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Rising Water Levels in Lonar Lake: A Conceptual Framework for Subsurface Hydrology and Cultural Heritage Risk

[1]Arjit Amol More, [2]Rani Amol More,

[1]Swami Vivekanand High School, Mumbai, India
[2]Independent Researcher, Mumbai, India
Correspondence: arjitamolmore@gmail.com

Abstract

Lonar Lake, a rare terrestrial meteorite impact crater formed within the Deccan Trap basalt of central India, represents a unique convergence of geological, hydrological, ecological, and cultural significance. In recent years, the lake has exhibited persistent increases in water level, resulting in periodic inundation affecting culturally significant structures such as the Kamalja Mata Temple within the crater basin. While surface hydrological inputs are often cited as explanatory factors, they may be insufficient to explain the magnitude and persistence of observed lake-level changes. This study presents a hypothesis-driven, interdisciplinary framework to examine potential subsurface controls on the hydrological behaviour of Lonar Lake. Drawing upon established knowledge of impact-modified basaltic geology, fracture-controlled groundwater systems, crater lake hydrology, historical water-management practices, long-term irrigation, and modern hydraulic interventions, a set of interlinked hypotheses is proposed suggesting that Lonar Lake may function as a semi-open hydrological system influenced by regional groundwater connectivity. Rather than advancing definitive conclusions, the study outlines conceptual propositions and methodological pathways to guide future geological, hydrogeological, and archaeological investigations. Understanding these processes is essential for advancing crater-lake hydrology and for informing conservation strategies aimed at safeguarding the cultural heritage and ecological integrity of the Lonar crater system.

Keywords: Kamalja Mata Temple; Lonar Lake; Impact crater hydrology; Deccan Trap basalt; Fracture-controlled groundwater; Subsurface hydrological connectivity; Cultural heritage risk;

1. Introduction

Lonar Lake, located in the Buldhana district of Maharashtra, India, is one of the world's few well-preserved terrestrial impact craters formed in basaltic terrain. Created by a meteorite impact approximately 50,000 years before present, the crater represents a rare natural system where impact geology, fractured hard-rock hydrogeology, unique limnological conditions, and long-standing human interaction intersect.

Beyond its scientific importance, Lonar Lake constitutes a living cultural landscape. For centuries, the lake has supported human settlement and religious continuity, reflected in temples and pilgrimage traditions within the crater basin. Among these, the *Kamalja Mata Temple* remains an active cultural institution situated close to the lake. In recent years, persistent rises in lake water level have resulted in periodic inundation affecting parts of the temple, transforming hydrological change from a purely academic issue into an urgent matter of cultural heritage preservation.

While rainfall and surface runoff are commonly cited as drivers of lake-level change, such explanations may be insufficient to account for the magnitude and persistence of observed increases. Previous studies have documented the impact origin of the crater, the fractured nature of Deccan Trap basalt aquifers, and the complexity of groundwater flow in hard-rock terrains, yet these elements have rarely been integrated within a unified framework for Lonar Lake.

This study addresses this gap by proposing a hypothesis-driven, interdisciplinary framework to investigate potential subsurface controls on Lonar Lake's hydrological behaviour. By formulating testable hypotheses and outlining feasible methodological pathways, the paper aims to guide future research and support evidence-based conservation of this scientifically and culturally significant landscape.

2. Review of Existing Knowledge

2.1. Establishment and Geological Origin of Lonar Lake

Lonar Lake is internationally recognized as a well-preserved terrestrial impact crater formed within the Deccan Trap basaltic province of central India. Geological investigations have established that the lake originated from a meteorite impact approximately 50,000 years before present, resulting in the excavation of a near-circular crater within multiple basalt flows [1–3]. Diagnostic features such as shock metamorphism, brecciation, and high-pressure mineral phases distinguish the Lonar structure from volcanic craters and confirm its impact origin [2,3].

