J., 1995. Reef drowning during the lastdeglaciation: evidence f or catastropic sea-level rise and ice-sheet collapse. Geology 23 (1), 4–8.
20. Blasco, F.; Saenger, P., and Janodet, E., 1996. Mangroves as indicators of coastal change. Catena, 27,167-178.
21. Boland, D. H. P., 1976, Trophic classification of lakes using Landsat-I (ERTS-l) multispectral scanner data, United States Environmental Protection Agency, Office of Research and Development, Corvallis Environmental Research Laboratory, Corvallis, Oregon.
22. Brammer H., 1996. The Geography of the Soils of Bangladesh. University Press, Dhaka, Bangladesh, 287 pp.
23. Bridge JS (1985) Palaeochannel patterns inferred alluvial deposits: a critical evaluation. Journal of Sedimentary Research. J Sediment Res 55(4):579–589.
24. Budja, M. and D. Mlekuz 2010. Lake or floodplain? Mid-Holocene Settlement Patterns and The Landscape Dynamic of The Izica Floodplain (Ljubljana Marshes, Slovenia), The Holocene 20 (8): 1269–1275.

25. Chakraborty. S. 2017 Archaeological sites of lower deltaic region of west Bengal and their context: Some preliminary observations. Pratna Samiksha, a journal of Archaeology, Volume- 8.
26. Challis, K., C. Carey, M. Kincey and A.J. Howard 2011. Assessing The Preservation Potential of Temperate, Lowland Alluvial Sediments Using Airborne Lidar Intensity, Journal of Archaeological Science 38 (2): pp. 301–311.
27. Chanda, S. and Hait, A.K., 1996. Aspects and appraisal of late Quaternary vegetation and lower Bengal basin. Palaeobotanist*,* 45*,* 117-124.
28. Chapman, G.P., Rudra, K., 2007.Water as foe, water as friend: lesson from Bengal millennium flood. J. South Asian Dev. 2, 19–49.
29. Chattopadhyay, Sagar (2005). Dakshin Chabbish Pargana Jelar Purakriti (in Bangla), Directorate of Archaeology and Museums, Government of West Bengal.
30. Chaudhary, B. S., & Aggarwal, S. (2009). Demarcation of palaeochannels and integrated ground water resources mapping in parts of Hisar district, Haryana. Journal of the Indian Society of Remote Sensing, 37(2), 251–260. doi:10.1007/s12524-009-0019-5.
31. Chaudhuri, A.B. and Choudhury, A., 1994. Mangroves of the Sundarbans. Volume One: India.
32. Chen, W., Xuanqing, Z., Naihua, H. & Yonghong, M. (1996) Compiling the map of shallow-buried palaeochannels on the North China Plain. Geomorphology, 18 (1), pp.47–52.
33. Chiverrell, R., G. Thomas and G. Foster 2008. Sediment-Landform Assemblages and Digital Elevation Data: Testing an Improved Methodology for The Assessment of Sand and Gravel Aggregate Resources in North-Western Britain, Engineering Geology 99 (1).
34. Ciampalini, A., Garfagnoli, F., Antonielli, B., Moretti, S., & Righini, G. (2013). Remote sensing techniques using Landsat ETM+ applied to the detection of iron ore deposits in Western Africa. Arabian Journal of Geosciences, 6 (11), 4529–4546. doi:10.1007/s12517-012-0725-0.
35. Crawford, D.G. 1903. A Brief History of the Hughli District. Bengal Secretariat Press, Calcutta, 81p.
36. Cudahy, T., & Ramanaidou, E. (1997). Measurement of the hematite: Goethite ratio using field visible and near-infrared reflectance spectrometry in channel iron

deposits, Western Australia. Australian Journal of Earth Sciences, 44(4), 411–420. doi:10.1080/ 08120099708728322

