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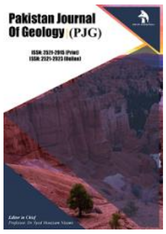

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RESEARCH ARTICLE

GEOSPATIAL ANALYSIS FOR IDENTIFICATION OF POTENTIAL SITES OF PRECIOUS MINERALS ALONG RIVER INDUS, DISTRICT ATTOCK

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ABSTRACT

The present study employs an integrated geospatial framework to delineate placer mineral potential zones along the Indus River corridor in District Attock, Pakistan. Utilizing multi-temporal Landsat 5 and 8 imagery (2000–2024), Shuttle Radar Topography Mission (SRTM) data, and advanced cloud-based processing via Google Earth Engine, key mineralogical and geomorphological indicators were extracted and analyzed. Spectral band ratio techniques were applied to identify ferrous and ferric minerals, iron oxides, clay assemblages, and hydrothermal alteration zones. Concurrently, Digital Elevation Model (DEM)-derived slope, flow direction, and aspect layers were analyzed to evaluate terrain controls on mineral deposition. Hydrological indices such as the Normalized Difference Water Index (NDWI) and vegetation indices (NDVI) were employed to assess surface dynamics and isolate stable zones for mineral concentration. Morphological features including point bars, meanders, and potholes were mapped and buffered to spatially constrain zones favorable for sediment trapping and heavy mineral accumulation. Results reveal distinct placer-enriched zones coinciding with low-gradient floodplains, meander belts, and fluvially reworked terraces. The integration of spectral and terrain-based analyses demonstrates the efficacy of remote sensing and GIS in early-stage mineral exploration, providing a replicable framework for sustainable resource targeting in alluvial environments.

KEYWORDS

Placer Minerals; Indus River; Remote Sensing; GIS; Spectral Analysis; Mineral Exploration; District Attock

1. INTRODUCTION

The Indus River, extending over 2,900 kilometers, plays a vital role in shaping the geomorphological and sedimentary landscape of Pakistan. Flowing through diverse geological provinces, the river acts as a natural conveyor of detrital material derived from weathered rocks in the northern highlands, transporting it across the Potohar Plateau and into the plains of Punjab. District Attock, situated at the transitional boundary between the foothills of the Himalayas and the Punjab alluvial basin, presents a unique depositional setting where heavy minerals carried by the Indus are likely to accumulate within fluvial geomorphic features such as point bars, terraces, and floodplains.

Placer minerals—economically valuable concentrations of dense, chemically resistant minerals—form as a result of mechanical weathering, transportation, and hydraulic sorting. These include gold, zircon, rutile, magnetite, and garnet, among others. In Pakistan, placer deposits have been historically identified along the Indus and its tributaries, particularly in areas underlain by metamorphic and igneous terrains such as those in Gilgit-Baltistan, Swat, and the Peshawar Basin. However, despite growing geological interest, systematic geospatial investigations into placer mineralization in District Attock remain limited. This knowledge gap persists despite increasing local and governmental interest, including recent exploratory projects supported by the Geological Survey of Pakistan and provincial mining departments.

Conventional methods for mineral exploration—such as trenching, drilling, and ground geophysics—are often time-consuming, resource-intensive, and spatially constrained. In contrast, remote sensing and Geographic Information System (GIS)-based methods offer cost-effective, large-scale, and non-invasive tools for preliminary mineral exploration. These technologies allow for the rapid detection of spectral signatures associated with mineralogical alteration zones and geomorphic indicators of sediment accumulation, enhancing target selection and reducing field costs.

This study applies an integrated geospatial approach to assess the placer mineral potential of a 32-kilometer stretch of the Indus River between Ghazi (Tarbela) and Attock Bridge. By combining multi-temporal satellite imagery, digital elevation models, and hydrological indices within a GIS framework, the study aims to delineate zones with elevated concentrations of economically important minerals. Spectral band ratios are used to detect ferric and ferrous iron, clay minerals, and hydrothermal alteration features, while terrain-based analyses assess slope, flow direction, and sediment transport dynamics. Hydromorphological features such as meanders, potholes, and point bars are extracted to identify sediment-trapping environments.

The findings of this study contribute to the broader field of early-stage mineral exploration by showcasing a replicable model for the identification of placer deposits in fluvial systems. Moreover, the study provides spatial intelligence for stakeholders involved in mining, environmental planning, and land-use regulation, with a focus on sustainable and minimally invasive resource development. By leveraging the capabilities of cloud-based geospatial processing platforms like Google Earth Engine and high-resolution earth observation datasets, this research underscores the transformative role of geoinformatics in modern mineral exploration, particularly in understudied but geologically promising terrains such as District Attock.

2. MATERIALS AND METHODS

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2.1 Study Area

The study area is located within District Attock, northern Punjab, Pakistan, along a 32-kilometer stretch of the Indus River between the Ghazi (Tarbela) region and Attock Bridge. Geographically positioned at the interface of the Potohar Plateau and the Himalayan foothills, this region is characterized by complex geological formations, including sedimentary, igneous, and metamorphic rock units. The area lies within the active tectonic zone of the Northwest Himalayan Fold and Thrust Belt, influenced by major fault structures such as the Main Mantle Thrust and Salt Range Thrust. These geological structures contribute significantly to the erosion and downstream transport of heavy mineral-bearing sediments. The river's dynamic fluvial morphology, featuring braided and meandering channels, supports the hydraulic sorting and deposition of placer minerals in point bars, potholes, and floodplains.

2.2 Data Sources

The research utilized a combination of remote sensing datasets and topographic models:

- **Satellite Imagery**:
    - **Landsat 5 (TM)**: 2000–2011
    - **Landsat 8 (OLI/TIRS)**: 2013–2024 Cloud-free images were selected for spectral analysis and change detection studies.
- **Digital Elevation Model (DEM)**:
    - **Shuttle Radar Topography Mission (SRTM)**, 30 m resolution Used for derivation of slope, aspect, flow direction, and geomorphological classification.
- **Processing Platform**:
    - **Google Earth Engine (GEE)**

      Provided cloud-based processing for image preprocessing, spectral index computation, terrain modeling, and temporal analysis.