Following crater formation, the depression evolved into a lacustrine system through the accumulation of precipitation, surface runoff, and subsurface inflow. Over geological time, weathering of exposed basalt and sediment deposition modified the crater morphology and hydrological characteristics. While the origin and structural framework of the crater are well established, the post-impact hydrological evolution of the lake remains less clearly constrained, particularly with respect to long-term groundwater interaction.

2.2. Hydrology of Deccan Basalt: Fractures, Vesicles, and Groundwater Movement

The Deccan Traps constitute one of the world's largest basaltic provinces and are characterized hydro-geologically by limited primary porosity, but significant secondary porosity developed through fractures, joints, vesicles, and weathered flow contacts [4,5]. Groundwater occurrence and movement in basaltic terrains are therefore highly heterogeneous and structurally controlled.

Previous studies across the Deccan plateau indicate that vesicular and amygdaloidal basalt horizons often form productive aquifers, while fracture networks facilitate lateral groundwater movement over considerable distances [4–6]. Weathered basalt zones commonly function as recharge and transmission layers, linking shallow and deeper groundwater systems. As a result, groundwater flow in basaltic regions rarely follows uniform patterns and is instead governed by lithological contrasts, structural discontinuities, and hydraulic gradients.

Given that Lonar Lake is embedded within this fractured basaltic framework, its hydrological behaviour must be interpreted in relation to the surrounding aquifer system rather than as an isolated surface water body.

2.3. Crater Lakes and Groundwater Interaction: Open versus Closed Systems

Crater lakes have traditionally been classified as closed systems dominated by precipitation evaporation balance or as open or semi-open systems influenced by groundwater inflow and outflow [7]. Recent hydrological research increasingly recognizes that many crater lakes, particularly those developed in fractured volcanic or impact modified substrates, exhibit varying degrees of subsurface connectivity.

Studies of crater lakes worldwide demonstrate that apparent surface isolation does not necessarily imply hydrological closure. Groundwater seepage through crater walls or floors, pressure-driven inflows, and fracture-controlled pathways may contribute significantly to lake water balance [6–8]. In basalt-hosted crater systems, impact-related fracturing and post-impact weathering further enhance the potential for subsurface water exchange.

Within this framework, Lonar Lake represents a system in which surface hydrological inputs alone may be insufficient to explain long-term water-level behaviour, particularly considering observed recent changes.

2.4. Ancient Indian Water Management Systems and Groundwater Context

Archaeological and historical studies across the Indian subcontinent document a long tradition of engineered water management, particularly in semi-arid and hard-rock regions [10]. Ancient settlements commonly employed reservoirs, tanks, stepwells, and interconnected surface-subsurface harvesting systems designed to regulate seasonal water availability and enhance groundwater recharge.

These systems frequently utilized natural fractures, depressions, and lithological boundaries within hard-rock terrains, allowing stored surface water to percolate into underlying aquifers [111]. Importantly, several studies note that subsurface components of such systems may continue to influence local groundwater regimes long after surface structures have degraded or fallen out of use.

This broader context highlights the relevance of considering legacy hydrological modification when interpreting present-day groundwater behaviour in regions with extended histories of human settlement.

2.5. Contextual Note on Bhon, Reservoirs, and Possible Hydrological Linkages

Historical accounts and regional traditions indicate that Bhon (Ancient Site) was an established ancient settlement within the same broader district as Lonar, with organized water reservoirs characteristic of early Indian urban water management [9]. Ancient settlements in basaltic and semi-arid regions commonly relied on integrated surface and subsurface water systems to ensure sustained supply. Within this context, it is conceptually plausible that reservoir structures associated with Bhon may have been hydrologically linked directly or indirectly to regional groundwater pathways feeding the Lonar Dhar through fracture-controlled basalt aquifers. Furthermore, the construction of a modern irrigation system in the vicinity of the Bhon area may have modified pre-existing groundwater gradients, potentially influencing subsurface flow patterns toward the Lonar basin.

This proposed linkage is presented here strictly as a contextual possibility intended to inform future hydrogeological and archaeological investigation rather than to assert a confirmed connection.

