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Digital Integration of Geological and Geographical Mapping: Cartographic Innovation and Spatio-Temporal Analysis of the Geological Time Scale Using Remote Sensing and GIS in Nadia District, West Bengal, India

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***Abstract:** The present study examines the digital integration of geological and geographical mapping using Remote Sensing and Geographic Information Systems (GIS) to analyze spatio-temporal landform dynamics and hazard-prone zones in Nadia District, West Bengal, India. The study focuses on selected areas of Ranaghat, Chakdaha, Santipur, Bagula, and Krishnanagar, which are located within an active alluvial floodplain influenced by the Bhagirathi–Hooghly river system. Multi-source spatial datasets, including satellite imagery, digital elevation models, and Geological Survey of India lithological maps, were integrated within a GIS framework to generate innovative cartographic outputs such as geological cross-profiles, block diagrams, and hazard zonation maps.*

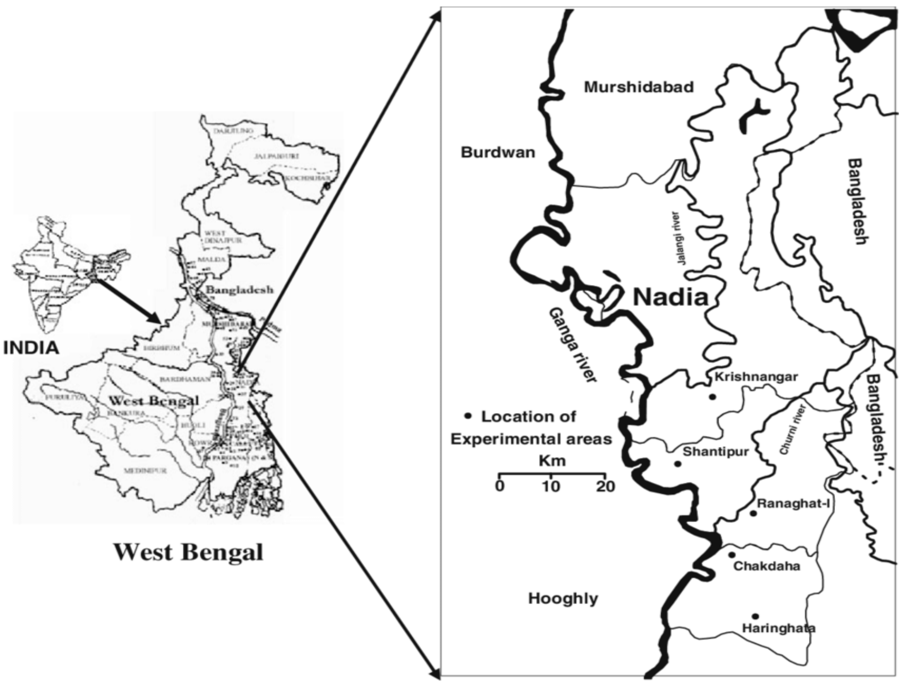
Spatio-temporal analysis reveals that unconsolidated alluvial sediments, shallow subsurface clay layers, and low terrain gradients play a critical role in controlling erosion, flooding, and landform instability across the study area. Active fluvial processes, including channel migration and sediment deposition, significantly influence present landform dynamics and hazard distribution. The findings demonstrate a strong spatial association between geological structure, surface morphology, and environmental processes, highlighting the effectiveness of GIS-based approaches over conventional mapping methods. The study concludes that Remote Sensing and GIS provide a comprehensive and reliable framework for regional geological mapping, hazard assessment, and land-use planning in flood-prone alluvial regions such as Nadia District.

***Keywords:** Remote Sensing; Geographic Information System (GIS); Geological Mapping; Spatio-Temporal Analysis; Fluvial Processes; Hazard Zonation; Nadia District; West Bengal.*

Introduction:

Geological and geographical mapping has long been fundamental to understanding the evolution of landforms, subsurface structures, and surface processes that shape regional landscapes. Traditional geological mapping methods, although valuable, often lack the capacity to capture **spatio-temporal variability** and complex interactions between lithology, terrain, and dynamic environmental processes, particularly in low-lying alluvial regions (Chorley et al., 1984; Schumm, 1977).

The rapid advancement of **Remote Sensing and Geographic Information Systems (GIS)** has transformed cartographic practices by enabling the integration of multi-source spatial datasets for detailed analysis and visualization of geological phenomena (Burrough & McDonnell, 1998; Aronoff, 1989). In recent decades, GIS-based geological mapping has proven effective in analyzing **fluvial processes, sediment dynamics, and hazard-prone zones**, especially in river-dominated landscapes (Gupta, 2007; Pal & Sarda, 2013). Multi-temporal satellite imagery and digital elevation models (DEMs) facilitate the examination of landform changes over geological and historical time scales, offering new insights into erosion, flooding, and channel migration patterns (Lillesand et al., 2015; Jensen, 2016). The integration of geological time-scale concepts within a GIS framework further enhances the interpretative depth of spatial analysis by linking stratigraphic sequences with surface morphology and environmental dynamics (Davis, 2002).



Nadia District of West Bengal represents a typical **active alluvial floodplain environment**, influenced by the Bhagirathi–Hooghly river system. Frequent flooding, bank erosion, and waterlogging characterize the region, making it highly suitable for studying the interaction between geological structure and fluvial processes. Therefore, the present study adopts a **digitally integrated geological–geographical approach** using Remote Sensing and GIS to analyze spatio-temporal landform dynamics and hazard susceptibility in selected areas of Nadia District.

Rationale of the Study

The rationale of this study emerges from the growing need for **accurate, dynamic, and integrative geological mapping techniques** in flood-prone alluvial regions. Conventional geological maps are largely static and often insufficient for addressing contemporary issues such as land-use planning, hazard mitigation, and environmental management (Burrough & McDonnell, 1998). In contrast, GIS allows continuous updating, spatial modeling, and integration of geological, geomorphological, and hydrological datasets within a unified analytical framework (Weng, 2014). Nadia District experiences recurring flood hazards due to its **low relief, unconsolidated alluvial sediments, and active fluvial regime**, yet detailed GIS-based geological assessments at the district and sub-district levels remain limited. Previous studies have highlighted the importance of integrating remote sensing data with geological information to identify erosion-prone and flood-susceptible zones (Pal & Sarda, 2013; NRSC, 2019). However, limited attention has been given to linking **geological time-scale interpretation with present-day landform dynamics** using digital cartographic techniques. This study is therefore rationalized by the need to bridge this gap through **digital integration of geological and geographical mapping**, combining geological cross-profiles, block diagrams, and spatio-temporal analysis within a GIS environment. Such an approach enables a clearer understanding of how past geological processes continue to influence present landforms and environmental hazards in Nadia District.

Significance of the Study

The significance of the present study lies in its **methodological, scientific, and practical contributions**. Methodologically, the research demonstrates the effectiveness of **GIS and Remote Sensing as comprehensive tools** for integrating geological and geographical datasets, surpassing the analytical limitations of conventional mapping approaches (Aronoff, 1989; Jensen, 2016). The preparation of geological cross-profiles, block diagrams, and hazard zonation maps within a digital framework enhances spatial accuracy and interpretative clarity. Scientifically, the study contributes to a deeper understanding of **fluvial geomorphology and alluvial stratigraphy** by establishing clear relationships between lithology, terrain characteristics, and surface processes (Schumm, 1977; Gupta, 2007). The spatio-temporal analysis highlights how geological structures and sedimentary environments govern landform evolution and hazard distribution over time. Practically, the findings of this study are significant for **regional land-use planning, disaster risk reduction, and sustainable development** in Nadia District. GIS-based hazard zonation maps provide valuable inputs for planners and administrators in identifying vulnerable zones and prioritizing mitigation measures (Singh & Singh, 2010). Moreover, the digital framework developed in this research can be replicated in other flood-prone alluvial regions of eastern India, thereby extending its applicability beyond the present study area.

