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Assessing the Impact of Soil Erosion on the Zehanpore Buddhist Archaeological Site in Baramulla (Kashmir, India): A Remote Sensing and GIS Analysis

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Abstract: *This study investigates soil erosion at Buddhist archaeological site on the Jhelum River bank in Baramulla, using Remote Sensing (RS) and GIS. Analysing Landsat and Google Earth imagery (1976–2022), we quantified cumulative spatial changes relative to the 1976 baseline channel area. The reach experienced significant lateral land erosion (32.5%) alongside massive fluvial deposition (71.6%), culminating in a net channel expansion of 39.1% driven by aggressive meander migration. The highest erosion recorded was between 1989-2000 (3,616 m²/year). Predicting future erosion possibilities, this study estimates an additional 10,122m² could be lost by 2050 without undertaking any preventive interventions. The research highlights a methodology for assessing riverbank erosion in archaeological sites using open-source data and emphasizes the importance of GIS and remote sensing in cultural heritage protection.*

Keywords: *Cultural Heritage, GIS, Remote Sensing, Fluvial Erosion, Site Conservation, Baramulla, Jhelum River.*

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Introduction

Archaeological sites provide an important understanding into the past human activities and cultures but at the same time these sites are vulnerable from natural and human factors (Binford, 1988; Nord *et al*., 2005; Talmage & Chesler, 1977). Among these factors, soil erosion caused by water, wind, ice, or gravity is significant, varying with site conditions and often damaging archaeological remains (Davidson *et al*., 1998; Tite & Mullins, 1970; Wainwright, 1994; Agapiou *et al*., 2017). This study examines the Zehanpore site on the river Jhelum in district Baramulla, (Figure1), assessing water and gravity induced erosion. Rivers, important to the water cycle, are dynamic systems influenced by rainfall, runoff, groundwater, and glacier melt but also face hazards like bank erosion and flooding (Robinson *et al*., 2002; Sinha & Ghosh, 2012). This study is focused on the Zehanpore Buddhist Archaeological Site on the Jhelum River (*ancient name Vitasta*), having the flow direction in south-north across Kashmir region, and has shaped its history and culture (Stein, 2020).

This cultural landscape exists within a highly sensitive river system, here, the Jhelum's response to water level, sedimentation, tectonics, and human activity results in frequent shifts from dynamic balance and the subsequent alteration of channels (Dar *et al*., 2014; Eaton *et al*., 2010; Ophra *et al*., 2018; Petts & Gurnell, 2005; Ramos & Gracia, 2012; Tooth, 2000; Winterbottom, 2000). Thus, making bank lines unstable and impermanent (Hassan *et al*., 1997). Such instability is driven primarily by river bank erosion, which occurs when river flow exceeds bank resistance a process dependent on hydro morphological parameters (Rinaldi & Nardi, 2013; Thorne & Tovey, 1981). While it can create habitats and shape floodplains it also causes land loss, damage, and heritage destruction (Gillespie *et al*., 2018; Khatun *et al*., 2022; Sharma, 2017; Tripathy & Mondal, 2019).