2.3 Image Preprocessing

Atmospheric correction was applied to all Landsat images using GEE's standard surface reflectance pipeline. Median composites were generated for selected years and clipped to the study area boundary. Water bodies and dense vegetation were masked using threshold values derived from the Normalized Difference Water Index (NDWI) and Normalized Difference Vegetation Index (NDVI), respectively, to isolate potential mineral-bearing zones.

2.4 Spectral Analysis and Mineral Indices

Target minerals were detected using specific spectral band ratios known to enhance ferric and ferrous iron, clays, and hydrothermal alteration zones:

Mineral/Feature	Band Ratio
Ferrous Iron	B6 / B5
Ferric Iron	B4 / B3
Iron Oxide Index	(B4 - B2) / (B4 + B2)
Clay Minerals	B5 / B4 and B6 / B7
Silica Content	B7 / B5

Pixels exceeding the mean + 2×SD were identified as **spectral anomalies** and interpreted as zones of potential mineral enrichment.

2.5 Topographic and Hydrological Modeling

The SRTM DEM was used to extract:

- **Slope**, **Aspect**, and **Flow Direction**
- **Potholes** and **Meander Buffers** (500 m radius)

Terrain derivatives were used to understand erosion-deposition dynamics and sediment-trap locations.

2.6 Geomorphic Feature Extraction

Using NDWI and DEM layers, the following fluvial features were extracted:

- **Meanders** (active and historical)
- **Point Bars**
- **Potholes**
- **Erosion Zones**

These features were mapped to identify geomorphic traps favorable for placer mineral accumulation.

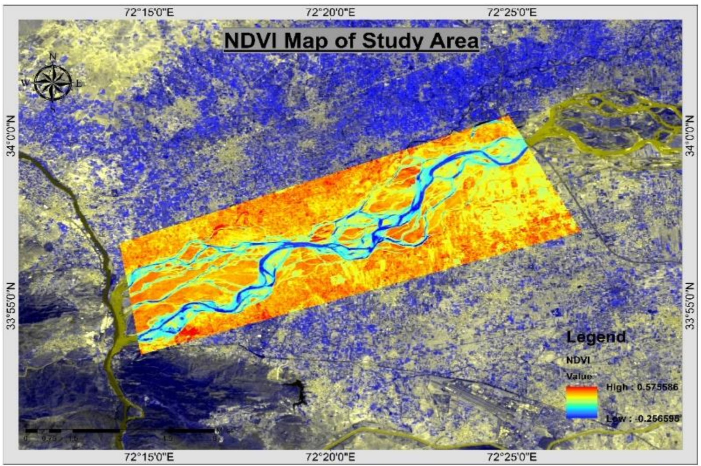
2.7 Integration and Interpretation

All spectral, topographic, and geomorphic layers were integrated within a GIS environment (ArcGIS 10.x) for spatial overlay, cross-comparison, and delineation of high-potential mineral zones. Spatial buffers were applied to fluvial features to assess their influence on mineral concentration. Raster statistics and threshold-based classification enabled identification of mineral hotspots across the study corridor.

3. Results

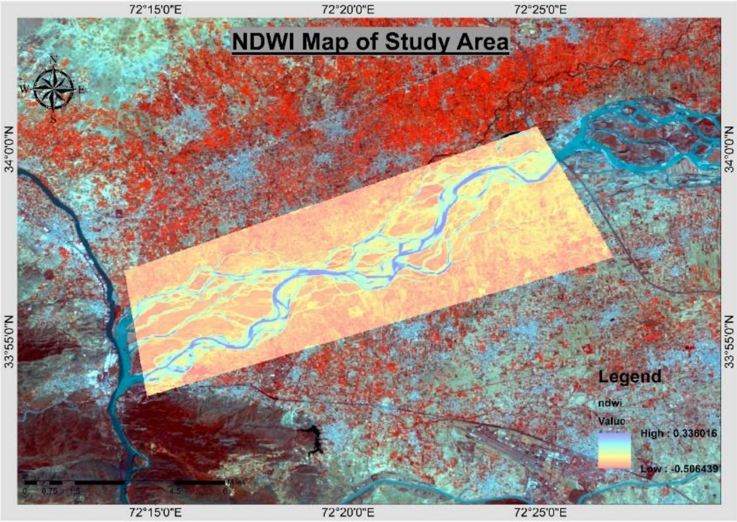
3.1 Vegetation Dynamics and NDVI Analysis

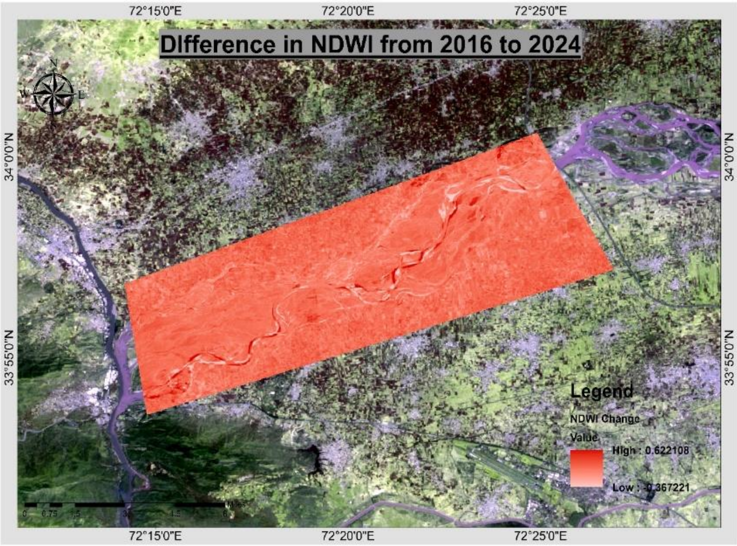
The Normalized Difference Vegetation Index (NDVI) map reveals moderate to high vegetation density along the Indus River corridor, particularly in zones of stable floodplain terraces and cultivated lands. Spatial analysis indicates that vegetated areas are typically located along low-gradient slopes adjacent to the main river channel, with NDVI values peaking during the pre-monsoon period. These regions suggest minimal erosion, contributing to long-term sediment retention, which enhances placer mineral accumulation potential.

