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Original Article

Quaternary Landscape Modification of the Luna Impact Crater: Coupled Fluvial, Aeolian and Impact-Related Processes in the Kutch Region, Gujarat, India

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Abstract
The Luna impact crater, located in Gujarat, western India, is a young terrestrial impact structure developed within Quaternary sediments of the semi-arid Banni Plains. This study examines the Quaternary landscape evolution of the crater with emphasis on the interaction between impact-related morphology and subsequent fluvial and aeolian processes. High-resolution digital elevation models, satellite imagery, and detailed field observations were used to quantify crater morphometry, rim degradation, sediment infilling, and drainage characteristics. Results indicate that post-impact fluvial activity, particularly during episodic monsoonal rainfall, has played a dominant role in modifying crater morphology through surface runoff, sediment transport, and localized ponding. Aeolian processes further contribute to infill and surface smoothing by redistributing fine-grained sediments across the crater floor. The combined action of these processes has resulted in reduced relief, asymmetric rim preservation, and partial obscuration of primary impact features. This study demonstrates that coupled fluvial–aeolian dynamics exert strong controls on the preservation and degradation of small, young impact craters in arid to semi-arid regions and provides a framework for assessing post-impact landscape evolution in similar environments.
Keywords: *Impact crater geomorphology, Quaternary landscape evolution, Fluvial–aeolian interactions, Semi-arid hydrogeomorphology, Kutch Basin, western India*

Introduction

Meteorite impact cratering is one of the most fundamental geological processes influencing planetary surfaces, yet on Earth its geomorphic expression is commonly obscured by erosion, sedimentation, tectonic activity, and climate-driven surface processes (Melosh, 1989; French, 1998). Consequently, well-preserved terrestrial impact craters are relatively rare, and those formed during the Quaternary period are of particular scientific value because they record the interaction between primary impact processes and near-modern surface dynamics (Grieve, 2006; Osinski and Pierazzo, 2013).

Quaternary impact craters provide important insights into post-impact landscape evolution, as their morphologies reflect rapid modification under prevailing climatic and environmental conditions (Morgan et al., 2018). In semi-arid and arid regions, crater degradation is typically governed by a combination of episodic fluvial activity, aeolian sediment transport, and lacustrine or playa-related sedimentation, which together contribute to rim erosion, crater infilling, and reduction of relief (Goudie, 2004; Lancaster, 2008). These coupled processes play a crucial role in determining the preservation potential of small and young impact craters and are increasingly used as analogues for interpreting crater modification on Mars and other planetary bodies (Grant et al., 2008).

The Kutch region of Gujarat, western India, represents a tectonically active and geomorphologically dynamic landscape characterized by semi-arid climate, seasonal monsoonal rainfall, extensive Quaternary sediment cover, and widespread aeolian landforms (Kar et al., 2004; Maurya et al., 2016). The region has experienced repeated phases of sedimentation, erosion, and landscape reorganization during the Quaternary, influenced by climate variability and neotectonic activity (Biswas, 2019). Within this complex setting, the Luna impact crater constitutes a rare geomorphic feature that offers an exceptional opportunity to examine post-impact landscape modification in a low-relief, sediment-dominated environment.

Recent investigations have confirmed the impact origin of the Luna crater through the identification of meteoritic fragments, elevated platinum-group elements, and diagnostic mineralogical characteristics indicative of shock processes (Suresh et al., 2023). However, existing studies have primarily focused on crater confirmation and geochemical characterization, while systematic analyses of geomorphic evolution, sedimentary infilling, and hydrological behavior remain limited. In particular, the relative contributions of fluvial and aeolian processes in modifying crater morphology during the Quaternary have not been quantitatively assessed.

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Fluvial processes in semi-arid environments are typically episodic but geomorphically effective, with short-duration, high-intensity rainfall events generating significant runoff, sediment transport, and localized erosion (Tooth, 2000). In enclosed or semi-enclosed basins such as impact craters, these processes often lead to sediment trapping, temporary water storage, and accelerated infilling (Bowler, 1986). Aeolian processes further modify crater landscapes by redistributing fine sediments across crater floors and rims, smoothing topography and masking primary impact features (Pye and Tsoar, 2009). The interaction between these fluvial and aeolian mechanisms results in complex patterns of landscape modification over Quaternary timescales.