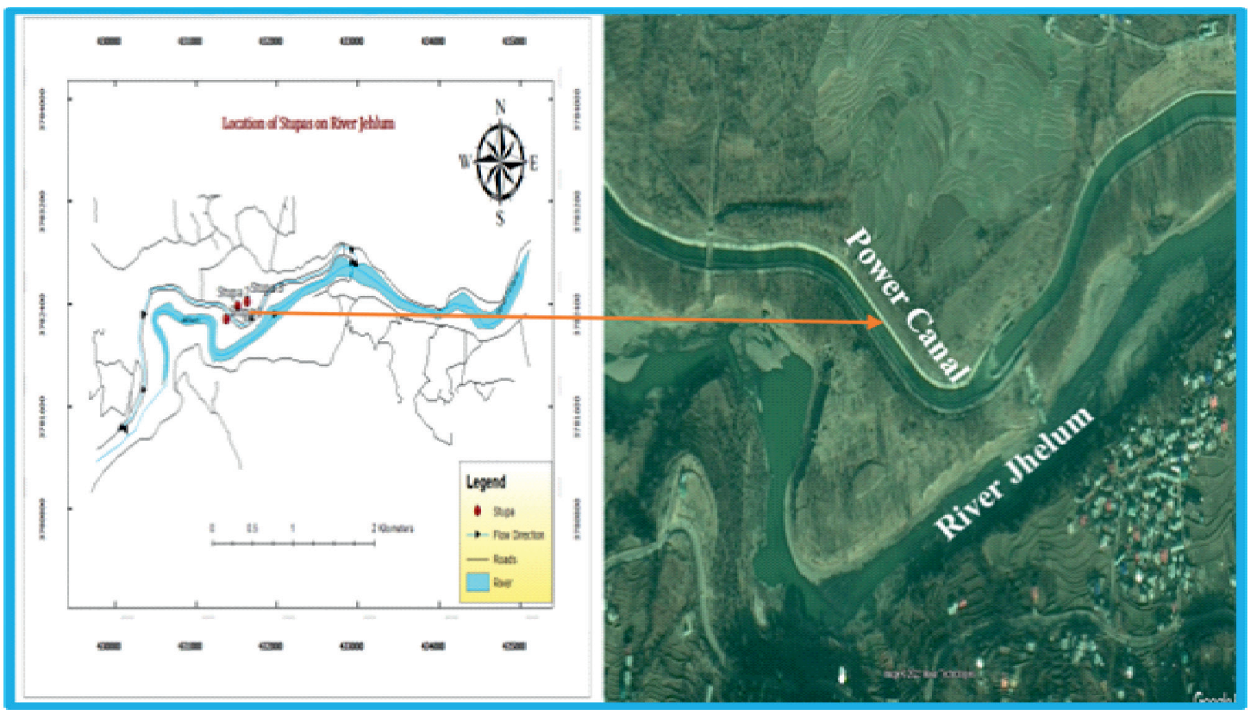

Figure 1: Location of the Zehanpore archaeological site on the Jhelum River in Baramulla district Jammu and Kashmir.

Comparative Context and Methodological Contribution

Our findings are consistent with studies from other major river systems, such as the Nile and Mekong, where anthropogenic activities have been identified as primary drivers of erosion threatening heritage sites. Similar concerns have been reported along the **Tigris and Euphrates,** where land cutting and land filling have endangered archaeological landscapes, and in the **Mississippi River basin**, where channelization and deforestation accelerated riverbank retreat affecting pre-Columbian mound sites (Altaweel, 2005; Knox, 2006). In **Europe,** the Danube floodplains have shown cultural site loss linked to sand mining and hydrological modifications (Habersack *et al*., 2016). In the Indian context, erosion along the **Ganga River** has severely impacted ancient settlements and temples in Bihar and West Bengal, with satellite monitoring showing rapid river course migration (Sinha & Ghosh, 2012). On the **Brahmaputra**, studies have documented large-scale riverbank retreat destroying villages and cultural landscapes in Assam (Bhuyan *et al*.,2024). Likewise, in Gujarat, **intertidal erosion near the Gulf of Khambhat** threatens Harappan coastal sites, highlighting the combined role of geomorphic processes and human activity (Davidson, 1998; Gaur & Sundaresh, 2014).

The methodological framework of this study prioritizes accessibility by utilizing the open-access, longitudinal Landsat satellite archive. This approach offers a replicable model for cultural heritage management, specifically tailored for environments where access to high-cost commercial data or LiDAR remains restricted. While such geospatial methodologies are established in other geographic contexts, this research represents a primary application of these remote sensing techniques to facilitate the quantitative protection of an archaeological site within the Kashmir Valley.

Geospatial Cultural Conservation

Archaeology recognizes cultural and environmental distortions to the record through c-transforms and n-transforms addressed by considering site formation, taphonomy, and post-depositional changes (Schiffer, 1972). Formation processes can be identified via observation and analysis, while post-depositional alterations, such as pottery changes, require comparative studies and profile measurements (Green, 2014). Digital technologies now model techonomic alterations, reflecting the field's evolving tools and methods (Doerr, 2009; Willems., 2008). Since some properties are large or require high precision, GIS and Remote Sensing (RS) are vital for cultural heritage studies (Walkington, 2010; Wernke *et al*., 2014). GIS manages, analyses, and visualizes spatial data while RS acquires information through electromagnetic interactions, capturing spectral signatures to study natural and human-made environments (Aggarwal, 2004; Awange & Kiema, 2013; Pisharoty, 1983; Stubbs & McKee, 2006; Vadrevu, 2013; Yadav *et al*., 2013). Their integration supports assessment of archaeological sites, using spatial, temporal, and spectral data to expose subterranean or endangered heritage (Negula *et al*., 2015; Toz & Duran, 2004). Assessment includes detecting looted or buried sites, measuring risks to sites, and identifying new archaeological areas, highlighting their importance for safeguarding cultural treasures (Agapiou *et al*., 2017; Laura *et al*., 2018).

Study Area

The study was carried out at Zehanpore village (34°10'42.87"N and 74°15'19.98"E) in Baramulla district, Kashmir, about 10 km from the Baramulla town on the right bank of the Jhelum (Figure 2). The Zehanpore Buddhist site was once located on an ancient route linking Kashmir with Gandhara and Central Asia (Shah, 2018, 2024). The landscape in and around the site was heavily altered in the 1970s by canal and road construction, which bifurcated the single landscape into the two cultural landscape and caused severe erosion around the Buddhist stupa, now at risk of collapse (Qazi, 2005). Baramulla, from the Sanskrit term Varahamula (Boar's place), is tied to the geological evolution of Kashmir, once submerged under water (Satisar lake) (Stein, 2020). Historical and scientific research highlight its key role in shaping Kashmir's landscape and history (Agrawal, 1992; Stein, 2020). As the valley's outlet, the Baramulla gorge defined Kashmir's drainage. The region has long been a trade and cultural link to Central Asia, with exchanges evident from the 5th/4th millennium BP (Shah, 2016; Spate *et al*., 2017). It hosts Neolithic and later sites such as Kanispur and Bomai, showing habitation from the Upper Palaeolithic onwards (Mani, 2000; Shah, 2018; Spate, 2019; Yatoo, 2012). The historical record of the valley was notably documented by Hiuen Tsang, who arrived in AD 631 and entered via the pass he mentioned as the Stone Gate, identified in the, Nilmatpurana as “Drava” (Beal, 1884). While Al-Beruni also mentioned about this route in his eleventh-century geographic records documented this same established route through the Buddhist centres of Baramulla, including the Jushka and Jayendra Viharas (Beal, 1884; Cunningham, 1924; Ray, 1969; Shah, 2018; Watters, 1961). During his travels, Hiuen Tsang lodged at the Jushka Vihara (Ushkur) before visiting the Jayendra Vihara, a site historically linked to the archaeological stupa at Zehanpore (Ray, 1969).