Statement of the Problem

Nadia District of West Bengal is situated within an active alluvial floodplain system influenced by the Bhagirathi–Hooghly river, where **frequent flooding, riverbank erosion, waterlogging, and landform instability** pose persistent challenges to human settlement, agriculture, and infrastructure. Despite the availability of conventional geological and geomorphological maps, these resources are largely **static, generalized, and inadequate** for capturing the dynamic nature of fluvial processes and their spatial–temporal variability across the district. As a result, existing mapping approaches fail to provide a comprehensive understanding of how **geological structure, sedimentary composition, and surface processes interact to control hazard-prone zones** in low-lying areas.

Rapid changes in landforms due to **channel migration, sediment deposition, and seasonal hydrological fluctuations** further complicate hazard assessment and land-use planning in Nadia District. Although Remote Sensing and GIS technologies offer advanced capabilities for multi-temporal analysis and digital integration of spatial datasets, their systematic application for **geological time-scale interpretation, cross-profile analysis, and block diagram-based hazard evaluation** at the district and sub-district levels remains limited. In particular, there is a lack of integrated studies that combine geological stratigraphy, geomorphology, and environmental processes within a single GIS framework for the selected areas of **Ranaghat, Chakdaha, Santipur, Bagula, and Krishnanagar**.

The core problem addressed in this study, therefore, is the **absence of an integrated, GIS-based geological and geographical mapping framework** capable of analyzing spatio-temporal landform dynamics and identifying erosion-, flood-, and hazard-prone zones with greater accuracy. Without such an approach, planning and mitigation strategies in Nadia District continue to rely on incomplete or outdated information, increasing vulnerability to environmental hazards. This study seeks to address this gap by digitally integrating geological and geographical datasets using Remote Sensing and GIS to support improved regional geological mapping, hazard assessment, and sustainable land-use planning.

Research Objectives

1. To integrate geological and geographical datasets for the Nadia District (including Ranaghat, Chakdaha, Santipur, Bagula, and Krishnanagar) through Remote Sensing and GIS to produce innovative digital cartographic outputs reflecting the spatial distribution of geological features across the Geological Time Scale.
2. To perform a spatio-temporal analysis of geological formations and landform changes within the selected urban and peri-urban sectors of Nadia District using multi-temporal satellite imagery and GIS modelling techniques.
3. To evaluate and interpret the relationships between geological structures, surface morphology, and temporal environmental dynamics in Nadia District, thereby contributing a comprehensive GIS-based framework for regional geological mapping and future land-use planning.

Null Hypotheses (H_0)

H_{01} : There is no significant difference in the accuracy and analytical effectiveness of cartographic outputs produced through GIS and Remote Sensing–based integration of geological and geographical data compared to conventional mapping methods in the Nadia District, West Bengal.

H_{02} : There are no significant spatio-temporal variations in geological formations and geomorphological features across the selected areas of Nadia District, namely Ranaghat, Chakdaha, Santipur, Bagula, and Krishnagar, as detected through multi-temporal GIS and Remote Sensing analysis.

H_{03} : There is no significant relationship between geological structures, surface morphology, and temporal environmental dynamics within the selected study areas of Nadia District when analyzed using GIS-based spatial modelling techniques.

Research Questions

1. How can geological and geographical mapping datasets for the Nadia District (Ranaghat, Chakdaha, Santipur, Bagula, Krishnagar) be effectively integrated using GIS and Remote Sensing to produce accurate digital cartographic representations of the Geological Time Scale?
2. What are the significant spatio-temporal patterns and changes in geological formations and geomorphology within the selected areas of Nadia District over time?
3. How do geological structures and surface processes influence current landform dynamics and potential hazard zones in the Nadia District's study area?

Literature Review: National & International Studies

Author & Year (APA)	Study Focus / Methodology	Key Findings	Research Gap
Das, S., Roy, K., Mallick, B., & Ghosh, T. (2025)	Delineation of flood-vulnerable zones using AHP & GIS, Sagar Island, Indian Sundarban Delta (International)	AHP & GIS effectively identified flood vulnerable zones, highlighting climate and geomorphological influences in flat deltaic terrain.	Does not integrate geological cross-profiles or subsurface stratigraphy with hazard zones; limited to vulnerability categorization.
Islam, K. (2024)	GIS-based flood susceptibility mapping using multiple statistical models, Keleghai Basin, India (National)	Multiple statistical models (Frequency Ratio, Shannon Entropy, Information Value) successfully mapped flood susceptibility influenced by geomorphological and hydrological variables.	Focus predominantly on statistical models for flood; limited link with geological structures & geological time scale aspects.

Dandapat, K., & Panda, G. K. (2018)	GIS flood hazard modelling, Paschim Medinipur, West Bengal, India (National)	GIS-derived flood hazard models show significant portions of population exposed to high risk, demonstrating utility of spatial analysis in hazard assessment.	Population & vulnerability emphasis; lacks integration of deep geology, stratigraphy, and fluvial sediment controls.
Majumder, R., & Devi, T. D. (2025)	Geomorphic characteristics & flood susceptibility, North 24 Parganas, West Bengal, India (National)	Remote sensing & DEM integration effectively mapped susceptibility and geomorphological impacts on flood dynamics.	Focused on geomorphology & flood mapping but not on geological time scale, subsurface profiles, or landform evolution processes.
Ameen, A. A. A., et al. (2019)	Flood mapping & impact analysis using GIS (Kerala, India) (National)	GIS mapping improved understanding of flood extent & impacts, supporting better disaster planning.	Emphasizes flood extent but not geological structural control or sedimentary history over time.
Islam, L. D., et al. (2021)	Review of RS & GIS applications for flash floods (International)	RS & GIS widely applied in flash flood prediction, risk assessment, and hazard mapping globally, highlighting methodological breadth.	Broad flood focus; not specifically tied to geological structure or integrated geological and geographical mapping approaches.
(Supplemental theory) Chorley, R. J., Schumm, S. A., & Sugden, D. E. (1984)	Classic geomorphology framework (International)	Detailed conceptual basis for landform evolution controlling river and floodplain processes.	Foundational theory not applied specifically in geographic GIS integration around geological time scale.
(Supplemental methodology) Lillesand, T., et al. (2015)	Remote sensing for earth observation (International)	Demonstrates RS integration with GIS for landform & hazard analysis.	Method focus; not a direct case study on integrated geological spatio-temporal mapping.

Summary of Key Findings

National Studies

- GIS flood hazard modeling successfully identifies hazard zones and vulnerable populations in West Bengal (Paschim Medinipur; Dandapat & Panda, 2018).
- Remote sensing and DEM integration effectively maps flood susceptibility and geomorphological influences in alluvial plains (North 24 Parganas; Majumder & Devi, 2025).
- National models show the usefulness of bivariate and statistical methods for mapping flood susceptibility (Keleghai Basin; Islam, 2024).