Despite the growing recognition of the importance of post-impact surface processes, integrated studies that explicitly address the coupling of fluvial, aeolian, and impact-related processes are scarce in the Indian subcontinent. The Luna impact crater therefore represents a critical case study for understanding how Quaternary climatic variability and surface processes influence the evolution and preservation of young impact structures in semi-arid regions.[1]

The present study investigates the Quaternary landscape modification of the Luna impact crater by analyzing the combined influence of fluvial, aeolian, and impact-related processes. Through integrated geomorphological mapping, morphometric analysis, and hydrogeomorphic interpretation, this research aims to improve understanding of post-impact landscape evolution and contribute to broader models of crater degradation applicable to both terrestrial and planetary environments.[2,3]

Research Objectives

The present study aims to investigate the Quaternary landscape modification of the Luna impact crater in the Kutch region of Gujarat, western India, with particular emphasis on the interaction between impact-related landforms and post-impact surface processes. The specific objectives are:

1. To characterize the geomorphological framework of the Luna impact crater by mapping crater morphology, rim characteristics, floor topography, and surrounding landforms using remote sensing data and field observations.
2. To quantify crater morphometry and degradation patterns through digital elevation model–based analysis, including crater depth, diameter, rim height variability, slope gradients, and asymmetry, in order to assess the extent of post-impact modification.
3. To evaluate the role of fluvial processes in crater evolution, focusing on surface runoff pathways, sediment transport, episodic flooding, and their influence on rim erosion, sediment accumulation, and temporary water storage within the crater.
4. To assess the contribution of aeolian processes to sediment redistribution, infilling, and surface smoothing of the crater floor and rim, particularly under semi-arid climatic conditions.
5. To examine the interaction between fluvial and aeolian processes and their combined impact on Quaternary landscape evolution and preservation of primary impact features.
6. To interpret the hydrogeomorphic behavior of the crater by analyzing surface–subsurface water interactions and their implications for sediment trapping and landscape stability.
7. To develop a conceptual model of post-impact landscape evolution for the Luna crater that integrates impact-related, fluvial, and aeolian processes and can be applied to similar young impact structures in semi-arid environments.

Study Area

The study focuses on the Luna impact crater, located in the Kutch (Kachchh) region of Gujarat, western India (Fig. 1). The crater lies within the Banni Plains, a low-relief depositional landscape situated south of the Great Rann of Kutch, approximately 40–50 km north-east of Bhuj town. The region forms part of the Kutch Basin, a tectonically active intracratonic basin along the western continental margin of India (Biswas, 2019; Maurya et al., 2016).

The Luna crater is a small, near-circular depression developed within Quaternary sediments, with a diameter of approximately 1.5–1.8 km and subdued topographic relief. The crater rim is discontinuous and exhibits variable preservation, while the crater floor is largely infilled with fine-grained sediments, reflecting significant post-impact modification. Recent studies have confirmed the impact origin of the structure based on meteoritic fragments and geochemical signatures, placing its formation within the Holocene epoch (Suresh et al., 2023).

Climatically, the study area experiences a semi-arid to arid climate, characterized by hot summers, mild winters, and highly variable annual rainfall. Mean annual precipitation ranges between 300 and 400 mm, the majority of which occurs during the south-west monsoon (June–September) (IMD, 2020). Rainfall is typically episodic and high-intensity, resulting in short-lived surface runoff events that play a key role in landscape modification (Tooth, 2000). Potential evapotranspiration greatly exceeds precipitation, favoring sediment exposure and aeolian activity for much of the year.

Geomorphologically, the Banni Plains are dominated by playa surfaces, mudflats, interdunal tracts, and stabilized to semi-active aeolian dunes, reflecting alternating wet and dry phases during the Quaternary (Kar et al., 2004). Drainage in the region is poorly organized, with ephemeral streams and shallow flow paths active only during intense rainfall events. The Luna crater functions as a local closed to semi-closed basin, temporarily storing runoff and sediments during monsoonal periods before drying out during prolonged dry phases.