37. Cullen, J.L., 1981. Microfossil evidence for changing salinity patterns in the Bay of Bengal over the last 20 000 years. Palaeogeography, Palaeoclimatology, Palaeoecology 35, 315–356.
38. Das K S, Ghosh S, Gangopadhyay K, Ghosh S and Hazra M. (2017) Provenance study of ancient potteries from West Bengal and Tamilnadu: Application of major element oxides and trace element geochemistry. Man and Environmrnt XLII (2): 11-20.
39. Das, D.K., Majumder, I.P. and Ganguly, A. (1985). Evolution of the landscapes in the Calcutta Sundarban coastal area of South Bengal, India, Indian Academy Science (Earth Planet Science), 95(3): 143-152.
40. Das, G. K., 2015. Estuarine morphodynamics of the Sundarbans. Springer Cham Heidelberg New York Dordrecht London, DOI 10.1007/978-3-319-11343-2, Vol-11.
41. Dasgupta, A.B., 1997. Geology of the Bengal Basin, Indian Journal of Geology, Vol. 69, No. 2, p. 161- 176.
42. Datta, K. 1930. Antiquities of Khari. Varendra Research Society's Monograph No. 3. Rajshahi: Varendra Research Society.
43. Deng, Y. 2007. New Trends in Digital Terrain Analysis: Landform Definition, Representation, and Classification, Progress in Physical Geography vol. 31: pp. 405-19.
44. Dentith, M., O'Neill, A. & Clark, D. (2010) Ground penetrating radar as a means of studying palaeofault scarps in a deeply weathered terrain, southwestern Western Australia. Journal of Applied Geophysics, 72 (2), pp.92–101.
45. DST,GoI https://pib.gov.in/PressReleasePage ,5.9.2024 accessed on 15.1.2025
46. Eisank, C., Smith, M. & Hillier, J. 2014, 'Assessment of multiresolution segmentation for delimiting drumlins in digital elevation models', Geomorphology, vol. 214, pp. 452-64.
47. Eklundh, L. and Singh, A., 1993, A comparative analysis of standardized and unstandardized principal components analysis in remote sensing. International Journal of Remote Sensing, v. 14, pp. 1359–1370.

48. Fairbanks, R. G., 1989. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep ocean circulation. Nature 342 (6250), 637- 642.
49. Fergussion J, 1863. On recent changes in the delta of Ganges. Quarterly Journal of the Geological Society London, v XIX, p. 321- 354.
50. Ford, L.A., A.M. Pollard, R.A.E. Coningham and B. Stern 2005. A Geochemical Investigation of the Origin of Rouletted and other related South Asian Fine Wares, Antiquity 79: 909-920.
51. Galloway, W.E., 1975. Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional system. Houston Geological Society, Houston, TX, pp. 87- 98.
52. Ganguly D et al, 2006, Geomorphological study of Sundarban Deltaic Estuary. Journal of the Indian society of Remote Sensing. Vol. 34, No. 4, 2006.
53. Garrett, J.H.E., 1910. Bengal District Gazetteer, Nadia. Reprinted by West Bengal District Gazetteer, Govt. of West Bengal in 2001, Kolkata, pp. 5–24.
54. Gascon, F., C. Bouzinac, O. Thépaut, M. Jung, B. Francesconi, J. Louis, V. Lonjou, B. Lafrance, S. Massera and A. Gaudel-Vacaresse 2017. Copernicus Sentinel-2A Calibration and Products Validation Status, Remote Sens 9: 584.
55. Gasse, F., et al., 1991. A 13,000-year climate record from Western Tibet. Nature 353, 742- 745.
56. Gastrell, J.E. 1868. Geographical and Statistical Report of the Districts of Jessore, Fureedpore and Backergunge, Office of Superintendant of Govt. Printing, Calcutta, 46p.
57. Ghosh, A 1990 “An encyclopaedia of Indian archaeology” Volume 1, Indian Council of Historical research, New Delhi.
58. Ghosh, A. 1990. An Encyclopaedia of Indian Archaeology. Volume I. Indian Council of Historical research, New Delhi.
59. Goodbred, S.L., Kuehl, S.A., Steckler, M.S., Sarker, M. H., 2003. Controls on facies distribution and stratigraphic preservation in the Ganges- Brahmaputra delta sequence. Sedimentary Geology 155, 30 316.
60. Goodbred. S.L & Kuehl, S. A. 2000. The significance of large sediment supply, active tectonism, and eustasy on margin sequence development: Late Quaternary delta

stratigraphy and evolution of the Ganges- Brahmaputra delta. Sedimentary Geology 133 227-248.