2.6. Historical, Mythological, and Ecological Significance of Lonar Lake

Beyond its geological and hydrological uniqueness, Lonar Lake occupies a prominent place in the historical memory, mythological traditions, and ecological landscape of the region. These dimensions provide important context for understanding why hydrological changes at Lonar warrant sustained scientific and conservation attention.

2.6.1. Historical and Cultural Significance

Lonar Lake has long functioned as a culturally significant water-associated landscape, where natural hydrological stability shaped patterns of settlement, ritual practice, and community life. Archaeological remnants, temples, and enduring pilgrimage traditions within and around the crater basin attest to sustained human engagement with the lake over centuries [9,12]. Such continuity indicates that Lonar Lake has historically been perceived not merely as a geological feature, but as a dependable and meaningful source of water within a hard-rock and semi-arid environment.

Within this cultural landscape, the *Kamalja Mata Temple* occupies a position of exceptional importance. The temple remains an active site of worship and represents a living cultural institution embedded within the crater environment. Its location within proximity to the lake underscores the historical interdependence between sacred architecture and water bodies, a relationship commonly observed in traditional Indian landscapes where water availability underpinned both spiritual and daily life.

Historical context further reinforces this relationship. During the early historic period, particularly under the *Mauryan Empire* following consolidation by *Samrat Ashoka,* central India including the broader Vidarbha–Berar region served as an important zone of administrative movement and trade connectivity linking northern and southern parts of the subcontinent [9]. In such settings, reliable water sources were essential for sustaining settlements, movement corridors, and cultural institutions. Lonar Lake thus formed part of a wider water-dependent landscape that supported long-term settlement continuity.

In recent years, however, this long-standing equilibrium has been disrupted. Rising lake water levels have resulted in periodic inundation affecting parts of the *Kamalja Mata Temple,* particularly during high-water episodes. This development marks a critical shift: hydrological change is no longer an abstract or distant process, but one that directly threatens a living heritage structure. The encroachment of lake water onto temple precincts highlights the vulnerability of culturally significant sites to changing subsurface and surface hydrological regimes.

Figure 1: *Kamalja Mata Temple within the Lonar crater complex, illustrating its historical significance and increasing exposure to inundation during periods of elevated lake water levels.*

This situation places the *Kamalja Mata Temple* at the center of the present investigation. Understanding the drivers of rising water levels at Lonar Lake is therefore essential not only for advancing geological and hydrological knowledge, but also for informing conservation strategies aimed at safeguarding a sacred and historically continuous cultural institution. The increasing interaction between lake hydrology and temple infrastructure provides a compelling and urgent rationale for the hypothesis-driven framework developed in this study.

2.6.2. Mythological Context and Cultural Narratives

Lonar Lake is deeply embedded in regional mythological traditions, most notably the narrative of the demon Lonasura, whose defeat is believed to have given rise to the crater and the name “Lonar” [9]. Such mythological interpretations represent an enduring cultural response to an unusual geological feature, integrating natural phenomena into religious and narrative frameworks.

These stories have contributed to the continued cultural relevance of the lake, reinforcing its status as a sacred landscape rather than a purely physical or scientific entity. The persistence of these narratives reflects the long-standing relationship between the lake and surrounding communities, strengthening the case for preserving both its physical integrity and cultural meaning.

2.6.3. Ecological and Wildlife Importance

Lonar Lake supports a unique and sensitive ecosystem shaped by its alkaline and saline water chemistry. The lake hosts specialized microbial communities, including alkaliphilic and extremophilic microorganisms, which play a significant role in biogeochemical cycling within the crater environment [13].

The crater slopes and surrounding forested areas provide habitat for a range of flora and fauna, including resident and migratory bird species that depend on the lake and its margins for feeding and nesting [14].

Variations in water level influence shoreline habitats, vegetation patterns, and nutrient availability, thereby affecting ecological balance within the crater system. Given its ecological sensitivity, changes in the hydrological regime of Lonar Lake have implications not only for water balance but also for biodiversity conservation and habitat stability.