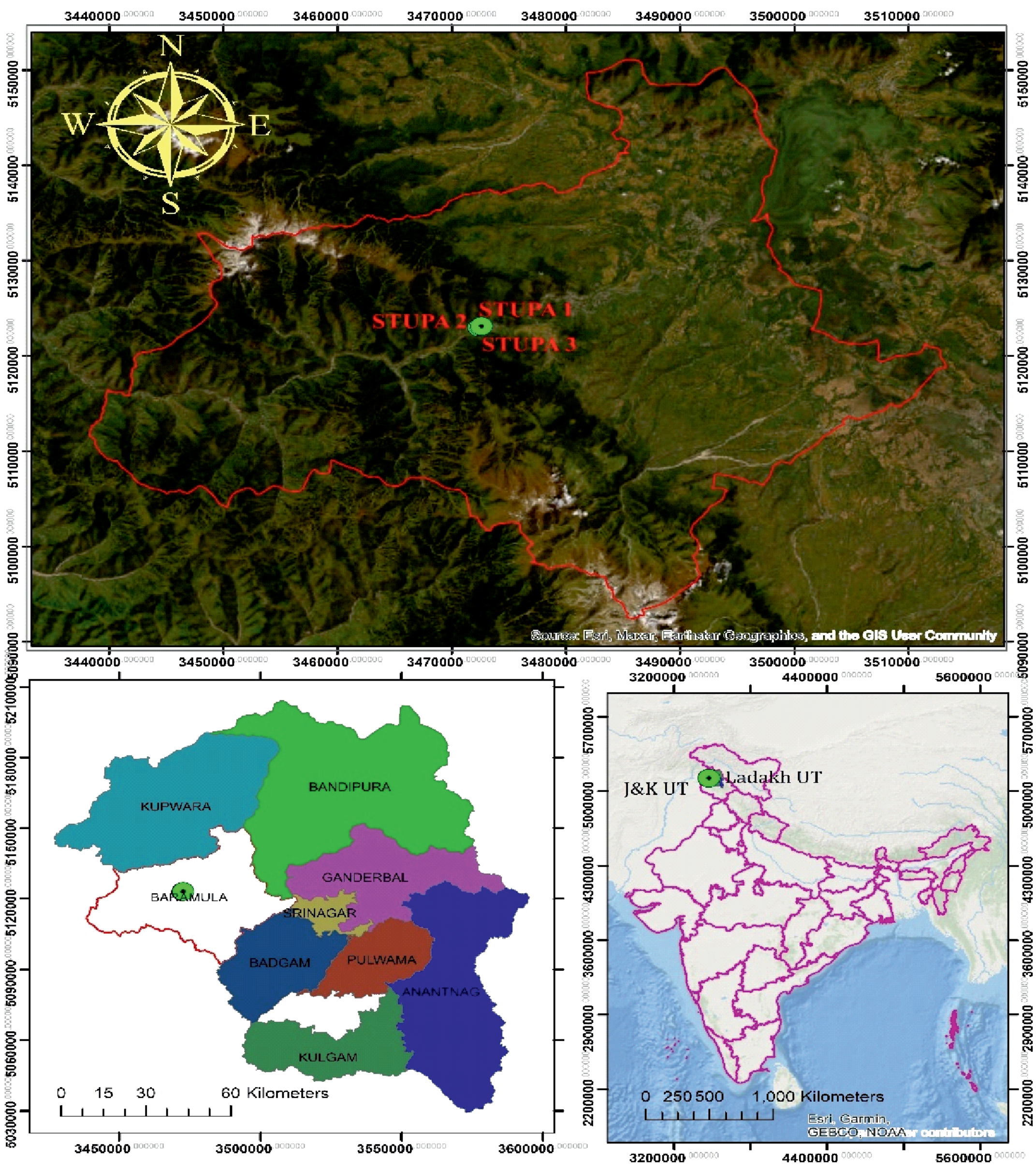

Figure 2: Detailed study area map with archaeological sites and settlements.

Methodology and Data Collection

This study assesses erosion and deposition at the riverine archaeological site of Zehanpore in the Baramulla district using openly available datasets. High-resolution Google Earth (GE) imagery was employed to capture valuable seasonal and temporal variations, which aid in detecting subtle archaeological features (Gupta *et al*., 2019; Lysandrou & Agapiou, 2016; Parcak, 2009). These datasets were complemented by multi-temporal Landsat imagery sourced from the USGS Earth Explorer. Integrating these geospatial tools is necessary to monitor the site's specific environmental context, as rivers naturally adapt to surrounding landscape changes (Martin *et al*., 2020). Such analysis is particularly critical because archaeological sites are often strategically located near watercourses for access to drinking water and for connectivity, which inherently increases their exposure to fluvial risks (Gaur & Sundaresh, 2014).