61. Guo, L., Li, L., Fang, L., Wang, Xu., Jin H and Wang, G. 2018. Identification of Palaeochannels of Mihe River: An Approach Based on the Integrated Geophysical Methods. Science and Technology publication. ISBN: 978-989-342-1.
62. Gupta, A.K., Das, M., and Anderson, D.M. 2005. Solar influence on the Indian summer monsoon during the Holocene. Geophysical Research Letters.V.32 L17703, doi:10.1029/2005GL022685.
63. Hambly, F.B. 2015. Mapping and Characterisation of Palaeochannels: A Comparison of Field and Remote Sensing-Based approaches. ResearchGate, DOI: 10.13140/RG.2.1.4460.1048.
64. Hayakawa EH, Rossetti DF (2015) Late quaternary dynamics in the Madeira River basin, southern Amazonia (Brazil), as revealed by paleomorphological analysis. Anais da Academia Brasileira de Ciências (Annals of the Brazilian Academy of Sciences) 87(1): 29–49. https://doi.org/10.1590/0001-3765201520130506
65. Hirst, F. C., 1915. Report on the Nadia Rivers 1915. Bengal Secretariat Book Depot, Cal., Plate- 7.
66. Hohenthal, J., P. Alho, J. Hyyppa and H. Hyyppa 2011. Laser Scanning Applications in Fluvial Studies, Progress in Physical Geography 35 (6): pp. 782-809.
67. Hou B, Mauger AJ (2005) How well does remote sensing aid palaeochannel identification? An example from the Harris Greenstone Belt. SA, MESA J 38:46–52.
68. https://archive.org/details/astatisticalacc06kiscgoog.
69. Hudson. P, 2017, "Fluvial Depositional Processes and Landforms", Research Gate, DOI: 10.1002/9781118786352.wbieg087.
70. Hunter, W.W. 1875. A Statistical Account of Bengal. 1 (Districts of 24 Parganas and Sundarbans), Trübner and Co., London, 404p. Accessed on 10 December 2014 from:
71. Hunter, W.W., 1875. A Statistical Account of Bengal, 1. Gazetteer Department, Government
72. Justine K (2001) The hydrology, geomorphology and quaternary palaeochannels of the Lachlan Valley. New South Wales. Published thesis, Australian National University, Canberra.
73. Kalickl T (1987) Late glacial paleochannel of the Vistula River in Kraków-Nowa Huta. Studia Geomorphologica Carpatho-Balcanica 21:93–108.

74. Karmokar S, Halder M & Nandy S (2021), ‘Identification of Paleochannels Using Remote Sensing: a Study on Upper Gangetic Delta in Parts of Murshidabad and Nadia Districts, West
75. Kemp J, Rhodes EJ (2010) Episodic fluvial activity of inland rivers in southeastern Australia: palaeochannel systems and terraces of the Lachlan River. Quat Sci Rev 29(5-6):732–752v.
76. Kemp, J. & Spooner, N.A. (2007) Evidence for regionally wet conditions before the LGM in southeast Australia: OSL ages from a large palaeochannel in the Lachlan Valley. Journal of Quaternary Science, 22 (5), pp.423–427.
77. Kendra, Madhyamgram, 24 Parganas, West Bengal, pp. 1–20.
78. Khan Z.A. 1987 Paleodrainage and paleochannel morphology of a Barakar River (Early Permian) in the Rajmahal Gondwana Basin, India. Palaeogeogr Palaeoclimatol Palaeoecol 58(3-4):235–247.
79. Khan, F. H., 1991. Geology of Bangladesh. University Press Limited, Dhaka, 207.
80. Khandoker, R.A., 1987. Origin of elevated Barind–Madhupur areas, Bengal Basin: results of neotectonic activities. Bangladesh Journal of Geology 6, 1–9.
81. Krishnan, K. and R.A.E. Coningham 1997. Microstructural Analysis of Samples of Rouletted Ware and Associated Pottery from Anuradhapura, Sri Lanka, in South Asian Archaeology, 1995: Proceedings of the Thirteenth International Conference of the European Association of South Asian Archaeologists (F.R. Allchin and B. Allchin Eds.), pp. 925-937. New Delhi: Oxford & IBH Publishing Co. Pvt. Ltd.
82. Kulp, S.A and Strauss, B.H 2004. CoastalDEM v3.0: Improving fully global coastal elevation predictions through a convolutional neural network and multi-source DEM fusion, Climate Central Scientific Report.
83. Lawrie, K. C, Chan RA,Gibson DL, Kovacs NS (1999) Alluvial gold potential in buried palaeochannels in the Wyalong district, Lachlan Fold Belt, New South Wales. AGSO Res Newsletter 30:1–5.
84. Lindsay, J.F.; Holliday, D.W., and Hulbert, A.G., 1991. Sequence stratigraphy and the evolution of the Ganges-Brahmaputra delta complex. The American Association of Petroleum Geologists Bulletin, 75 (7), 1233-1254.
85. M A Mohammed Aslam and A Balasubramanian. (2001). ‘Identification of Palaeochannels Around Cauvery River Near Talakad, Karnataka Using Remote Sensing Data’. Photonirvachak Journal of the Indian Society of Remote Sensing, Vol. 29, No. 4, 2001.