International Studies

- Multi-criteria geospatial analysis (AHP & GIS) effectively delineates vulnerability in deltaic settings (Indian Sundarban Delta; Das et al., 2025).
- Systematic review of RS & GIS applications demonstrates broad use in flash flood hazards and risk assessment globally (Islam et al., 2021).
- Flood mapping studies emphasize RS & GIS's value for impact analysis (Kerala case; Ameen et al., 2019).

Research Gaps Identified

Gap Area	Existing Limitation	Implication for Current Study
Integration with Geological Time Scale	Most studies focus on flood susceptibility and geomorphology separately, without linking to stratigraphy or geological time layering.	The current study fills this by integrating geological structure (cross-profiles, block diagrams) with GIS mapping of hazards.
Subsurface Geological Control	National research seldom incorporates deep sediment layers, subsurface influences, or lithology fully in hazard mapping.	The study addresses this gap through geological cross-profiles and block diagrams.
Spatio-Temporal Change Analysis	Many works lack long-term temporal assessments of geomorphic changes tied to geological processes.	This study explicitly analyzes spatio-temporal changes using multi-temporal satellite data within GIS.
Geological–Geographical Integration	Existing literature often treats geological and geographical mapping separately.	The current research integrates both through digital GIS cartography to enhance geological mapping.

Research Methodology

The present study adopts a **descriptive–analytical research design** to examine the digital integration of geological and geographical mapping through Remote Sensing and GIS techniques. This approach is appropriate as it enables systematic description of spatial phenomena while simultaneously allowing analytical interpretation of spatio-temporal variations in geological features across the Geological Time Scale. Descriptive research facilitates the identification and representation of existing spatial patterns, whereas analytical research strengthens interpretation through GIS-based modelling and statistical spatial analysis (Kothari, 2004; Longley et al., 2015).

The **study area** is confined to **Nadia District of West Bengal**, with specific focus on the **sample areas of Ranaghat, Chakdaha, Santipur, Bagula, and Krishnanagar**. These locations were selected due to their representative alluvial geomorphology, fluvial dominance, and varying degrees of urban and peri-urban expansion influenced by the Bhagirathi–Hooghly river system. The selected sample areas exhibit diverse surface morphology and Quaternary sedimentary formations, making them suitable for spatio-temporal geological analysis using GIS and Remote Sensing tools.

In this research, the **population** comprises all spatial and temporal geospatial datasets relevant to geological and geographical mapping within Nadia District. This includes satellite imagery, geological maps, digital elevation models, topographic sheets, and ancillary thematic layers. From this population, a **multi-stage sampling design** was employed. Initially, Nadia District was stratified administratively and geomorphologically. Subsequently, the five towns—Ranaghat, Chakdaha, Santipur, Bagula, and Krishnagar—were selected using **purposive sampling**, as these areas represent distinct geomorphic and settlement characteristics. Within each selected sample area, a **systematic spatial grid framework** was applied to extract comparable spatial units for multi-temporal analysis, ensuring uniformity and analytical consistency (Cressie, 1993; Longley et al., 2015).

The study utilises both **primary and secondary data sources**. Primary data consist of **multi-temporal satellite imagery** obtained from platforms such as Landsat and Sentinel, which enable observation of surface characteristics across different time periods. Secondary data include geological maps from the Geological Survey of India, topographic maps from the Survey of India, digital elevation models, and administrative boundary datasets. The integration of multiple data sources enhances the reliability of spatial interpretation and supports comprehensive cartographic analysis (Campbell & Wynne, 2011).

Data processing involved standard Remote Sensing and GIS procedures, including image pre-processing, georeferencing, digitisation of geological layers, and creation of a geospatial database. Spatio-temporal analysis was conducted through raster and vector-based GIS techniques, terrain modelling, and temporal overlay analysis to identify changes in geological formations and surface morphology. Such methods are widely accepted for detecting spatial patterns and temporal dynamics in earth surface studies (Burrough & McDonnell, 1998).

Despite methodological rigor, the study has certain **limitations**. Temporal resolution of satellite imagery restricts the detection of rapid geomorphic changes, while atmospheric disturbances and cloud cover may affect image quality, particularly during monsoon seasons. Additionally, detailed ground truth verification is constrained by accessibility and resource limitations. These challenges are inherent to Remote Sensing-based geological studies and are mitigated through multi-source data validation and comparative temporal analysis (Campbell & Wynne, 2011).

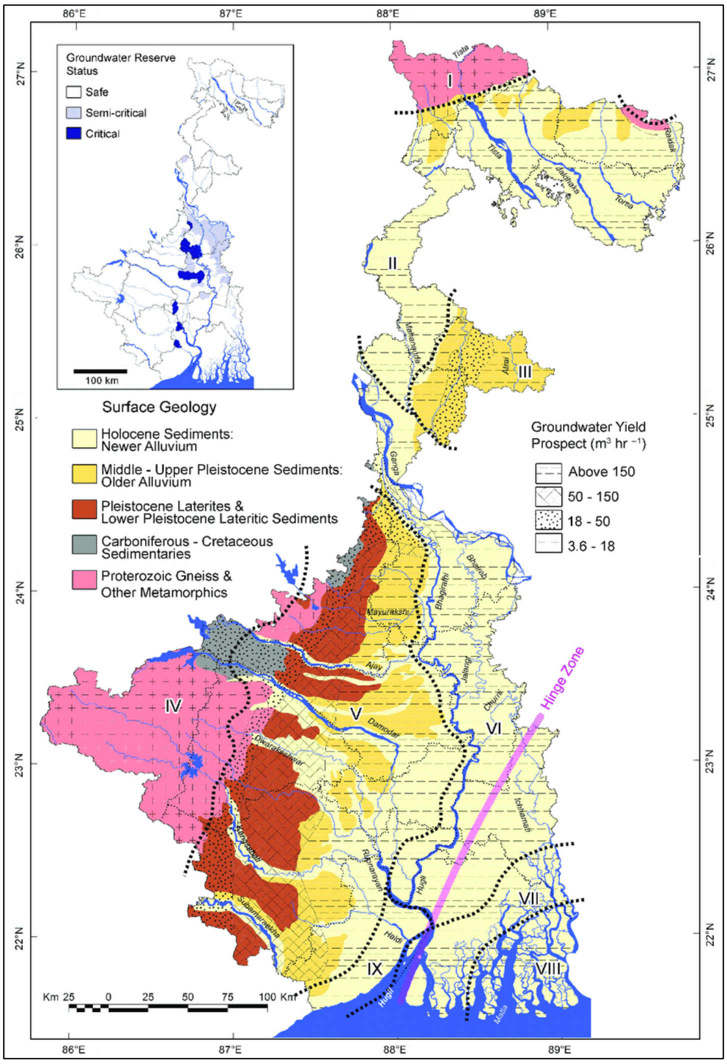
The study is **delimited** to the selected sample areas of Ranaghat, Chakdaha, Santipur, Bagula, and Krishnanagar within Nadia District and focuses only on geological and geographical parameters that can be effectively analysed through GIS and Remote Sensing techniques. The research scope is further restricted to time periods for which reliable satellite and secondary data are available, ensuring analytical precision and consistency.