Geologically, the Kutch region is underlain by Mesozoic sedimentary formations, overlain by thick Quaternary alluvial, fluvial, and aeolian deposits (Biswas, 2019). Neotectonic activity along major faults has influenced regional topography and sedimentation patterns, contributing to the complex geomorphic evolution of the basin (Maurya et al., 2016). The presence of unconsolidated sediments and low gradients makes the landscape highly sensitive to both fluvial reworking and aeolian redistribution. The combined influence of episodic fluvial processes, active aeolian dynamics, and post-impact sedimentation makes the Luna impact crater an ideal natural laboratory for examining Quaternary landscape modification in a semi-arid environment. Its location within the climatically and tectonically dynamic Kutch region provides valuable context for understanding crater degradation, edimenttrapping, andydrogeomorphic evolution in young terrestrial impact structures.

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Fig.1. Location Map of Luna Crater (a) Physical map of India (b) Physical map of Gujarat (c) NASA Satellite image

4. Data and Methods

4.1 Data Sources

To investigate the Quaternary landscape modification of the Luna impact crater, an integrated dataset comprising remote sensing data, digital elevation models (DEMs), geological information, and field observations was used.

1. **Satellite Remote Sensing Data**
   - Multispectral satellite images from Landsat-8 OLI/TIRS and Sentinel-2 MSI were used for geomorphological mapping, landform identification, and surface process interpretation.
   - Images representing different seasons were selected to examine variations in surface water presence, sediment exposure, and vegetation cover.
2. **Digital Elevation Models (DEMs)**
   - SRTM DEM (30 m resolution) and ASTER GDEM were used to analyze crater morphology, elevation variations, slope, and drainage characteristics.
   - DEMs were corrected for sinks and artifacts prior to morphometric analysis.
3. **Topographic and Geological Data**
   - Survey of India (SOI) topographic maps were used for base mapping and validation of drainage and relief.
   - Published geological and tectonic maps of the Kutch region were consulted to understand regional stratigraphy and structural controls (Biswas, 2019; Maurya et al., 2016).
4. **Field Data**
   - Field investigations were conducted to verify geomorphic features interpreted from remote sensing data.
   - Observations included rim morphology, sediment characteristics, evidence of fluvial erosion, aeolian deposition, and temporary water accumulation.
   - GPS measurements were used to record key geomorphic locations such as rim breaks, sediment accumulation zones, and drainage inlets.

Methodology

The methodological framework involved a combination of geomorphological mapping, morphometric analysis, hydrogeomorphic assessment, and process interpretation, as outlined below.

4.2.1 Geomorphological Mapping

- Visual interpretation of satellite imagery was carried out to delineate crater boundaries, rim segments, crater floor, surrounding plains, and associated landforms such as dunes, playas, and ephemeral channels.
- Landforms were mapped in a GIS environment using on-screen digitization techniques.
- Mapped features were classified based on morphology, process dominance, and relative age following standard geomorphological mapping approaches (Goudie, 2004).

4.2.2 Morphometric Analysis

- DEM-based analysis was performed to quantify crater geometry, including:
  - Crater diameter and depth
  - Rim height and slope gradients
  - Elevation profiles across multiple transects
  - Asymmetry and relief reduction patterns
- Slope, aspect, and curvature maps were generated to assess erosion patterns and sediment accumulation zones.
- Longitudinal and transverse profiles were extracted to evaluate rim degradation and floor infilling.

4.2.3 Fluvial Process Analysis

- Drainage networks and surface runoff pathways were derived from DEMs using hydrological tools in GIS.

- Flow direction, flow accumulation, and catchment boundaries were analyzed to understand runoff concentration and sediment transport into the crater.
- Field evidence of rills, gullies, sheet wash, and flood deposits was used to support fluvial interpretations.
- The role of episodic monsoonal rainfall in driving geomorphic change was assessed following dryland fluvial models (Tooth, 2000).