86. Majumdar. R. C., 1942. The History of Bengal, The University of Dacca. Volume. 1.
87. Mallinson, D.J., Smith, C.W., Culver, S.J., Riggs, S.R. & Ames, D. (2010) Geological characteristics and spatial distribution of paleo-inlet channels beneath the outer banks barrier islands, North Carolina, USA. Estuarine, Coastal and Shelf Science, 88 (2), pp.175–189.
88. Mandal, A. (2018) "Myth and reality of the Adi Ganga: A palaeodistributary of the Ganges in West Bengal, India" International Journal of Applied Social Science Volume 5 (8), 1347-1353
89. McFeeters, S. K., (1996). 'The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. International Journal of Remote Sensing. VOL. 17, No.7, 1425-1432. https://doi.org/10.1080/01431169608948714
90. Mehdi, M.S., C.N. Pant, S.H. Saini, S.A.I Majtaba and P. Pande 2015. Identification of Palaeochannel Configuration in The Saraswati River Basin in parts of Haryana and Rajasthan, India, Through Digital Remote Sensing and GIS, Vol. 39 p. 1.
91. Middya, D. 2014. Jatar Deul. In: A. Chattopadhyay, ed. Jatar Deul-er Itibrittyo [The Chronicles of Jatar Deul]. Raydighi: Jatar Deul Sanskriti Sangha, pp. 3–24.
92. Milliman, J.D., 2000. Relict shelf ooids: Late Quaternary Sea level and tropical aridity. American Geophysical Union Ocean Sciences Meeting, San Antonio, TX.
93. Mitra, S., 1995. Uttar Chabbis Parganar Nadi O Prachin Savyata (in Bengali). Jana Sanhati
94. Mohammed-Aslam, M. & Balasubramanian, A. 2010, 'History of river channel modifications-A review', Journal of Ecology and the Natural Environment, vol. 2, no. 10, pp. 207-12.
95. Mondal, B. 2015. Anthropogenic impact on river of sundarban deltaic settlement area; with special references to the Piyali River, South 24 Parganas, West Bengal, India. International journal of multidisciplinary research and development.
96. Morgan, J.P., McIntire, W.G., 1959. Quaternary geology of the Bengal Basin, East Pakistan and India. Geological Society of America bulletin. 70, 319- 342.
97. Morgan, J.P., McIntire, W.G., 1959. Quaternary geology of the Bengal Basin, East Pakistan and India. Geological Society of America bulletin. 70, 319- 342.
98. Mukerjee, R.K. 1938. The Changing Face of Bengal: A Study of Riverine Economy, Unversity of Calcutta, 137p.
99. Mukherjee, A. and Hazra, S., 1997. Changing paradigm of petroleum exploration in Bengal basin. Indian journal of Geology, 69 (1), 41-64.

100. Mukhopadhyay, A. 1970. Chabbish Parganar mondir [The Temples of 24 Parganas]. Anandadhara Prakashan.

101. Munyati, C., 2008, Use of Principal Component Analysis (PCA) of Remote Sensing Images in Wetland Change Detection on the Kafue Flats, Zambia. Geocarto International, 19:3, 11-22, DOI: 10.1080/10106040408542313

102. Nandini, C., Sanjeevi, S. & Bhaskar, A.S. (2013) An integrated approach to map certain palaeochannels of South India using remote sensing, geophysics, and sedimentological techniques. International Journal of Remote Sensing, 34 (19), pp.6507–6528.

103. Naskar, K. 1993. Plant wealth of the lower Ganga delta. Vol- I, Daya Publishing House, Delhi, ISBN 81-7035-118-9.

104. Neal, A. (2004) Ground-penetrating radar and its use in sedimentology: principles, problems and progress. Earth-Science Reviews, 66 (3), pp.261–330.