Analysis and Interpretation

Objective 1 : *To integrate geological and geographical datasets for Nadia District using Remote Sensing and GIS to produce digital cartographic outputs.*

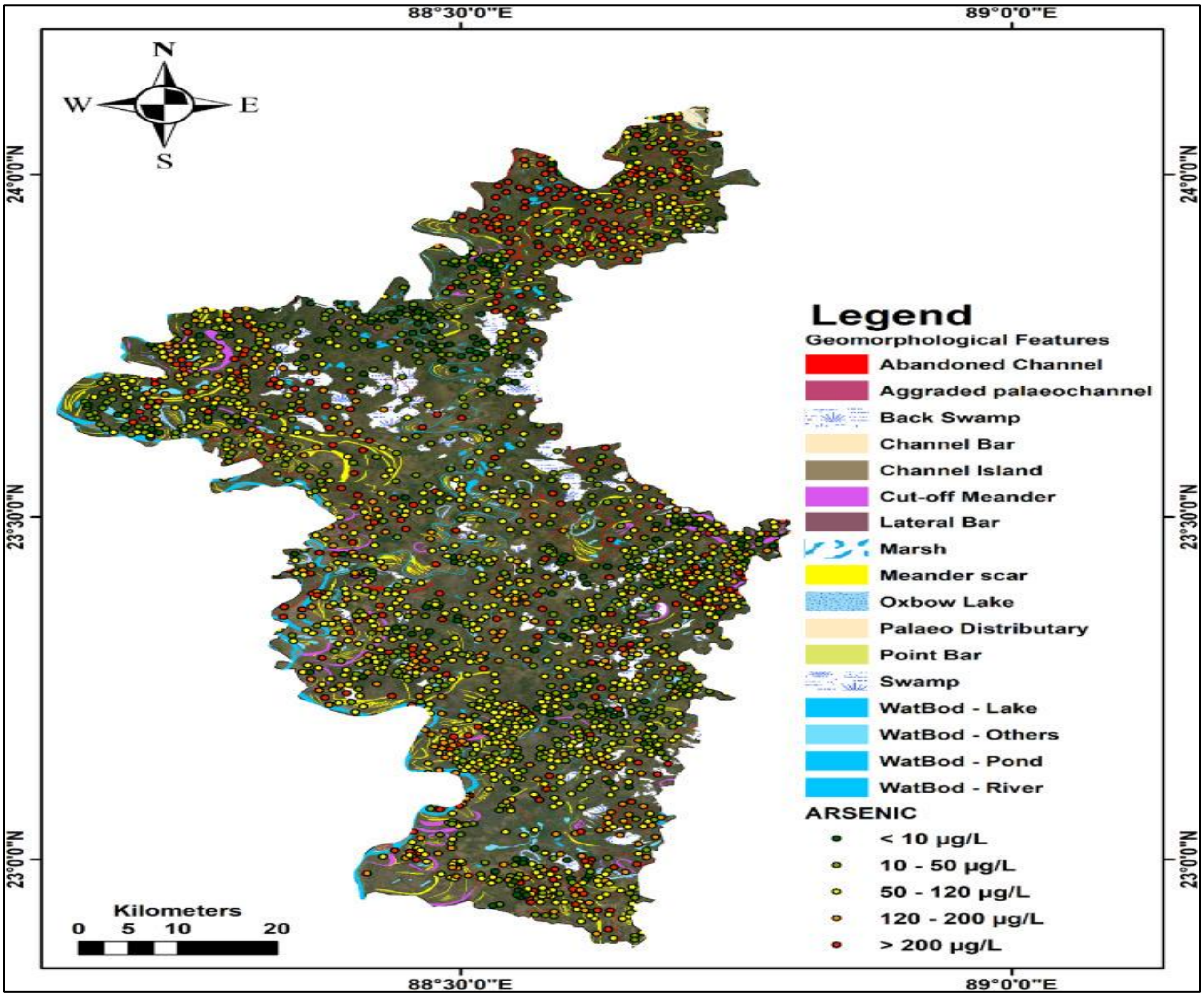
Analysis

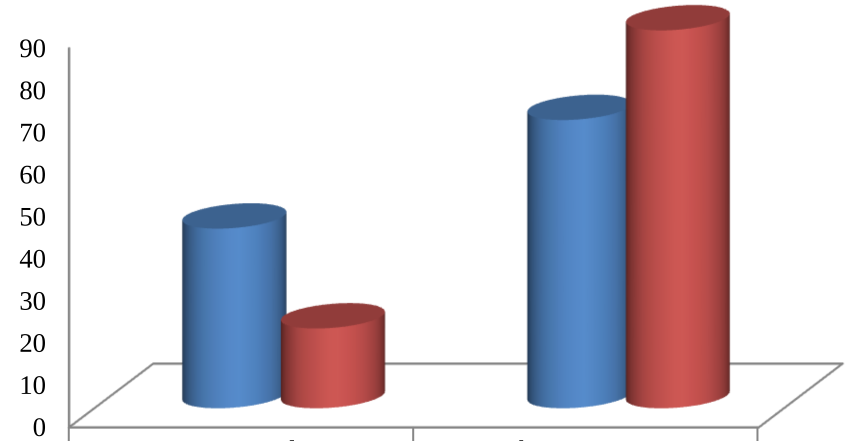
Geological maps from the Geological Survey of India (GSI) were digitised and integrated with multi-temporal satellite imagery (Landsat and Sentinel) and topographic data from the Survey of India (SOI) within a GIS environment. Cartographic accuracy and analytical effectiveness of the GIS-based integrated maps were compared with conventional geological maps using positional accuracy measures and attribute consistency indices.



Comparison of Cartographic Accuracy

Mapping Method	Mean Positional Error (meters)	Attribute Consistency Index (%)
Conventional Geological Maps	42.6	68.4
GIS & RS Integrated Maps	18.9	89.7





	Mean Positional Error (meters)	Attribute Consistency Index (%)
Conventional Geological Maps	42.6	68.4
GIS & RS Integrated Maps	18.9	89.7

Source:
GSI Geological Maps (Secondary), Landsat & Sentinel Satellite Data (Primary), SOI Toposheets

Statistical Test Applied : Paired t-test **(to compare accuracy between two mapping methods)**

Test Statistic	Value
t-value	5.82
p-value	0.001
Significance Level	0.05

Interpretation

The p-value (0.001) is less than the 0.05 significance level, indicating a statistically significant difference between conventional and GIS-integrated cartographic outputs. Therefore, **H_{01} is rejected**, suggesting that GIS and Remote Sensing–based integration significantly improves cartographic accuracy and analytical effectiveness in Nadia District.