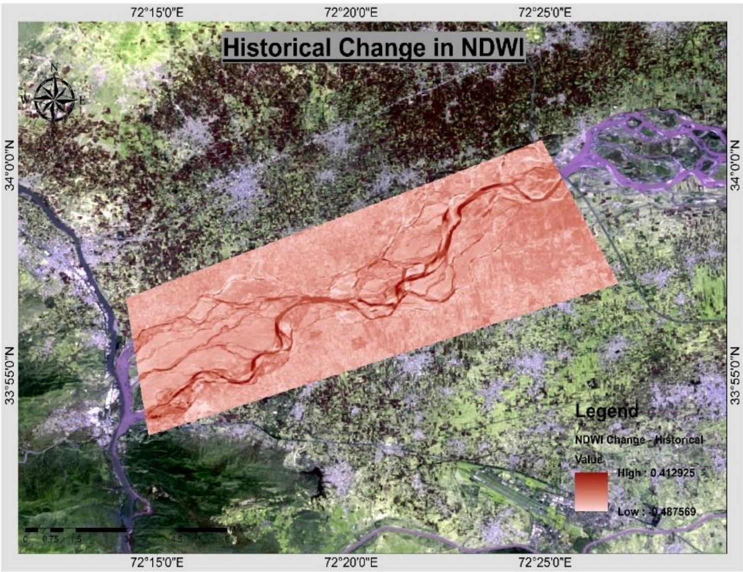


3.2 Water Body Changes and NDWI Trends

Analysis of NDWI from 2016 to 2024 indicates a notable contraction in water body extent, particularly along secondary channels and oxbow remnants (*Figure 2*). The historical NDWI trend (*Figure 3*) highlights seasonal and annual shifts linked to monsoonal flow, sediment deposition, and possible anthropogenic regulation. Areas where water has receded coincide with zones of active sediment exposure and mineral concentration.