105. of West Bengal, Kolkata, pp. 9–13 (Reprinted by). Kolkata Port Trust 2000. Unpublished Annual Report of Hydraulic Study Department, Kolkata. Kolkata Port Trust, 2010. Tide Tables for Hugli River, (Kolkata).

106. Page, K. & Nanson, G. (1996) Stratigraphic architecture resulting from Late Quaternary evolution of the Riverine Plain, south-eastern Australia. Sedimentology, 43 (6), pp.927–945.

107. Pels, S. (1966) Late Quaternary chronology of the riverine plain of southeastern Australia. Journal of the Geological Society of Australia, 13 (1), pp.27–40.

108. Rajawat AS, Verma PK, Nayak S 2003 Reconstruction of palaeochannel network in northwest India: retrospect and prospects of remote sensing-based studies. Proc Indian Natl Sci Acad 69:217– 230.

109. Ramanaidou, E., Morris, R., & Horwitz, R. 2003. Channel iron deposits of the Hamersley Province, Western Australia. Australian Journal of Earth Sciences, 50(5), 669–690. doi:10.1111/j.1440-0952.2003. 01019.x

110. Rathore VS, Nathawat MS, Champatiray PK 2010 'Palaeochannel detection and aquifer performance assessment in Mendha River catchment, Western India' J Hydrol 395(3-4):216–225. https://doi.org/10. 1016/j.jhydrol.2010.10.026.

111. Ray, N.R. 1979: Tamralipta and Ganga: two port- cities of ancient Bengal and connected consideration, Geogr. Rev. Ind., 43(3), pp 205-222.

112. Re. G. L, Fuller. I. C, Sofia. G, Tarolli. P., 2018. 'High-resolution mapping of Manawatu palaeochannels'. New Zealand Geographical Society. doi:10.1111/nzg.12186.

113. Rennel, J. 1779. Bengal Atlas

114. Rennel, J. 1783/1793. Memoir of a Map of Hindoostan

115. Roy, R.K and Chattopadhyay, G. S., 1997. Quaternary Geology of the environs of Ganga delta, West Bengal and Bihar. Indian Journal of Geology, vol. 69, No. 2, p. 177- 209.

116. Roybarman A., 1992. Geological history and hydrocarbon explorations in Bengal basin. Indian Journal of Geology*,* 64 (3), 235-258.

117. Rudra, K. 2014. Changing River Courses in The Western Part of The Ganga–Brahmaputra

118. Rudra, K., 1981. Identification of the ancient mouths of the Ganga as described by Ptolemy. Geogr. Rev. India 43, 97-104

119. Ryan, D.A., Bostock, H.C., Brooke, B.P. & Marshall, J.F. 2007 Bathymetric expression of the Fitzroy River palaeochannel, northeast Australia: Response of a major river to sea-level change on a semi-rimmed, mixed siliciclastic-carbonate shelf. Sedimentary Geology, 201 (1), pp.196–211.

120. Salles, J F. and A. Dominque 2005. Rouletted Wares from Mahasthangarh, Pratnatattva 11: 27-34.

121. Sanyal, P., 1990. Ecological problems of Sundarbans mangrove. In: Proceeding of the Workshop on Wasteland Development Programme, Calcutta, India: Jadavpur University, 1-6.

122. Sarkar, A. 2015. "Degeneration of the original channel of river Hooghly: the Adi Ganges, West Bengal, India". The journal of bengal geographer, volume iv number iv, ISSN 2319-619X.

123. Selvakumar, V. 2008. Ceramics of the Iron Age-Early Historic Period in Tamil Nadu and Kerala, in Archaeology of Early Historic South Asia (Gautam Sengupta and S. Chakraborty Eds.), pp. 420-449. New Delhi: Pragati Publications.

124. Sen, P. and Banerjee, M. 2016. Holocene Bio- stratigraphic Zones Corresponding Litho- Chronostratigraphy, Environment of Deposition and Successive Changes in the Geomorphology of Bengal Basin, India during Last 10,000 Years. International Journal of Geosciences, 7, 615-629

http://dx.doi.org/10.4236/ijg.2016.74047

125. Sentinel- 2 user handbook, European Space Agency. ASA Standard Document. Dt. 24/07/2015, Issue 1, Rev 2.

126. Sesoren, A., 1984. Geological interpretation of Landsat imagery of the Bangladesh Ganges delta. ITC journal 3, 229- 232.