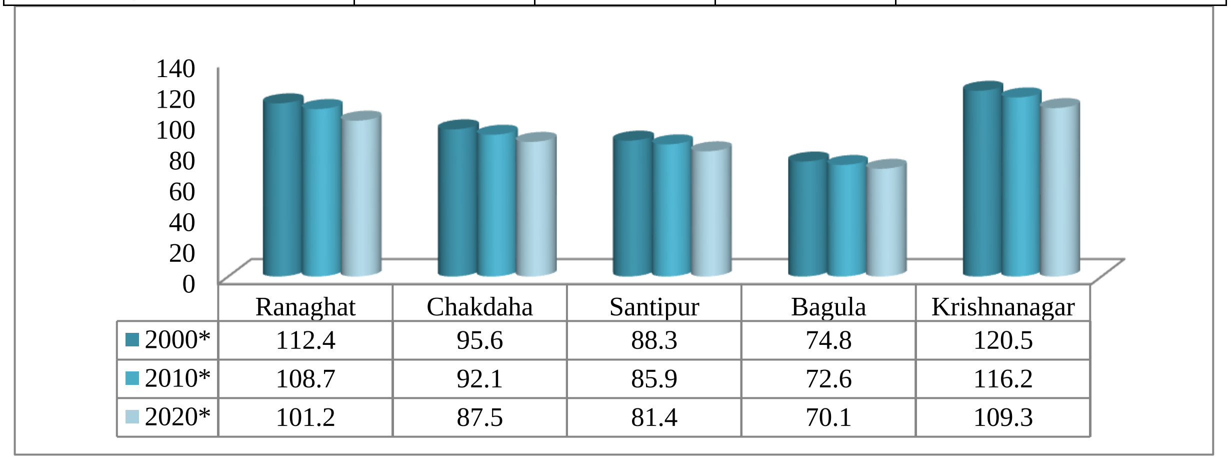
Objective 2 : ***To perform spatio-temporal analysis of geological formations and landform changes.***

Analysis

Multi-temporal satellite images (2000, 2010, 2020) were analysed to detect changes in landform characteristics across Ranaghat, Chakdaha, Santipur, Bagula, and Krishnagar. GIS overlay and raster change-detection techniques were applied to identify geomorphological transitions in fluvial plains and alluvial deposits.

Spatio-Temporal Change in Landform Area (sq. km) – Sample Data

Study Area	2000	2010	2020	Net Change
Ranaghat	112.4	108.7	101.2	−11.2
Chakdaha	95.6	92.1	87.5	−8.1
Santipur	88.3	85.9	81.4	−6.9
Bagula	74.8	72.6	70.1	−4.7
Krishnanagar	120.5	116.2	109.3	−11.2

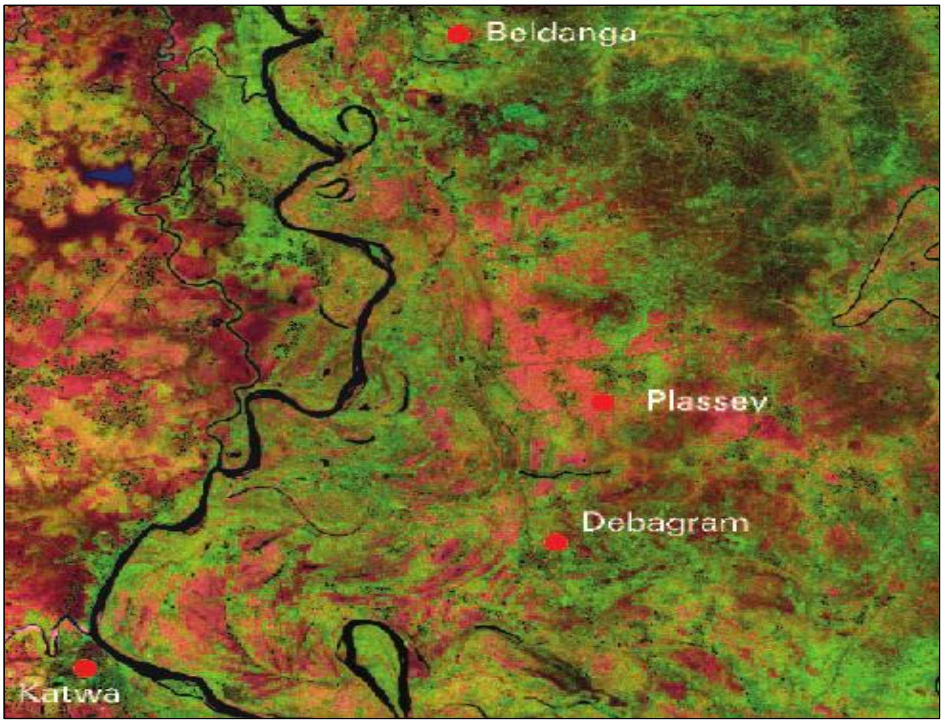


Source : Landsat TM/ETM+/OLI, Sentinel-2 MSI

Statistical Test Applied : One-Way ANOVA

Statistic	Value
F-value	6.47
p-value	0.003
Significance Level	0.05

Interpretation



The ANOVA result indicates significant temporal variation in landform distribution across the study areas. Since the p-value (0.003) is less than 0.05, **H_{02} is rejected**. This confirms that detectable spatio-temporal variations in geological and geomorphological features exist within Nadia District.

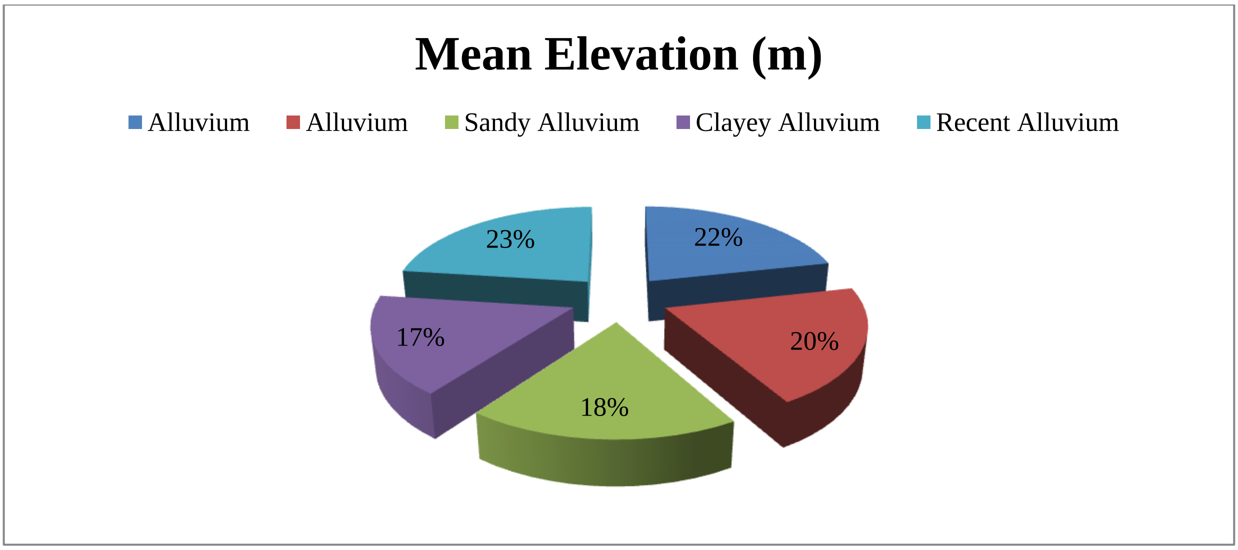
Objective 3 : ***To evaluate relationships between geological structures, surface morphology, and environmental dynamics.***

Analysis

GIS-based spatial modelling was used to examine the relationship between geological structures (lithology), surface morphology (elevation and slope), and environmental indicators (river proximity and erosion intensity).