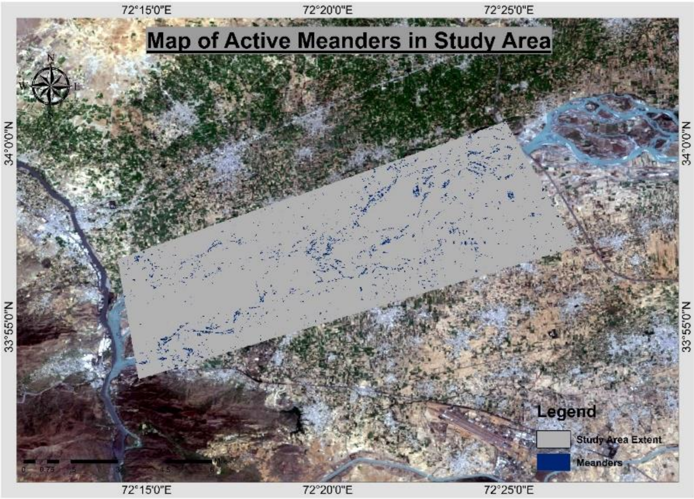


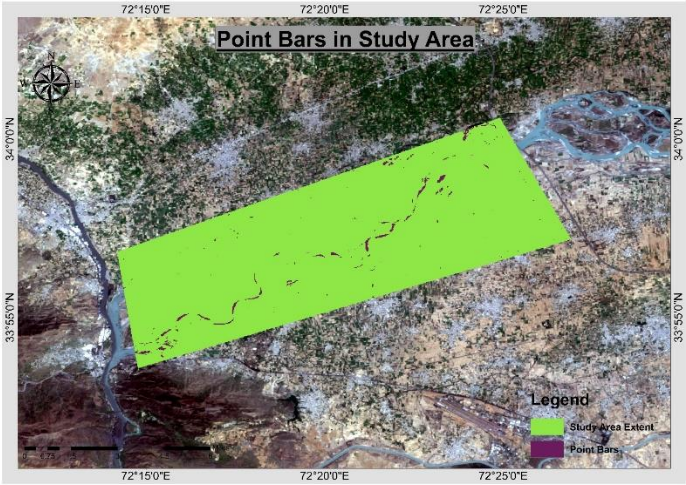


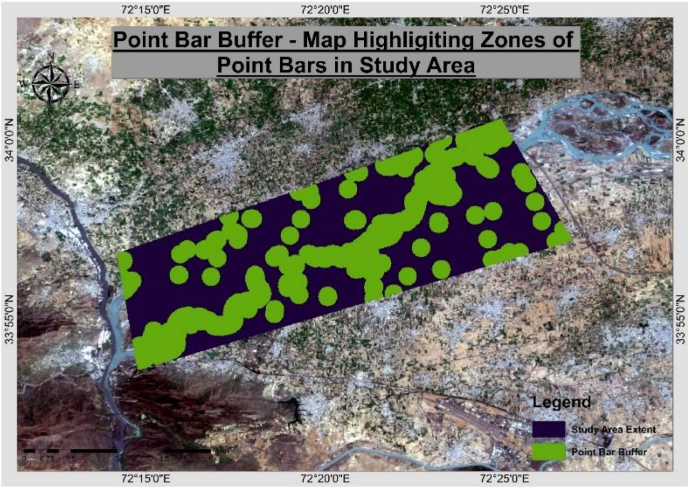


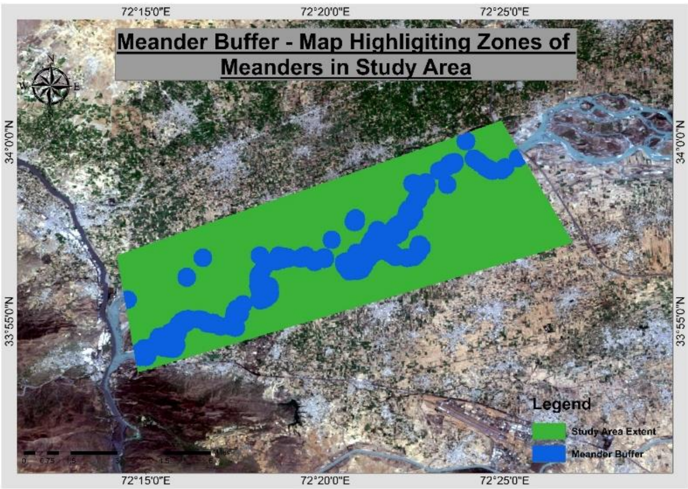
3.3 Geomorphological Mapping: Meanders, Potholes, and Point Bars

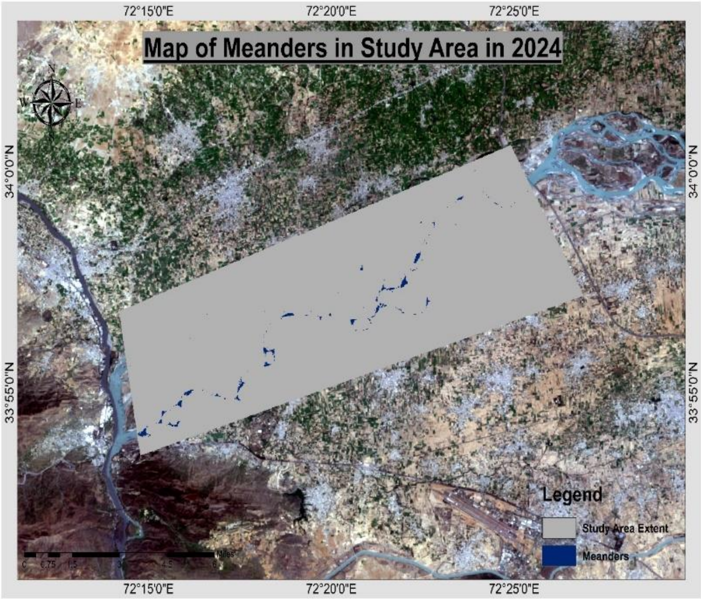
DEM-based hydromorphic analysis identified multiple active and historical meanders throughout the study stretch, many with well-defined point bars and pothole formations. These geomorphic traps are known to promote the deposition of heavy minerals. Buffer analysis around meanders and point bars (500 m) delineated key areas of sediment entrapment (*Figures 4–6*). These features are especially concentrated in the mid-section of the study area, where river sinuosity is highest.


Map of Active Meanders in Study Area
72°15'0"E
72°20'0"E
72°25'0"E
34°0'0"N
33°55'0"N
Legend
Study Area Extent
Meanders


Point Bars in Study Area
72°15'0"E
72°20'0"E
72°25'0"E
34°0'0"N
33°55'0"N
Legend
Study Area Extent
Point Bars

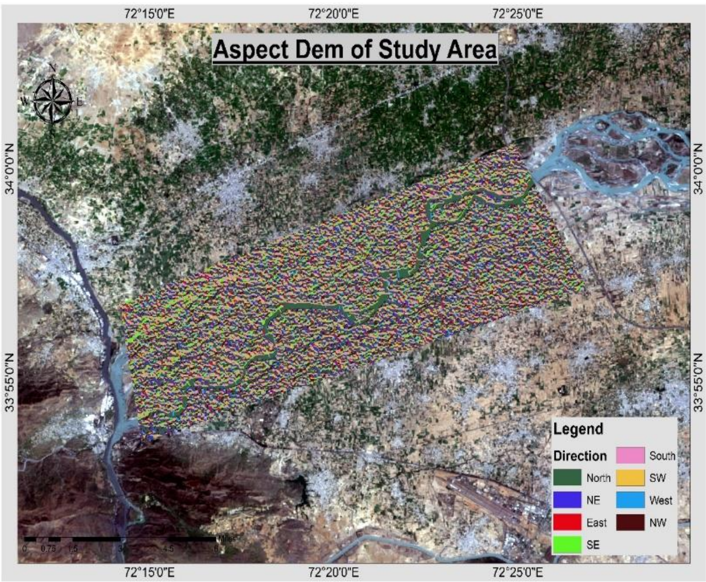

Point Bar Buffer - Map Highligiting Zones of Point Bars in Study Area
72°15'0"E
72°20'0"E
72°25'0"E
34°0'0"N
33°55'0"N
Legend
Study Area Extent
Point Bar Buffer

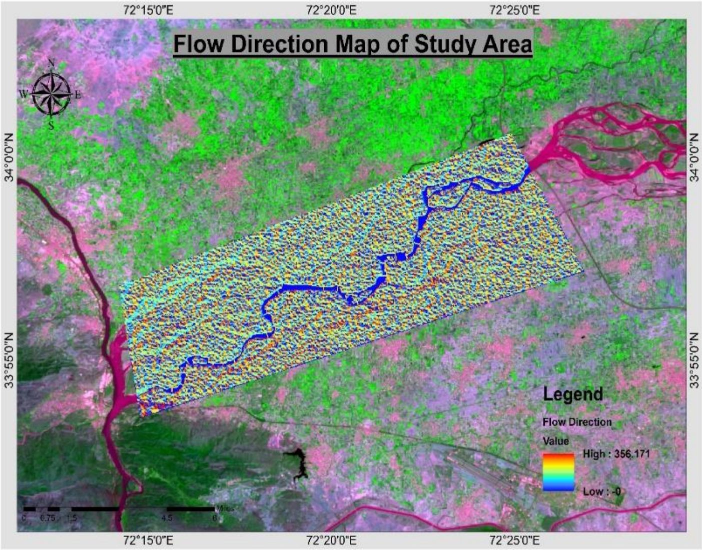

Meander Buffer - Map Highligiting Zones of Meanders in Study Area
72°15'0"E
72°20'0"E
72°25'0"E
34°0'0"N
33°55'0"N
Legend
Study Area Extent
Meander Buffer