Data and Pre-processing

The analysis utilized Landsat imagery spanning 1976 to 2022, obtained from the USGS Earth Explorer. The integration of Landsat Multispectral Scanner (MSS) data from 1976 provides a vital longitudinal baseline, though its coarse 60m spatial resolution necessitates cautious interpretation. While the nearest-neighbour resampling to 30m ensures computational consistency with subsequent TM, ETM+, and OLI sensors, it introduces an inherent positional uncertainty. Consequently, the calculated erosion of 10,636 m^2 for the 1976–1989 period should be viewed as an indicative geomorphic trend rather than a precise measurement of stratigraphic loss. This margin of error is particularly relevant when assessing lateral retreat near the Zehanpore stupa, where the scale of archaeological features may be smaller than the sensor's original pixel dimensions. All imagery was standardized to UTM Zone 43N/WGS84 for comparability.

Spatio-temporal analysis of riverbank shifts (1976–2022) was conducted using Landsat surface reflectance imagery (Table 1). Land Use and Land Cover (LULC) maps for 1976 and 2022 were produced via maximum likelihood supervised classification[1] into five categories, River, Forest, Built-up, Agriculture, and Vegetation. Validation involved cross-referencing randomly generated points with GE imagery to confirm classification accuracy. Additionally, riverbank lines for four time periods were delineated through visual interpretation, after which GIS-based analysis was applied to quantify erosion, deposition, and shifting channel patterns.

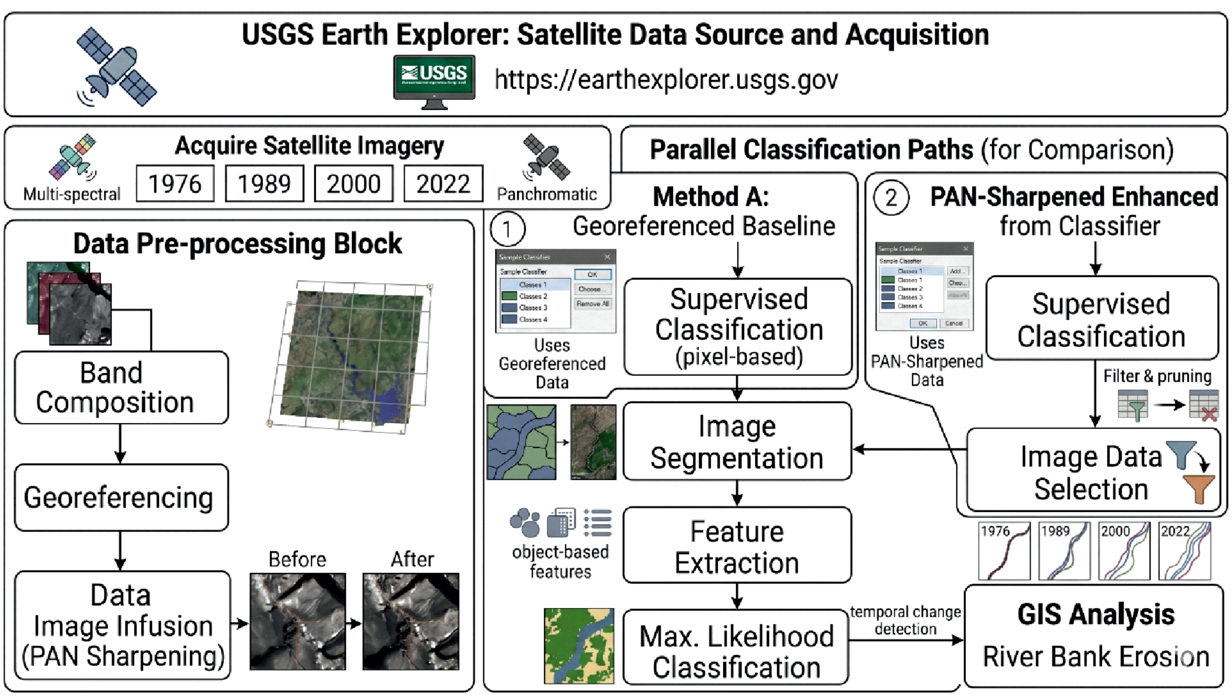

Figure 3: Methodology workflow diagram.

(Image generated from Adobe illustrator https://www.adobe.com/in/products/illustrator.html)

Table 1: Landsat Data Used to Analyse Spatial and Temporal Patterns

Landsat Scene Identifier	*Sensor*	*Path/Row*	*Date of Acquisition*	*Spatial Resolution (m)*	*UTM Zone/Datum*
LM21610361976149 FAK03	MSS	161/036	1976/05/28	60	43/WGS84
LT51490361989040 ISP00	TM	149/036	1989/02/09	30	43/WGS84
LE71490362000239 SGS00	ETM+	149/036	2000/08/26	30	43/WGS84
LC91490362022219 LGN01	OLI_TIRS	149/039	2022/08/07	30	43/WGS84
Google Earth Pro	Maxer	–	2022/12/15	0.5	43/WGS84

$$\text{Accuracy (Producer's Accuracy)} = \frac{\text{Total number of correct pixels in a category}}{\text{Total number of pixels of that category derived from the reference data}}$$

$$\text{Average Accuracy} = \frac{\text{Total number of correct pixels in a category}}{\text{Total number of pixels of that category derived from the reference data}}$$

$$\text{Overall accuracy} = \frac{\sum \text{diagonal elements}}{\text{Total number of accuracy sites (pixels)}} = \frac{18}{20} = 0.90$$