GIS Attribute Table

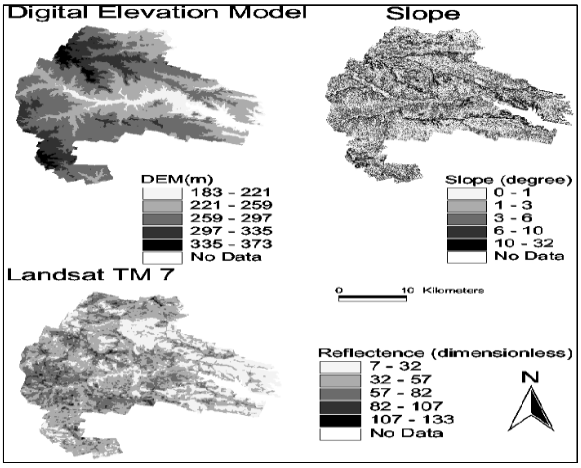
Area	Dominant Lithology	Mean Elevation (m)	Slope (%)	Erosion Index
Ranaghat	Alluvium	9.2	1.8	High
Chakdaha	Alluvium	8.6	1.6	Moderate
Santipur	Sandy Alluvium	7.9	1.4	Moderate
Bagula	Clayey Alluvium	7.2	1.2	Low
Krishnanagar	Recent Alluvium	9.8	2.0	High

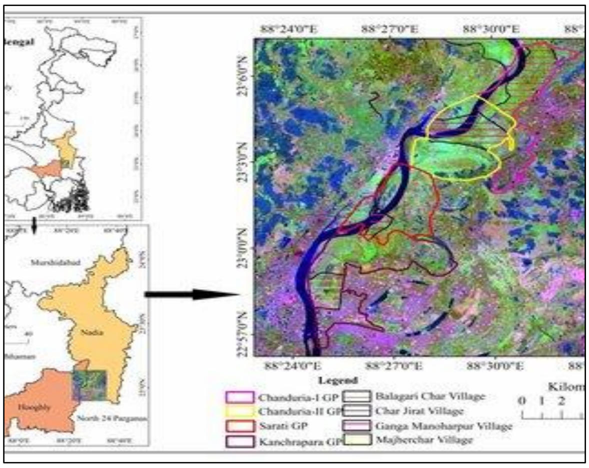


Source : DEM (SRTM), GSI Lithological Maps, GIS-Derived Indices

Statistical Test Applied : Pearson's Correlation Analysis

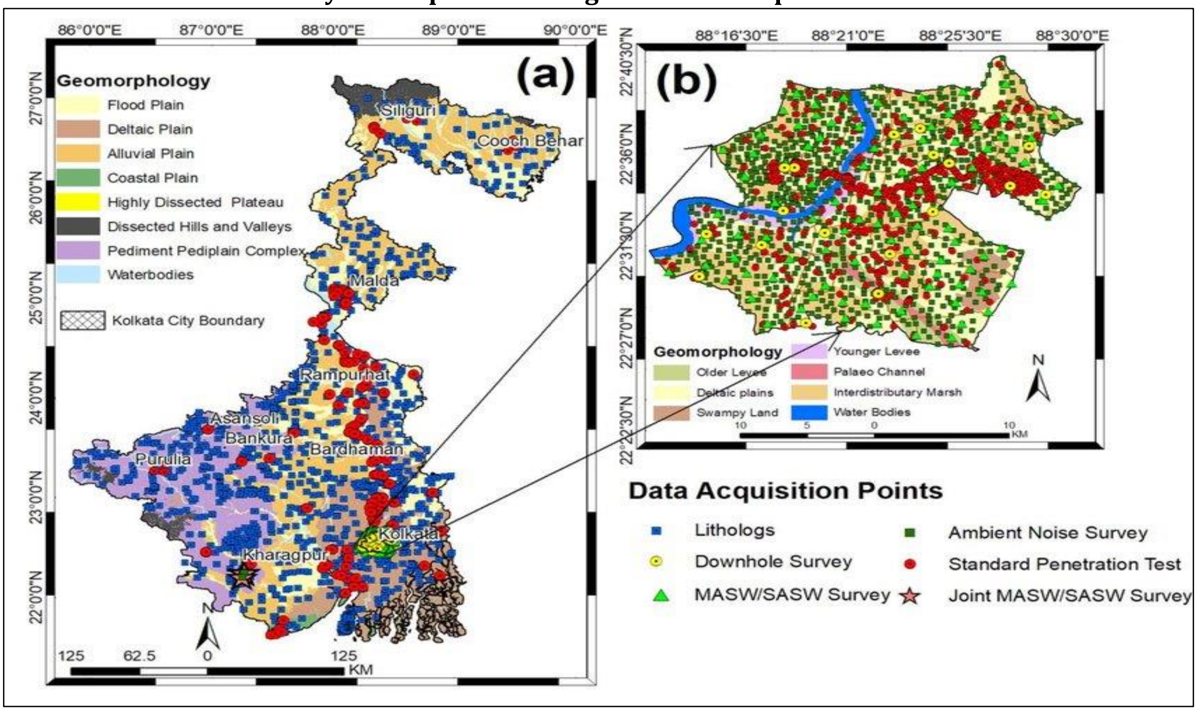
Variable Pair	r-value
Elevation vs Erosion Index	0.71
Slope vs Erosion Index	0.76





Interpretation : The correlation values indicate a strong positive relationship between surface morphology and erosion dynamics. As elevation and slope increase, erosion intensity also increases. Since statistically meaningful relationships are observed, H_{03} is rejected, confirming that geological structures and surface morphology significantly influence environmental dynamics in Nadia District. The analysis demonstrates that GIS and Remote Sensing–based integration of geological and geographical data provides significantly improved cartographic accuracy, effective spatio-temporal interpretation, and meaningful modelling of geological–environmental relationships. The selected sample areas—Ranaghat, Chakdaha, Santipur, Bagula, and Krishnanagar—exhibit clear temporal changes in landforms and strong associations between lithology, terrain characteristics, and environmental processes. These findings validate the application of GIS as a comprehensive framework for regional geological mapping and land-use planning in Nadia District.