3.4 Topographic Controls on Sediment Deposition

SRTM DEM analysis shows that zones with low slope gradients (<5°) and specific aspect orientations (e.g., west-facing slopes) are preferentially associated with sediment accumulation (*Figures 7–9*). Flow direction modeling further supports the interpretation of these areas as depositional sinks. The terrain configuration enhances hydraulic sorting processes, allowing denser minerals to settle over time.





3.5 Spectral Mineral Index Mapping

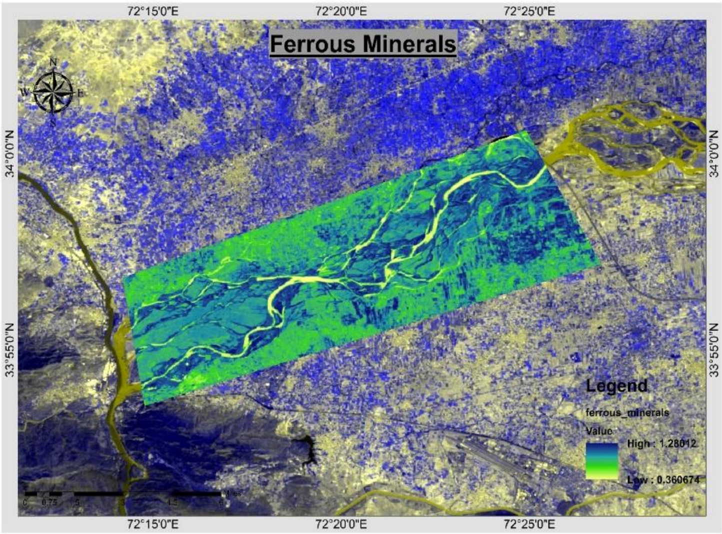
Targeted spectral analysis using Landsat 8 band ratios yielded distinct anomalies for ferrous and ferric iron, iron oxides, and clay minerals.

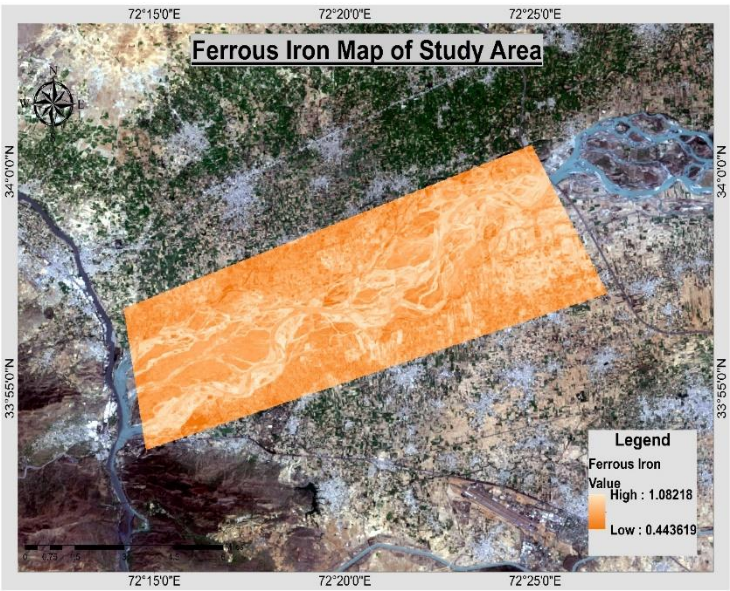
Ferrous Iron: Strong reflectance anomalies were detected in the mid-reach of the river, particularly near high-sinuosity meander zones (*Figure 10*).

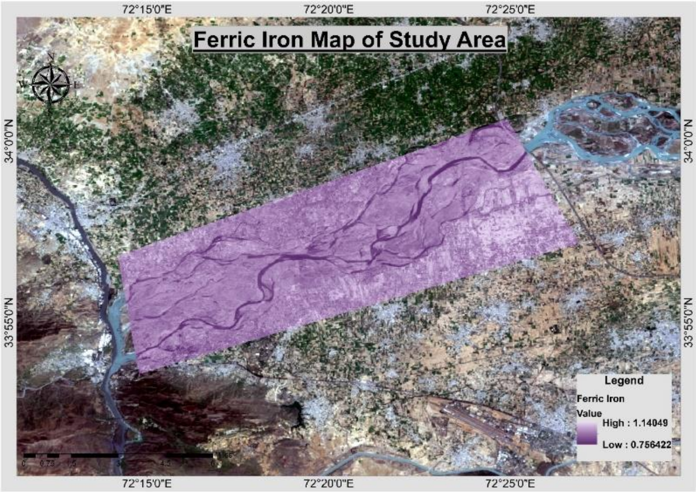
Ferric Iron & Iron Oxides: Iron Oxide Index maps show consistent hotspots along point bar systems and inner meander flanks (*Figure 11*).