127. Seto, K. C. (2011). Exploring the dynamics of migration to mega-delta cities in Asia and Africa: Contemporary drivers and future scenarios. Global Environmental Change, 21S, S94–S107. https://doi.org/10.1016/j.gloenvcha.2011.08.005

128. Shukla Z, Thakkar MG (2014) Palaeochannel investigations and geo hydrological significance of Saraswati River of Mainland Gujarat, India: using remote sensing and GIS techniques. J Environ Res Dev 9(2):472–479

129. Singh, I., 1996. Geological Evolution of the Ganga Plain- An overview. Department of Geology, Lucknow University, Lucknow- 226007. Journal of the Paleontological society of India. Vol.41, pp. 99, 118- 120.

130. Sinha, A, Cannariato, G.C., Stott, L.D., Cheng H, Edwards, R.L., Yadava, M.G., Ramesh, R. and Singh, I.B,2007. A 900-year (600 to 1500 A.D.) record of the Indian summer monsoon precipitation from the core monsoon zone of India Geophysical Research Letters. V 34 L1607, doi:10.1029/2007GL030431

131. Slowik, M. (2011) Changes of river bed pattern and traces of anthropogenic intervention: The example of using GPR method (the Obra River, western Poland). Applied Geography, 31 (2), pp.784–799.

132. Smedt PD,MeirvenneMV,Meerschman E, Saey T, BatsM, Court- Picon M et al (2011) Reconstructing palaeochannel morphology with a mobile multicoil electomagnetic induction sensor. Geomorphology 130(3–4):136–141

133. Smith DN, Fletcher M, Head K, Smith W, Howard AJ (2010) Environmental reconstruction of a later prehistoric palaeochannel record from Burrs Countryside Park, Bury, Greater Manchester. Environ Archaeol 15(1):16–31

134. Sola, I., A.G. Martin, S.L. Pozo, J.A. Mozos, F.P. Cabello, M.G. Audicana and R.M. Lloveria 2018. Assessment of Atmospheric Correction Methods for Sentinel- 2 Images in Mediterranean landscape, Geoinformation 73 pp. 63-76.

135. Srivastava, K.S., Hambly, B., Davies, P., McCallum, A., Clewett, T & Gontz, M. A. 2016. Mapping possible palaeochannel: an integration of remote sensing-based approaches. Research Gate. Pp 1-16.

136. Stanley, D.J. and Chen, Z., 1993. Yangtze delta, eastern China: 1. Geometry and subsidence of Holocene depocenter. Marine Geology, 112, 1-11.

137. Stanley, D.J., Hait, A.K., 2000. Holocene depositional patterns, neo- tectonics and Sundarbans mangroves in the western Ganges- Brahmaputra delta. Journal of Coastal Research 14, 794- 825.

138. Stanley, D.J., Warne, A.G., 1994. Worldwide initiation of Holocene marine deltas by deceleration of sea – level rise. Science 265, 228- 231.

139. Straatsma, M. & Middelkoop, H. (2006) Airborne laser scanning as a tool for lowland floodplain vegetation monitoring. Hydrobiologia, 565, pp.87–103.

140. Sylvia, D. A. & Galloway, W. E. 2006, 'Morphology and stratigraphy of the late Quaternary lower Brazos valley: Implications for paleo-climate, discharge and sediment delivery', Sedimentary Geology, vol. 190, no. 1-4, pp. 159-75.

141. Syvitski, J. P. M., & Saito, Y. (2007). Morphodynamics of deltas under the influence of humans. Global and Planetary Change, 57(3–4), 261–282. https://doi.org/10.1016/j.gloplacha.2006.12.001

142. Szabo, S., Brondizio, E., Renard, F. G., Hetrick, S., Nicholls, R. J., Matthews, Z., et al. (2016). Population dynamics, delta vulnerability and environmental change: Comparison of the Mekong, Ganges–Brahmaputra and Amazon delta regions. *Sustainability Science*, *11*(4), 539–554. https://doi.org/10.1007/s11625-016-0372-6.

143. Thakur, M. 2022. Ancient terracotta art of Bengal- a living tradition. Journal of Arts, Humanities and Social sciences, Volume-

144. Timár, G., Sümegi, P. & Horváth, F. 2005 Late Quaternary dynamics of the Tisza River: evidence of climatic and tectonic controls. Tectonophysics, 410 (1), pp.97–110.