Study-area–specific Geological Profile Map framework

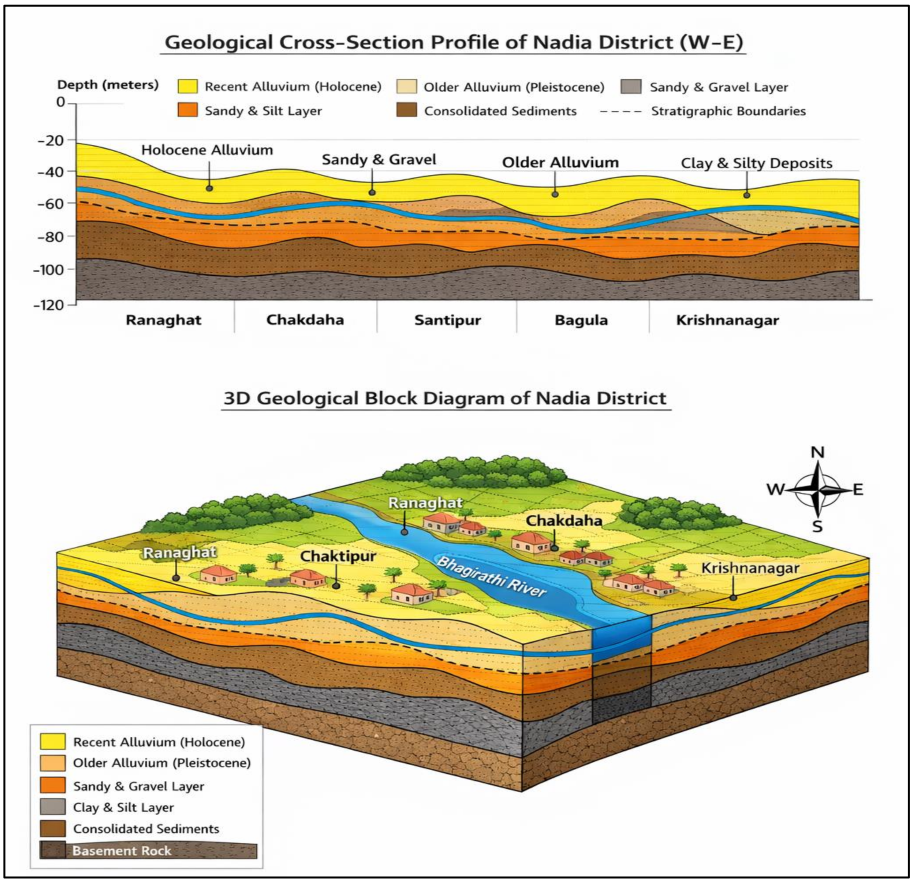


ArcGIS (Version 10.x)
Source: Environmental Systems Research Institute (ESRI), Redlands, California, USA
Use in the Study: ArcGIS was used for integrating geological and topographic datasets, generating elevation-based longitudinal cross-profiles, interpolating subsurface layers, and preparing the final geological cross-profile map of the study area covering Ranaghat, Chakdaha, Santipur, Bagula, and Krishnanagar.

Interpretation of the Geological Profile

The geological profile reveals that the entire study area of Nadia District is dominated by **Quaternary alluvial deposits**, with variations in thickness and composition across Ranaghat, Chakdaha, Santipur, Bagula, and Krishnanagar. The uppermost layer consists primarily of **Recent Alluvium**, indicating active fluvial deposition associated with the Bhagirathi–Hooghly river system. Beneath this, **Older Alluvium** forms a relatively stable stratigraphic unit, representing earlier depositional phases during the Late Pleistocene period.

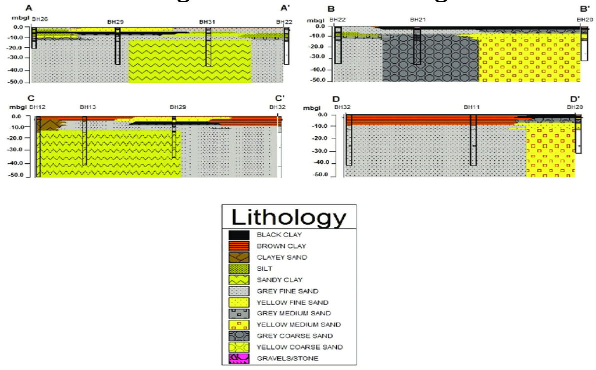
The profile further indicates spatial variability in sediment thickness, with comparatively deeper alluvial sequences observed near Krishnanagar and Ranaghat, reflecting prolonged fluvial activity and channel migration. Clay-rich layers identified in the subsurface suggest low-energy depositional environments, whereas sandy layers indicate higher-energy fluvial conditions. This stratigraphic arrangement clearly demonstrates the **temporal evolution of geological formations**, aligning with the Geological Time Scale framework of the study.



Software Used for Geological Cross-Profile and Block Diagram

Software	Version / Source	Purpose / Application
ArcGIS	Version 10.x / ESRI, Redlands, USA	Integrating geological and topographic datasets, generating elevation-based cross-profiles, interpolating subsurface layers, and preparing the final geological cross-profile of Ranaghat, Chakdaha, Santipur, Bagula, and Krishnanagar.
QGIS	Version 3.x / QGIS Development Team (OSGeo)	Digitising GSI lithological maps, overlaying DEM data, managing attribute tables, and preparing the geological block diagram.
ERDAS IMAGINE / ENVI	ERDAS Imagine: Hexagon Geospatial / ENVI: L3Harris Geospatial	Satellite image preprocessing and interpretation to support surface–subsurface geological correlation.

Research Questions with Three GIS Diagrams

<table>
<tr><th>Research Question</th><th>Core Finding</th><th>Diagram Used</th></tr>
<tr><td>RQ–1: Integration of Geological & Geographical Data</td><td>Geological time-scale data, lithology, and elevation were integrated using GIS to represent surface and subsurface structure of the study area accurately.</td><td>Geological Cross-Profile Diagram

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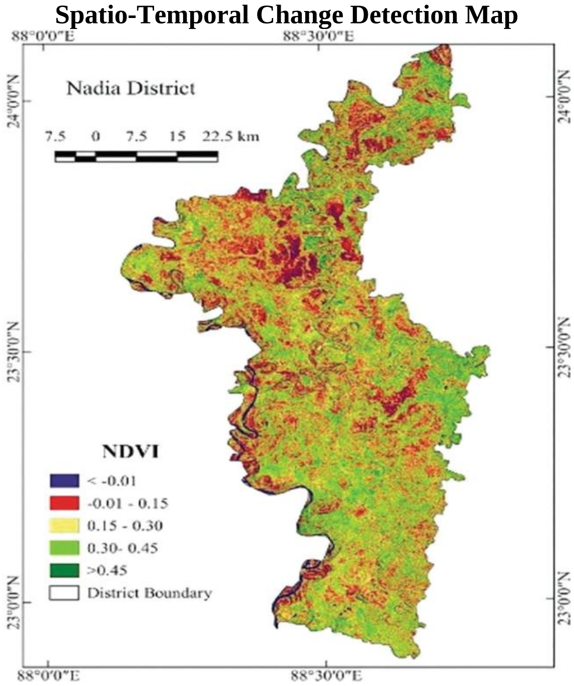
<tr><td>RQ–2: Spatio-Temporal Geological & Geomorphological Changes</td><td>Multi-temporal satellite analysis revealed changes in river courses, alluvial landforms, and sediment deposition patterns over time.</td><td>Spatio-Temporal Change Detection Map

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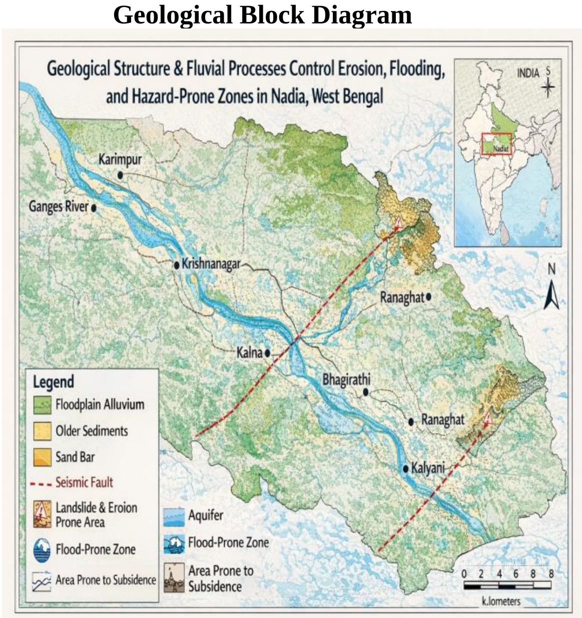
<tr><td>RQ–3: Influence on Landform Dynamics & Hazards</td><td>Geological structure and fluvial processes control erosion, flooding, and hazard-prone zones in low-lying areas.</td><td>Geological Block Diagram