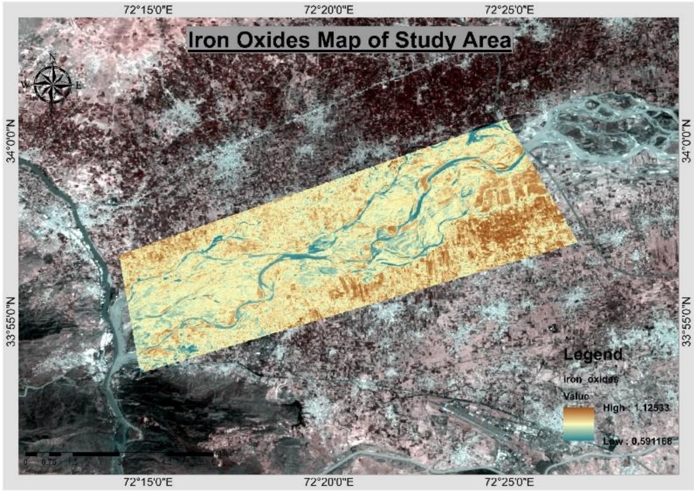
Clay Minerals: Detected primarily in overbank areas and lateral accretion zones where fine sediments accumulate (*Figure 12*).

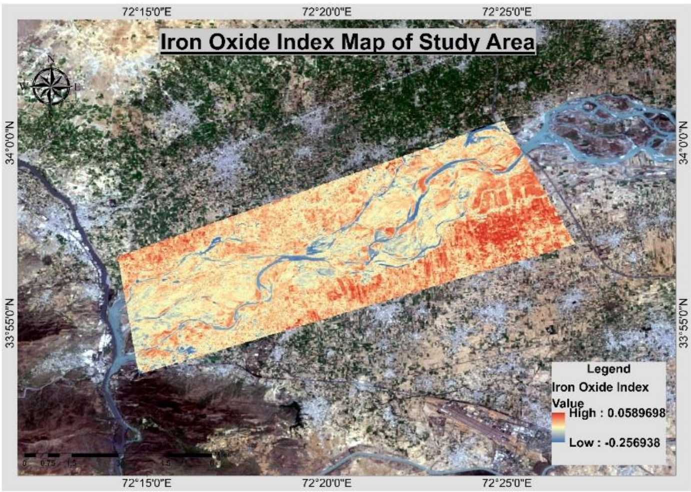
Silica and Hydrothermal Zones: Spatial overlays indicate potential hydrothermal alteration signatures in upstream segments, though further field validation is recommended.

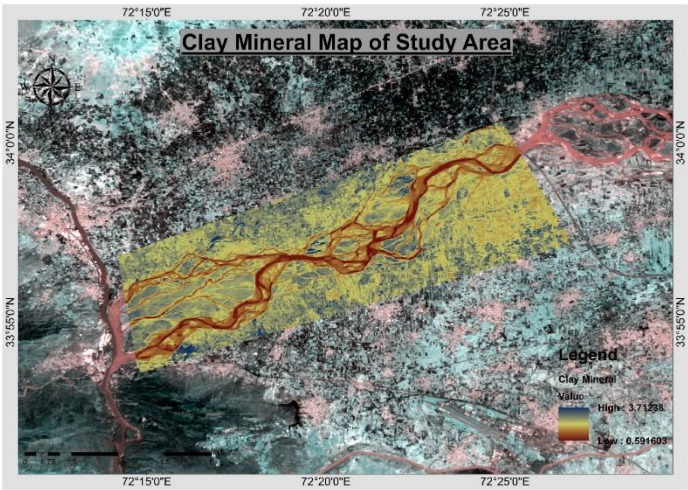





Ferric Iron Map of Study Area
72°15'0"E
72°20'0"E
72°25'0"E
34°0'0"N
33°55'0"N
Legend
Ferric Iron
Value
High : 1.14049
Low : 0.756422

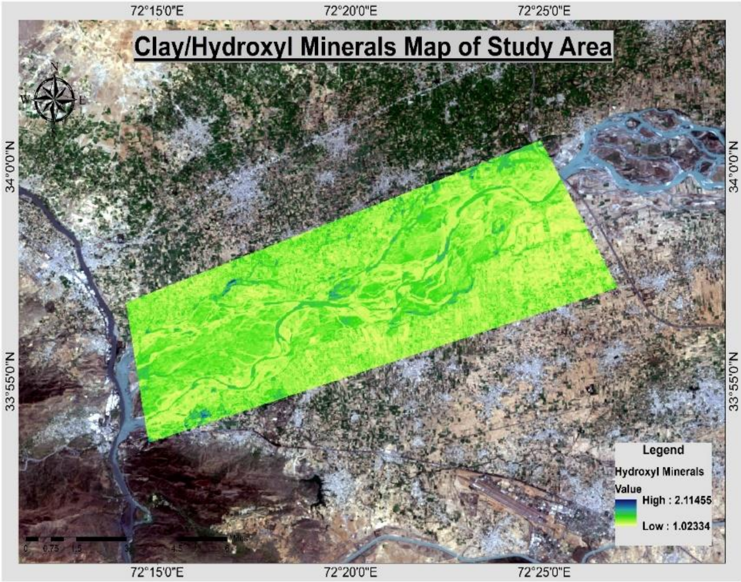

Iron Oxides Map of Study Area
72°15'0"E
72°20'0"E
72°25'0"E
34°0'0"N
33°55'0"N
Legend
Iron_oxides
Value
High : 1.12533
Low : 0.591168