4.2.4 Aeolian Process Assessment

- Aeolian landforms such as dunes, sand sheets, and deflation surfaces around and within the crater were identified using satellite imagery and field observations.
- Sediment texture, surface patterns, and depositional features were examined to infer aeolian transport and deposition.
- Seasonal water accumulation within the crater was analyzed using multi-temporal satellite imagery.
- The crater was treated as a local closed to semi-closed basin to assess water retention and sediment trapping.
- Surface–subsurface interactions were inferred from geomorphic evidence, sediment characteristics, and regional hydroclimatic conditions.
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Fig.3. Field Visit for Soil Sampling and measurement of Luna crater

Fig.4. Image showing Luna crater, Lake and Aerial view

Results

1. **Geomorphological Characteristics of the Luna Impact Crater**
   Geomorphological mapping reveals that the Luna impact crater is expressed as a near-circular to slightly elliptical depression within the low-relief Banni Plains. The crater boundary is clearly identifiable in satellite imagery and DEMs, although rim preservation is spatially variable. The crater rim is discontinuous and subdued, with better preservation along the northern and north-eastern sectors, while the southern and south-western margins show pronounced degradation and breaching.

The crater floor is characterized by a broad, gently sloping surface dominated by fine-grained sediments. No permanent water body is present; however, multi-temporal imagery indicates seasonal ponding during monsoonal periods, followed by desiccation in the dry season. Surrounding geomorphic units include mudflats, shallow playa surfaces, interdunal tracts, and ephemeral drainage channels, highlighting the influence of fluvial and aeolian processes on the crater landscape.

2. **Morphometric Attributes and Crater Degradation**
DEM-based morphometric analysis indicates that the Luna crater has a diameter of approximately 1.5–1.8 km, with relatively low relief compared to fresh impact craters of similar size. The maximum crater depth is modest, reflecting substantial post-impact sediment infilling. Elevation profiles across multiple transects show asymmetric rim heights, with greater rim relief preserved in the north and east and reduced relief toward the south and west.[1]
Slope analysis reveals gentle to moderate slopes along the crater rim and floor, with steeper gradients restricted to localized rim remnants. Curvature maps highlight zones of sediment accumulation within the central crater floor and along breached rim sections. These morphometric characteristics collectively indicate an advanced stage of geomorphic modification and partial masking of primary impact morphology.[2]

3. **Fluvial Processes and Surface Runoff Patterns**
Hydrological analysis derived from DEMs demonstrates that the crater functions as a local sediment and runoff sink within the surrounding plains. Several shallow, ephemeral drainage pathways converge toward the crater interior, particularly from the southern and south-western sectors where rim breaches are evident.[3]
Field observations confirm the presence of sheet wash deposits, shallow rills, and fine-grained flood sediments along these entry zones. During episodic monsoonal rainfall, surface runoff is temporarily impounded within the crater, promoting sediment deposition on the crater floor. The absence of well-defined outlet channels indicates that water loss primarily occurs through evaporation and infiltration rather than surface outflow.[4]

4. **Aeolian Processes and Sediment Redistribution**
Aeolian landforms surrounding the crater include low dunes, sand sheets, and deflation surfaces, reflecting active wind-driven sediment transport during dry periods. Within the crater, aeolian processes contribute to the redistribution of fine sediments across the floor and lower rim slopes.[5]

a. Satellite imagery and field evidence show surface smoothing and infilling associated with wind-blown sediments,particularly in areas with limited vegetation cover. Aeolian deposition is most prominent on the leeward side of the crater, suggesting directional wind influence. These processes play a significant role in reducing topographic expression and obscuring impact-related features over time.[6]

5. **Hydrogeomorphic Behaviour of the Crater Basin**
The Luna crater exhibits hydrogeomorphic characteristics of a closed to semi-closed basin. Seasonal water accumulation is evident during periods of intense rainfall, while prolonged dry conditions lead to rapid desiccation and surface cracking of fine sediments. The repeated alternation between wet and dry phases promotes sediment compaction, redistribution, and surface reworking.[7]
The integration of fluvial inflow and aeolian sediment supply has resulted in progressive crater floor aggradation and stabilization, contributing to long-term reduction in crater relief. This hydrogeomorphic behaviour highlights the efficiency of semi-arid surface processes in modifying young impact landforms.[8]
Integrated Pattern of Quaternary Landscape Modification
The combined results demonstrate that the present-day morphology of the Luna impact crater is the outcome of strong coupling between impact-related initial morphology and subsequent fluvial and aeolian processes. Fluvial activity dominates during short, high-intensity monsoonal events, driving sediment transport and deposition, while aeolian processes operate during extended dry periods to redistribute fine materials and smooth surface relief.[9]