Kappa coefficient

$$K = \frac{(Obs - exp)}{(1 - exp)}$$ Where:

Obs = Observed correct, it represents accuracy reported in error matrix (overall accuracy)
exp = Expected correct, it represents correct classification

The 2022 classification achieved a Kappa Coefficient of 0.85, compared to 0.79 for the year 2000 classification. These are dimensionless agreement statistics, not percentages.

Overall Accuracy: 0.90
Kappa: 0.85

Land Use/Land Cover (LULC) Analysis

To understand the broader landscape context, a supervised maximum likelihood classification was performed on the 1976 to 2022 images. The purpose was to identify large-scale anthropogenic changes (e.g., expansion of agriculture, built-up areas) that might contribute to altered river dynamics. The accuracy of the 2022 classification was evaluated using 100 random validation points cross-referenced with high-resolution Google Earth imagery. The analysis yielded an overall accuracy of 90% and a Kappa Coefficient of 0.85, indicating a high level of agreement. The complete categorical performance metrics, including user and producer accuracies for each land cover type, are summarized in Table 2 and 3.

The Producer's Accuracy of 50% for the Built-Up category in the 2022 classification indicates a significant omission error, where anthropogenic structures were misclassified, likely as Agriculture or Vegetation. In the Baramulla region, the spectral signatures of traditional building materials such as unbaked clay, stone, and timber frequently overlap with fallow fields or exposed riverine deposits. This spectral confusion underscores the difficulty of distinguishing rural archaeological remains from their environmental matrix using 30m resolution data. Despite this limitation, the Overall Accuracy (90%) and Kappa Coefficient (0.85) confirm that broader landscape transitions, specifically the expansion of the river channel, remain statistically valid for assessing fluvial impact.

Table 2: Categorical Performance Metrics (User and Producer Accuracies)

Class	*User Accuracy*	*Producer Accuracy*	*Overall Accuracy (%)*	*Kappa*
River	1.00	0.71		
Forest Cover	0.83	0.90		
Built Up	0.83	0.75		
Agriculture	0.84	0.87		
Vegetation	0.81	0.86		
Total			83	0.79

Table 3: Classification accuracy assessment for 2000 and 2022

Class Value	*River*	*Forest Cover*	*Built Up*	*Agriculture*	*Vegetation*	*User Accuracy*	*Producer Accuracy*
River	1	0	0	0	0	1.00	1.00
Forest Cover	0	9	1	0	0	0.90	1.00
Built Up	0	0	1	0	0	1.00	0.50
Agriculture	0	0	0	2	1	0.67	1.00
Vegetation	0	0	0	0	5	1.00	0.83
Total	1	9	2	2	6	0.90	0.90

Erosion and Deposition Quantification

- **Erosion:** Area present in the 1976 river polygon but absent in the 1989 polygon.
- **Deposition:** Area absent in the 1976 river polygon but present in the 1989 polygon.

This procedure was repeated sequentially for the intervals 1976-1989, 1989-2000, and 2000-2022 to calculate the area and average annual rate of change (Figure 4).