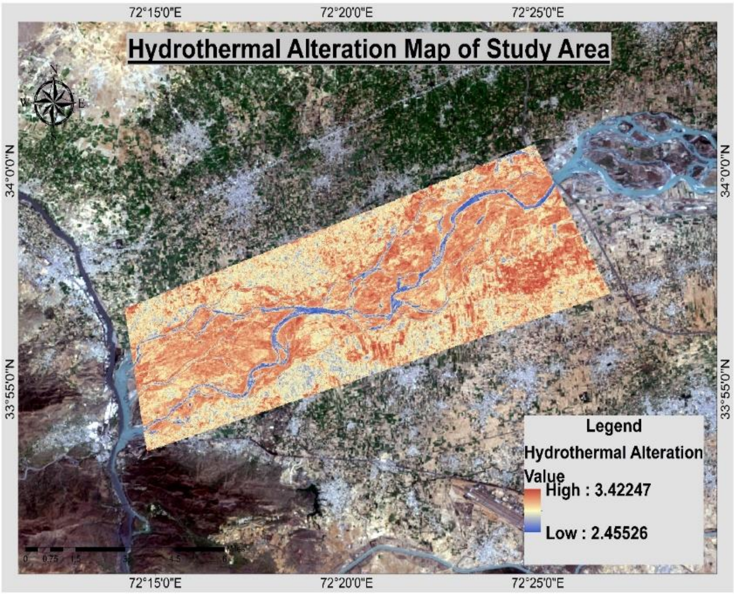

Iron Oxide Index Map of Study Area
72°15'0"E
72°20'0"E
72°25'0"E
34°0'0"N
33°55'0"N
Legend
Iron Oxide Index
Value
High : 0.0589698
Low : -0.256938

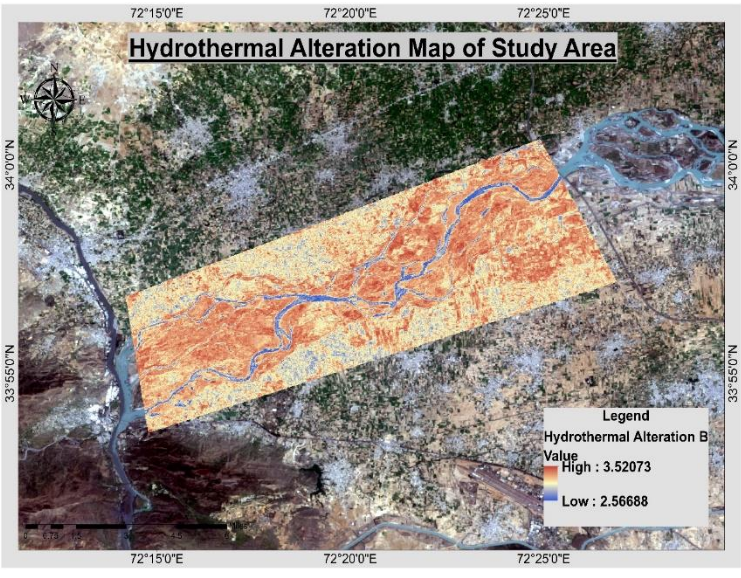

Clay Mineral Map of Study Area
72°15'0"E
72°20'0"E
72°25'0"E
34°0'0"N
33°55'0"N
Legend
Clay Mineral
Value
High : 3.71238
Low : 0.591603

3.6 Integrated Mineral Potential Zones

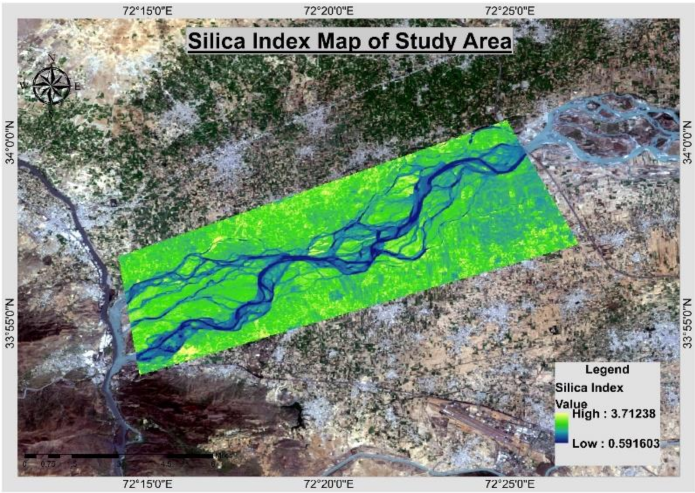
By integrating geomorphological, hydrological, and spectral datasets within a GIS framework, several zones were identified as having high placer mineral potential (*Figure 13*).







These zones are characterized by a combination of low-energy depositional settings, spectral anomalies, and sediment traps. Raster-based classification confirmed the concentration of high-value indicators in 7 discrete clusters, most notably between Ghazi and Attock Khurd.



4. DISCUSSION

The results of this study reveal a clear spatial correlation between geomorphic features, spectral mineral indicators, and placer mineral prospectivity along the Indus River in District Attock. The integration of terrain modeling, spectral band analysis, and hydrological indices presents a compelling case for the effectiveness of remote sensing and GIS as early-stage exploration tools for mineral resource assessment in fluvial environments.

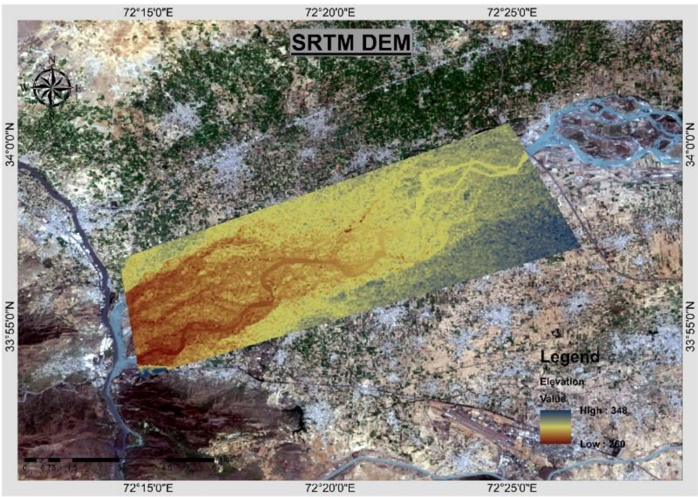
4.1 Placer Deposition and Geomorphic Controls

The observed alignment of ferrous and ferric mineral anomalies with meander belts and point bars substantiates established sedimentological theory, which posits that low-energy depositional environments promote the accumulation of dense, weathering-resistant minerals such as gold, zircon, and magnetite (Bochneva et al., 2021; Saleh and Gabr, 2024). The morphological settings identified — particularly the reworked floodplain terraces and inner flanks of meanders — correspond with known placer traps reported in regional studies across the Peshawar Basin and Gilgit-Baltistan (Mateen et al., 2022; Mahboob et al., 2024).