Discussion

1. **Post-Impact Landscape Evolution of the Luna Crater**
The results demonstrate that the present-day morphology of the Luna impact crater is the outcome of sustained post-impact geomorphic modification, rather than preservation of pristine impact features. Although the crater originated as a well-defined circular depression, its current subdued relief and discontinuous rim indicate significant degradation during the Quaternary. Similar patterns of rapid modification have been documented for small and young terrestrial impact craters in sediment-rich environments, where surface processes operate efficiently to reduce topographic expression.
In the semi-arid setting of the Kutch region, episodic fluvial activity associated with monsoonal rainfall emerges as a dominant agent of geomorphic change. Short-duration, high-intensity rainfall events generate surface runoff that is concentrated along shallow flow paths toward the crater interior. These flows promote rim breaching, slope retreat, and transport of fine sediments into the crater basin, accelerating floor aggradation. The absence of a permanent outlet enhances sediment trapping and reinforces the crater's role as a local geomorphic sink.

2. **Role of Aeolian Processes in Crater Modification**
Aeolian processes play a complementary but persistent role in shaping the crater landscape. During prolonged dry periods, wind-driven sediment transport redistributes fine-grained materials across the crater floor and lower rim slopes, contributing to surface smoothing and infilling. The observed association of sand sheets and low dunes with the crater margins indicates that aeolian deposition has progressively masked primary impact features. This interaction between fluvial deposition during wet phases and aeolian reworking during dry phases reflects a **process alternation model**, typical of semi-arid Quaternary landscapes.

3. **Hydrogeomorphic Significance of the Crater Basin**
The Luna crater functions as a closed to semi-closed hydrogeomorphic basin, temporarily storing runoff and sediments during monsoonal events. Seasonal water accumulation enhances fine sediment deposition, followed by desiccation, compaction, and redistribution during dry phases.

Such cyclic wet–dry conditions promote rapid morphological adjustment and reduction in crater depth. This hydrogeomorphic behavior underscores the importance of basin hydrology in governing the rate of crater degradation and preservation potential in low-relief terrains.

4. **Implications for Impact Crater Preservation**
The findings from the Luna crater highlight the vulnerability of small, young impact craters to rapid degradation in semi-arid, sediment-dominated environments. The strong coupling between impact morphology and surface processes suggests that crater preservation is controlled not only by age but also by climatic regime, sediment availability, and hydrological setting. These observations have broader implications for interpreting degraded impact structures on Earth and for understanding analogous features on planetary surfaces where fluvial–aeolian interactions are inferred.

Limitations

Despite the robust integration of remote sensing, DEM analysis, and field observations, the study has certain limitations. The spatial resolution of available DEMs restricts detection of subtle micro-topographic features and small-scale erosion patterns. Limited subsurface data constrain precise quantification of sediment thickness and stratigraphic architecture within the crater floor. In addition, the absence of long-term hydrological monitoring data limits direct assessment of infiltration rates and groundwater interactions. Future studies incorporating high-resolution LiDAR data, sediment coring, geophysical surveys, and chronological techniques would further refine interpretations of post-impact landscape evolution.

Conclusion

This study demonstrates that the Quaternary landscape evolution of the Luna impact crater in the Kutch region of Gujarat is governed by the strong coupling of impact-related morphology with fluvial and aeolian surface processes. The crater exhibits advanced geomorphic modification characterized by rim degradation, sediment infilling, reduced relief, and partial masking of primary impact features. Episodic monsoonal runoff drives sediment transport and basin infilling, while aeolian processes redistribute fine sediments and smooth surface topography during dry periods.

The Luna crater functions as a localized hydrogeomorphic sink within the Banni Plains, where cyclic wet–dry conditions promote rapid morphological adjustment. These findings highlight the efficiency of Quaternary surface processes in modifying young impact structures in semi-arid environments and underscore the importance of integrated geomorphic and hydrological approaches in assessing crater preservation. The conceptual framework developed in this study provides a basis for comparative analysis of terrestrial and planetary impact craters and contributes to a broader understanding of post-impact landscape dynamics.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

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