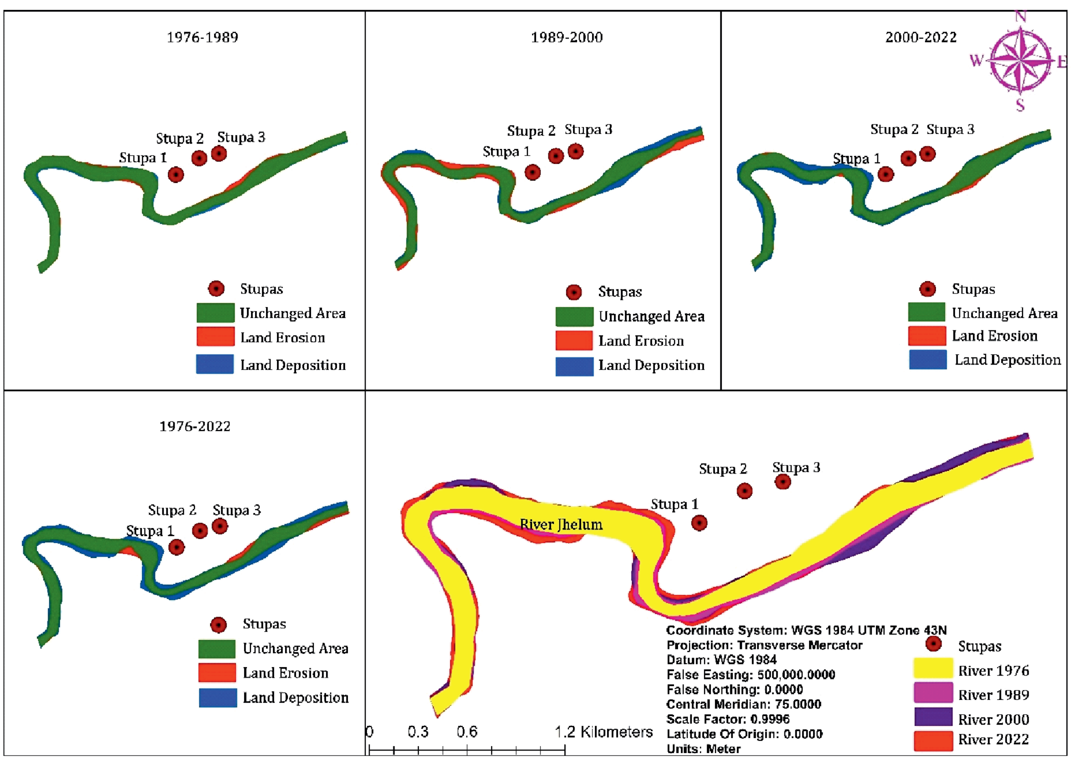

Figure 4: Spatio-temporal changes in riverbank (1976, 1989, 2000, 2022) with erosion/deposition highlighted. (Image generated from ArcMap 10.8.2 https://www.arcgis.com)

Results

Erosion Rate

- The average annual erosion rate increased from 818.15 m²/year in 1976–1989 to 3,616.09 m²/year in 1989–2000 (Figure 5).
- It then decreased significantly to 361.50 m²/year in 2000–2022.

Deposition Rate

- The average annual deposition rate also increased from 2,453.15 m²/year in 1976–1989 to 3,082.18 m²/year in 1989–2000.
- It then decreased to 2,853.95 m²/year in 2000–2022.

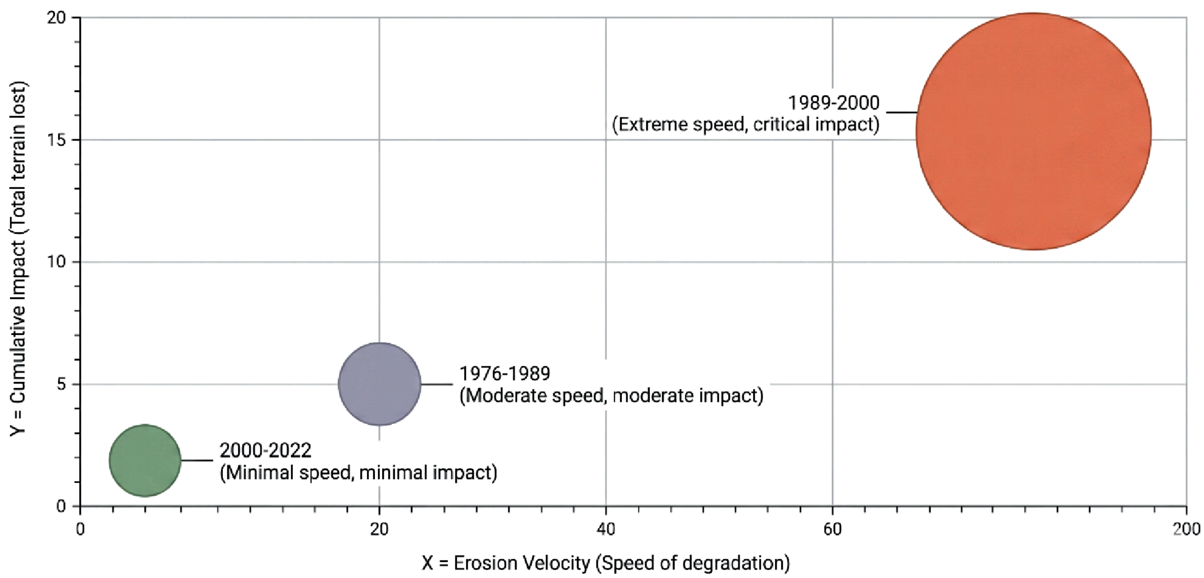

Figure 5: Historical diagnostic matrix 1976- 2022.

Spatio-Temporal Erosion and Deposition

The study has shown the massive spike in erosion at the rate of 3,616 m²/year between 1989 and 2000 (Table 4; Figures 4 and 6), nearly 4.5 times higher than the preceding period and 10 times higher than the subsequent period. While extensive deposition occurred downstream, this specific period was characterized by aggressive land cutting directly at the archaeological site.

Table 4: Quantification of Erosion, Deposition, and Unchanged Areas (1976–2022).

Years	*Previous Year*	*Next Year*	*Unchanged Area*	*Land Erosion*	*Land Deposition*
1976-1989	179493	200748	168857 m^2	10636 m^2	31891 m^2
1989-2000	200748	194874	160970 m^2	39777 m^2	33904 m^2
2000-2022	194874	249709	186922 m^2	7953 m^2	62787 m^2

Direct Impact on Archaeological Site

The multi-scalar diagnostic of the Zehanpore Buddhist archaeological site (Figure7), illustrating the catastrophic impact of both natural fluvial processes and unregulated human activity on the cultural landscape. The evidence presented here confirms that the site is undergoing significant stratigraphic collapse due to a combination of n-transforms (natural river dynamics) and c-transforms (anthropogenic mining).

Figure 6: Site Plan (Place A) in Relation with Thalweg, Expanding Meander, and Section Washaway.