145. Timmons, E.A., Rodriguez, A.B., Mattheus, C.R. & DeWitt, R. 2010 Transition of a regressive to a transgressive barrier island due to back-barrier erosion, increased storminess, and low sediment supply: Bogue Banks, North Carolina, USA. Marine Geology, 278 (1), pp.100–114.

146. Triantafilis, J. & Buchanan, S. 2009 Identifying common near-surface and subsurface stratigraphic units using EM34 signal data and fuzzy k-means analysis in the Darling River valley. Australian Journal of Earth Sciences, 56 (4), pp.535–558.

147. Umitsu, M., 1987. Late Quaternary sedimentary environment and landform evolution in the Bengal Lowland. Geographical Review of Japan 60, 164- 178.

148. Umitsu, M., 1993. Late Quaternary sedimentary environment and landforms in the Ganges delta. Sedimentary Geology 83, 177- 186.

149. Upadhyay, R.K., K. N. Kishore and M. Sharma 2021. Delineation and Mapping of Palaeochannels Using Remote Sensing, Geophysical, and Sedimentological Techniques: A Comprehensive Approach, Water Science pp. 100-108.

150. Vervoort, R., & Annen, Y. 2006. Palaeochannels in Northern New South Wales: Inversion of electromagnetic induction data to infer hydrologically relevant stratigraphy. Soil Research, 44(1), 35–45. doi:10.1071/ SR05037.

151. Vishnu- Mittre, E., Gupta, H.P., 1972. Pollen analytical study of Quaternary deposits in the Bengal Basin. Palaeobotanist 19, 297- 306.

152. Wang XY, Guo HD, Chang YM, Zha LS 2004 On paleodrainage evolution in mid-late Epipleistocene based on radar remote sensing in northeastern Ejin Banner, Inner Mongolia of China. J Geogr Sci 14(2):235–241

153. Wang, X., Guo, Z., Wu, L., Zhu, C., & He, H. 2012. Extraction of palaeochannel information from remote sensing imagery in the east of Chaohu Lake, China. Frontiers in Environmental Science, 6(1), 75–82.

154. Weber, M.E., Wiedicke, M.H., Kudrass, H.R., Hubscher, C., Erlen-Keuser, H., 1997. Active growth of the Bengal Fan during sea-level rise and highstand. Geology 25 (4), 315- 318.

155. Wheeler, R.E.M., A. Ghosh and K. Deva 1946. Arikamedu: an Indo-Roman trading station on the east coast of India.

156. Wiedicke, M., Kudrass, H.R., Hubscher, C., 1999. Oolitic beach barriers of the last Glacial sea -level lowstand at the outer Bengal shelf. Marine Geology 157, 7- 18.

157. Wilson, C.R. (1892): Note on the topography of the river in the 16th century from Hugli to the sea as represented in the Da Asia of De Barros, j. Asia Soc. Bengal, 61(J), pp 109-117.

158. Wray A.L. R, (2009), ‘Palaeochannels of the Namoi River Floodplain, New South Wales, Australia: the use of multispectral Landsat imagery to highlight a Late Quaternary change in fluvial regime’. Australian Geographer. ISSN: 0004-9182 (Print) 1465-3311.

159. Wu C, Xu QH, Zhang XQ, Ma YH 1996 Palaeochannels on the North China Plain: types and distribution. Geomorphology 18(1): 5–14.

160. Xu QH, Wu C, Zhu XQ, Yang XL (1996) Palaeochannels on the North China Plain: stage division and palaeoenvironments. Geomorphology 18(1):15–26.

161. Xu. Z, Khan M. R, Ahmed K. M, Zahid. A, Hariharan. J, Passalacqua. P, Steel. E, Chadwick. A, Paola. C, Goodbred. L. S, Paldor. A, and Michael. A., 2023. ‘Predicting Subsurface Architecture from Surface Channel Networks in the Bengal Delta’. Journal of Geophysical Research: Earth Surface. 10.1029/2022JF006775.

162. Zani, H. & Rossetti, D. de F. (2012) Multitemporal Landsat data applied for deciphering a megafan in northern Amazonia. International Journal of Remote Sensing, 33 (19), pp.6060–6075.

163. Zanter, K., 2015. Landsat 8 (L8) Data Users Handbook. Department of the Interior US