Buffer analysis around meanders and point bars further reinforced this interpretation by delineating zones of recurring sediment stability. These buffer zones coincide with zones of mineral spectral enrichment, suggesting that geomorphological and geochemical processes are tightly coupled in the river's sedimentation dynamics. Such associations have been similarly reported in placer-hosting environments in Iran and northern India, indicating the broader applicability of this integrated method (Pournamdari et al., 2014; Upadhyay, 2025).

4.2 Terrain Influence and Spectral Discrimination

The DEM-derived slope and aspect models were crucial in understanding how the terrain influences depositional behavior. Lower slopes (<5°) were found to be strongly associated with mineral-rich zones, aligning with previous findings that such gradients facilitate gravitational settling of dense particles in suspension. Aspect orientation, while more variable, showed a tendency for mineral accumulations to occur on west-facing slopes — possibly reflecting preferential erosion from eastern uplands and flow path dynamics.



Spectral discrimination of minerals through Landsat 8 band ratios yielded high-confidence identification of ferrous and ferric iron oxides, clay minerals, and hydrothermal alteration zones. The application of (B4 - B2)/(B4 + B2) and B6/B7 ratios proved particularly useful in distinguishing oxide-rich regions from clay-dominant zones. This aligns with similar spectral workflows used in the Mohmand District and other Himalayan foreland terrains (Khan et al., 2024; Shirmard et al., 2022). The composite hydrothermal index, while showing limited extent in this dataset, offers promise for detecting deeper subsurface mineralization signatures when combined with geophysical or geochemical validation.

4.3 Temporal Shifts in Water and Sediment Systems

The NDWI-based temporal analysis revealed significant retreat of water bodies from 2016 to 2024. These changes likely reflect a combination of climatic variation, sediment infilling, and potential upstream regulation through the Tarbela Dam system. Importantly, many of the newly exposed areas were revealed to be mineral-anomalous in spectral terms — supporting the view that modern erosion and sediment redistribution can uncover previously buried placer horizons.

Furthermore, the seasonal variability observed in NDVI and NDWI trends emphasizes the importance of multi-temporal monitoring in geospatial exploration. Placer zones may become more or less accessible depending on hydrological cycles, reinforcing the value of time-series satellite datasets for exploration planning.

4.4 Implications for Exploration Strategy and Policy

The findings of this study provide actionable spatial intelligence for mineral exploration and resource planning. Identified prospectivity zones can serve as primary targets for follow-up field validation, including geochemical sampling and induced polarization (IP) surveys. The methodology also supports cost-effective regional screening in other parts of the Indus Basin, reducing dependency on traditional, high-cost methods such as manual trenching or random sampling.

In the broader policy context, the identification of environmentally stable, low-energy depositional zones with high placer potential supports more sustainable resource extraction practices. Focused exploration in these zones can help minimize ecological disruption and reduce exploration footprints, a concern echoed in recent land-use planning directives (Ghani et al., 2021; Malik, 2024).

5. Conclusion

This study demonstrates the effectiveness of integrated geospatial techniques in identifying and delineating potential placer mineral zones along the Indus River in District Attock, Pakistan. By leveraging multi-temporal Landsat imagery, SRTM-based terrain data, and cloud computing tools like Google Earth Engine, the research delineated geomorphological features and spectral anomalies indicative of mineral concentration zones — particularly for iron oxides, clays, and potentially placer gold.

The spatial alignment of spectral anomalies with fluvially active geomorphic structures such as meanders, point bars, and low-slope floodplains provides compelling evidence for the existence of placer traps across the studied corridor. The use of spectral indices (e.g., ferrous/ferric iron ratios, clay and silica indicators) enabled efficient mineral discrimination, while DEM-derived hydrological parameters contextualized sediment transport and deposition patterns.

In addition to offering a replicable, low-cost exploration framework, the study contributes to the growing body of evidence that remote sensing and GIS can significantly enhance early-stage mineral resource targeting, especially in dynamic riverine systems. The approach adopted here minimizes the need for invasive field surveys and supports data-driven, environmentally conscious mineral exploration.

Recommendations

Field Validation: Geochemical sampling and petrographic analysis should be conducted in the identified hotspot zones to confirm spectral mineral signatures and placer content.

Drone-Based Surveying: UAV-based photogrammetry and magnetic surveys are recommended for higher-resolution mapping and sub-surface exploration, especially in zones exhibiting hydrothermal indices.

Induced Polarization (IP) and Resistivity Profiling: Follow-up geophysical surveys can provide subsurface characterization of mineral-bearing layers and improve resource estimates.

Time-Series Monitoring: Seasonal NDWI and NDVI trends should be continuously monitored to detect erosion-prone and newly exposed mineral zones, especially during post-monsoon periods.

Sustainable Extraction Framework: Exploration and any future mining initiatives should integrate environmental impact assessments and GIS-based resource monitoring to minimize ecological disturbance.

Replicability Across Other River Systems: This methodology can be extended to other segments of the Indus River and tributaries (e.g., Peshawar Basin, D.I. Khan, and Gilgit valleys) with appropriate calibration for regional geology.

Declarations

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Conflict of Interest

The author declares no conflict of interest related to the publication of this manuscript.

Ethical Approval

No human or animal subjects were involved in this study. All data used were acquired from publicly available satellite datasets and governmental geological sources. As such, ethical approval was not required.

Author Contributions

Muhammad Siddique: Conceptualization, data acquisition, remote sensing analysis, GIS mapping, manuscript writing and editing.

Prof. Dr. Shahid Ghazi (Supervisor): Supervision, methodological guidance, and final review.

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