Note: The red highlighted region (Place A) marks the epicentre of the erosion. Site plan generated in AutoCAD. Field photographs demonstrate gravity-induced collapse, meander migration, and fluvial shear.

Site Layout and Vulnerability

- Archaeological Alignment: The site plan shows the linear arrangement of Stupa 1, Stupa 2, and Stupa 3.

- Location: The complex is situated on the right bank of the Jhelum River in the Baramulla district.
- Place A: The red highlighted region, identified as Place A, marks the epicentre of the erosion and was subjected to intensive, illegal instream mining between 1989 and 2000.

Mechanisms of Erosion

The field photographs (Figure 6) and satellite overlays demonstrate three distinct erosional drivers:

(A) Gravity-Induced Collapse (Undercutting): The extraction of substrate from the bottom of the bank has created unstable erosion scarps. As the base is removed through mining, the upper archaeological layers lose structural support, leading to mass gravitational erosion of cultural debris.

(B) **Meander Migration and Stratigraphic Cutting:** The area shows the Jhelum's meander migrating directly into the archaeological stratigraphy. This lateral retreat is accelerated by a thalweg shift, which redirects high-velocity erosive currents toward the fragile bank.

(C) **Fluvial Shear and Human Interference:** This illustrates the direct cutting of the riverbank. The removal of riparian vegetation and the creation of mining pits have reduced the bank's resistance to fluvial shear stress, causing the irreversible loss of the site's buffer zone.

These field observations provide the material evidence required to ground the remote sensing data, proving that the erosion surge recorded in the satellite archive corresponds to the physical destruction of the monumental architecture seen in these photographs.

Erosion Forecasting

Predictable Land Erosion Dynamics up to 2050 by linear extrapolation
Time Period 1976-1989:

Average Annual Land Erosion Rate (1976-1989 E1976-1989)

$$E1976-1989=\frac{\text{Number of Years } (1989-1976)}{\text{Land Erosion}(1989-1976)}$$

E1976-1989≈**818.15m^2 /year**

Time Period 1989-2000:

Average Annual Land Erosion Rate (1989-2000 E1989-2000)

$$E1989\text{-}2000=\frac{\text{Number of Years}(2000-1989)}{\text{Land Erosion}(2000-1989)}$$

E1989-2000≈**3,616.09m^2/year**

Time Period 2000-2022:

Average Annual Land Erosion Rate (2000-2022 E2000-2022)

$$E2000\text{-}2022=\frac{\text{Number of Years}(2022-2000)}{\textit{Land}\text{ and Erosion }(2022-2000)}$$

E2000-2022≈**361.50m^2/year**

Time Period 2022-2050: Extrapolate the Average Annual Land Erosion Rate (2000-2022 E2000-2022) to the 2022-2050 period:

E2000-2022×Number of Years (2022-2050)

Projected Land Loss (PLL) (2022-2050) ≈**10,122m^2**

The projection of 10,122m² of potential land loss by 2050 is a linear extrapolation based on the status quo of the 2000–2022 erosion rate (361.50 m²). This forecast serves as an investigative for conservation management rather than a deterministic hydrological model, it does not account for probabilistic high-magnitude events, such as mega floods, or non-linear responses to future climatic shifts in the Jhelum basin. Accordingly, these figures should be treated as a minimum risk threshold. In the absence of geotechnical interventions such as retaining walls or bio-engineering the primary monument faces an acute risk of structural failure within the next three decades (Table 5).

Table 5: Results of projected Land erosion up to 2050

Time Period	*Average Annual Land Erosion Rate (m²/Year)*	*Projected Land erosion (m²/Year)*
1976-1989	818.15	10636
1989-2000	3,616.09	39777
2000-2022	361.50	7953
2022-2050 (Extrapolated)	-	10,122

Discussion

The dramatic spike in erosion rates between 1989 and 2000 (3,616 m²/Year) is situated within a period of intensive n-transforms (natural processes) exacerbated by significant c-transforms (cultural activities). Material evidence of unregulated instream mining specifically the formation of mining pits and the resultant thalweg shift (Figure 7) directly contributed to the undercutting of the bank supporting