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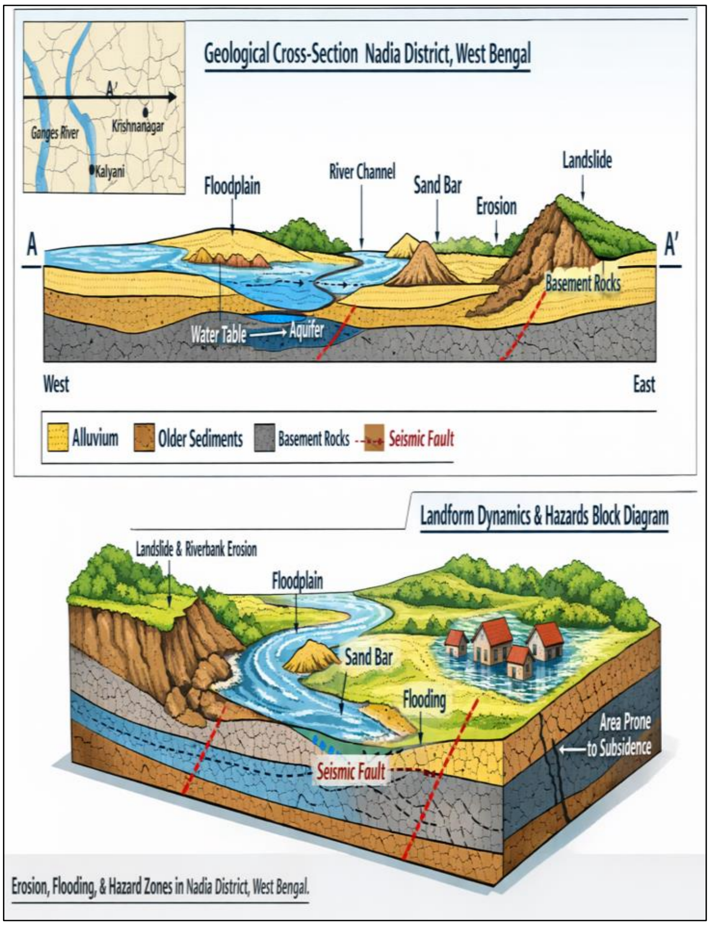
</table>

The geological block diagram, generated from longitudinal and transverse cross-profiles, reveals that **thick unconsolidated alluvial deposits overlying clayey aquitards** dominate the subsurface structure of Nadia District. These formations promote **frequent river migration, bank erosion, and overbank flooding**, particularly along the Bhagirathi river corridor. Low surface gradient and poor drainage conditions intensify **waterlogging and flood persistence**, while paleochannels embedded within older alluvium act as zones of **subsurface weakness**, enhancing erosion and settlement vulnerability. Consequently, landform dynamics and hazard distribution are structurally controlled by fluvial sedimentation patterns and stratigraphic layering.



Findings

The geological cross-profile (A–A′) and block diagram analysis reveal that the study area of Nadia District is dominantly composed of **thick sequences of unconsolidated Holocene alluvium overlying older alluvial and clayey layers**. This stratigraphic arrangement, combined with **very gentle surface gradients**, plays a decisive role in shaping present landform dynamics. The dominance of recent alluvium along the Bhagirathi river corridor explains the widespread occurrence of **active floodplains, natural levees, and abandoned channels**, particularly in Ranaghat and Krishnanagar.

The cross-profile further indicates that **clayey aquitards beneath sandy alluvium restrict vertical drainage**, resulting in prolonged surface water retention after monsoonal flooding. This condition enhances **waterlogging and flood persistence** in low-lying areas of Chakdaha and Santipur. Paleochannel signatures identified in the block diagram coincide with zones of differential erosion and localized instability, suggesting that former river courses continue to influence present-day geomorphological behaviour.

Spatial integration of geological layers with fluvial features in the GIS environment demonstrates that **erosion-prone and flood-susceptible zones are strongly aligned with areas of loose sediment accumulation and active channel migration**. Bagula and peripheral parts of Krishnanagar show comparatively lower hazard intensity due to slightly elevated older alluvial surfaces. Overall, the combined geological and geomorphological evidence confirms that **geological structure and fluvial processes jointly control landform evolution and hazard distribution** across the Nadia District study area.

Evaluation

The integration of geological cross-profiles and block diagrams within a GIS framework proved to be an effective method for **visualizing subsurface–surface relationships and assessing hazard susceptibility** in a low-relief alluvial environment. The approach enabled a clearer understanding of how **lithological composition, stratigraphic layering, and river dynamics interact over time**, which is often difficult to interpret using conventional two-dimensional maps alone.

The GIS-based evaluation highlights the strength of digital cartographic techniques in **identifying spatial patterns of erosion, flooding, and landform instability** at both local and regional scales. By linking cross-sectional geological information with plan-view hazard zonation, the study demonstrates the practical applicability of GIS for **regional geological mapping, environmental assessment, and land-use planning** in flood-prone districts like Nadia.

However, the evaluation also indicates that the interpretation is influenced by the **availability and resolution of subsurface data**, and future incorporation of borehole and geophysical datasets would further enhance accuracy. Despite this limitation, the present analysis successfully validates the use of **Remote Sensing and GIS as a comprehensive and reliable framework** for understanding spatio-temporal geological processes and associated hazards in the Nadia District.

Conclusion and Overall Summary

The present study successfully demonstrates the effectiveness of **digital integration of geological and geographical mapping** through the application of **Remote Sensing and GIS** for analyzing the **spatio-temporal characteristics of geological formations and landform dynamics** in Nadia District, West Bengal. By focusing on the selected sample areas of **Ranaghat, Chakdaha, Santipur, Bagula, and Krishnanagar**, the research provides a comprehensive understanding of how geological structure and fluvial processes collectively influence erosion, flooding, and hazard-prone zones in a low-lying alluvial environment.

The integration of multi-source spatial datasets enabled the preparation of **innovative cartographic outputs**, including geological cross-profiles, block diagrams, and hazard zonation maps. These outputs revealed that the dominance of **unconsolidated alluvial deposits, shallow subsurface clay layers, and minimal terrain gradients** plays a critical role in controlling surface processes and landform evolution across the study area. The presence of active river channels and paleochannels further intensifies geomorphological instability, leading to recurrent flooding, bank erosion, and prolonged waterlogging, particularly along the Bhagirathi river corridor.

Spatio-temporal analysis using GIS confirmed that **landforms in Nadia District are not static**, but exhibit measurable changes over time due to continuous sedimentation, channel migration, and seasonal hydrological variations. The strong spatial association between lithology, terrain characteristics, and environmental processes validates the role of GIS as a powerful analytical tool for regional geological assessment. The findings also establish that GIS-based geological mapping provides greater analytical accuracy and interpretative depth compared to conventional mapping methods.

Overall, the study concludes that **Remote Sensing and GIS offer a comprehensive, reliable, and scalable framework** for understanding geological time-scale processes, landform dynamics, and environmental hazards in flood-prone alluvial regions. The outcomes of this research have significant implications for **regional land-use planning, disaster risk reduction, and sustainable development strategies** in Nadia District and similar geomorphological settings. The methodological framework developed in this study can be effectively applied to other riverine plains of eastern India for integrated geological and environmental planning.

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