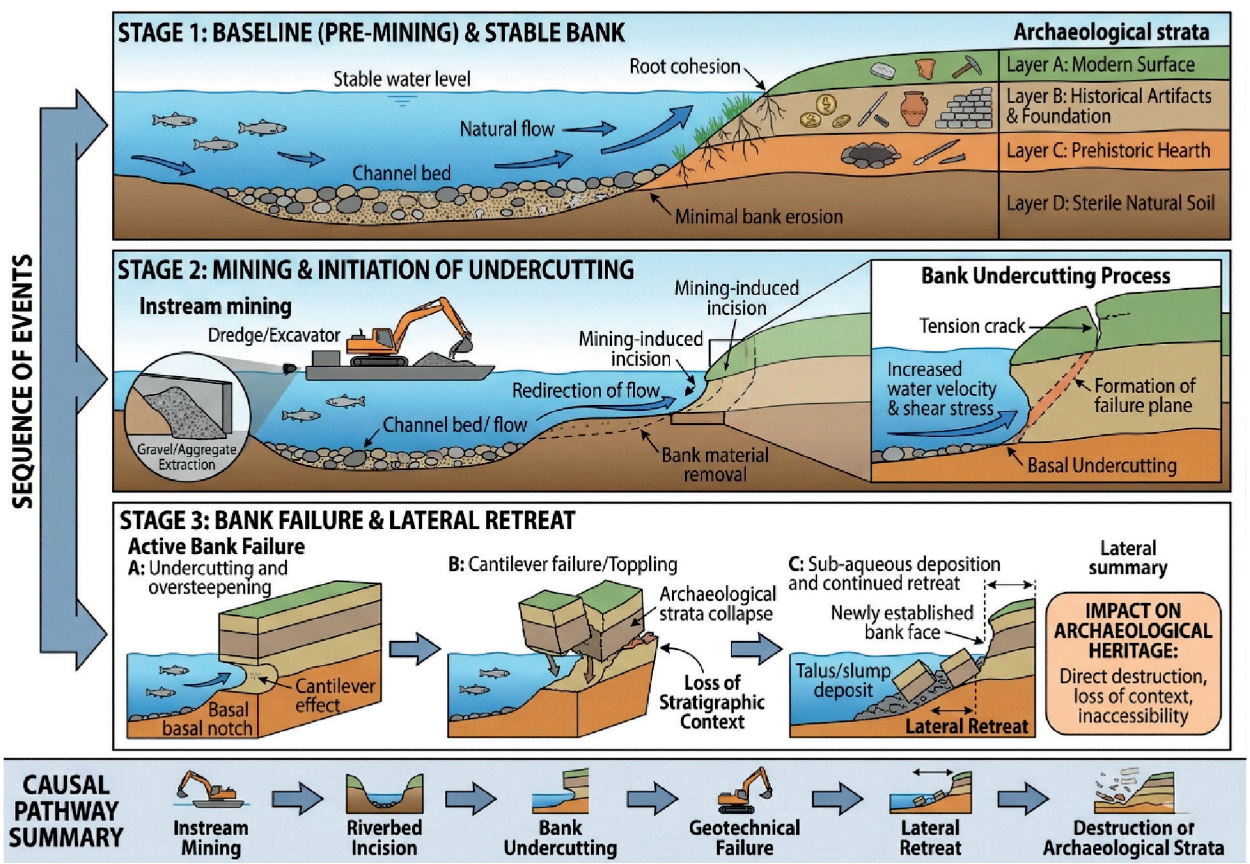

Figure 7: Schematic illustrating mining impact, thalweg shift, and bank collapse (Image generated from Adobe illustrator https://www.adobe.com/in/products/illustrator.html)

the Buddhist complex. These processes were compounded by the removal of riparian vegetation, which reduced the bank's resistance to fluvial shear stress. The resulting formation of prominent erosion scarps, visible in the site's current profile, demonstrates that these anthropogenic pressures did not merely result in land loss, but caused the physical collapse of monumental architecture. The transformation of primary archaeological contexts into secondary depositional layers at Zehanpore highlights the immediate threat posed when industrial aggregate extraction overlaps with sensitive archaeological zones. The magnitude of erosion during this 11-year window is 4.5 to 10 times higher than adjacent periods (Figure 5), confirming that it was an outlier driven primarily by human activity rather than climatic variability. The subsequent decline in erosion rates post-2000 correlates with reduced mining and localized replanting efforts, consistent with studies showing that re-vegetation and reduced aggregate extraction promote partial channel re-stabilization (Zaimes *et al*., 2019).

Regional studies further demonstrate that unregulated sand mining in Kashmir has caused lowered riverbeds, bank instability, and damage to riparian habitats, while deforestation and forest degradation across the Himalayas have exacerbated slope and bank vulnerability (Dar *et al*., 2023). Taken together, the evidence strongly indicates that the intensive mining and deforestation at the Zehanpore archaeological site were the primary drivers of the 1989–2000 erosion surge.

Implications for Conservation and Management

This study transitions the threat to Zehanpore from a qualitative observation to a quantified, time bound risk. The data provides a compelling, evidence-based argument for immediate intervention. The forecast of over 10,000 m² of potential land loss by 2050 underscores that a do-nothing approach will almost certainly result in the loss of the main stupa. These findings can be used to justify and guide the implementation of urgent site stabilization measures, such as geotechnical solutions (retaining walls, gabions) or nature-based bio-engineering (strategic planting of deep-rooted vegetation like vetiver).

Conclusion

The study successfully employed a 46-year remote sensing analysis to quantify the severe threat of riverine erosion to the Zehanpore archaeological site. We identified a critical decade of accelerated erosion (1989-2000) likely driven by a confluence of climatic and anthropogenic pressures, which resulted in tangible damage to the site's monumental architecture. Our forecast indicates that the primary monument is at high risk of collapse within the next three decades if no protective measures are taken. The study demonstrates how the freely available geospatial data can be used as an important tool for cultural heritage diagnostics and preservation. It provides a clear, data-driven foundation for policymakers and conservation bodies to move from passive monitoring to active, informed intervention to safeguard this irreplaceable piece of Kashmir's history.

Note

1. Maximum likelihood supervised classification: A supervised classification algorithm, primarily used in remote sensing, that statistically assigns a pixel to the class for which it has the highest probability of belonging.

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