2.6.4. Conservation Relevance

Taken together, the historical, mythological, and ecological dimensions of Lonar Lake establish it as a multi-value landscape, where geological processes, cultural heritage, and biodiversity intersect. Understanding the drivers of rising water levels is therefore essential not only from a scientific perspective but also for safeguarding cultural heritage sites and maintaining ecological integrity within the crater system.

2.7. Synthesis and Identified Knowledge Gap

The reviewed literature establishes Lonar Lake as a site of exceptional scientific, cultural, and ecological significance. Its origin as a meteorite impact crater within Deccan Trap basalt is well documented, and existing studies have clearly identified the structural and hydrogeological characteristics of basaltic terrains that enable complex groundwater movement through fractures, vesicles, and weathered horizons. Research on crater lakes further demonstrates that such systems may function as closed, semi-open, or open hydrological basins depending on subsurface connectivity, particularly in fractured volcanic or impact-modified substrates.

Parallel bodies of knowledge highlight the long history of engineered water management in the Indian subcontinent, where reservoirs, stepwells, and infiltration systems were designed to interact with hard-rock geology and groundwater systems. Contextual historical accounts suggest that ancient settlements such as Bhon may have possessed organized reservoir systems, raising the possibility of legacy hydrological modifications within the broader regional aquifer framework. Additionally, modern interventions, including dam construction and long-term irrigation practices, are known to alter groundwater gradients and recharge dynamics in basaltic regions.

At the same time, Lonar Lake is recognized as a living heritage and ecological landscape. Its mythological associations, the presence of culturally significant structures such as the *Kamalja Mata Temple,* and its role as a habitat for specialized microbial communities and avifauna underscore that changes in lake water levels have implications extending beyond geology and hydrology alone. The recent and recurring inundation of parts of the *Kamalja Mata Temple* highlights the urgency of understanding ongoing hydrological changes from both conservation and management perspectives.

Despite this extensive body of knowledge, a critical gap remains. Most existing studies examine Lonar Lake through discipline-specific approaches, focusing separately on impact geology, geochemistry, ecology, archaeology, or cultural history. There is limited integrative research that simultaneously considers;

i. impact-modified basaltic structure,
ii. fracture-controlled groundwater flow,
iii. legacy effects of ancient water management systems,
iv. long-term irrigation-driven recharge, and
v. recent hydraulic interventions explaining contemporary changes in lake water levels.

Furthermore, while surface hydrological inputs such as rainfall and runoff are commonly emphasized, the potential role of subsurface groundwater connectivity and flow modification remains insufficiently explored in a unified framework. The absence of a consolidated conceptual model constrains the ability to distinguish between short-term climatic influences and long-term subsurface reorganization as drivers of rising water levels.

This synthesis highlights the need for a hypothesis-driven, interdisciplinary framework that integrates geological, hydrological, archaeological, ecological, and cultural perspectives. Addressing this gap is essential for advancing scientific understanding of Lonar Lake's hydrological behaviour and for informing conservation strategies aimed at protecting its cultural heritage, ecological integrity, and long-term sustainability. The hypotheses presented in the following section are developed in direct response to this identified gap.

3. Hypothesis Framework

Building upon the established geological, hydrological, and contextual background outlined in the previous section, this study proposes a set of interlinked hypotheses to explain the observed hydrological behaviour of Lonar Lake. These hypotheses are not presented as confirmed explanations but as conceptual propositions intended to guide future interdisciplinary research.

3.1. Hypothesis I: Lonar Lake as a Semi Open Subsurface Hydrological System

Proposition

Lonar Lake may function as a semi-open hydrological system, receiving sustained subsurface groundwater inflow in addition to surface inputs such as precipitation and runoff.

Rationale

The crater is hosted within fractured Deccan basalt, a geological setting known for structurally controlled groundwater movement. The presence of freshwater springs and wells near a saline lake suggests ongoing interaction between the lake and surrounding aquifers. Such conditions are consistent with crater lakes elsewhere that exhibit partial hydrological openness through subsurface pathways.

Hypothesis Statement

"Lonar Lake receives continuous or episodic groundwater inflow through fracture-controlled basaltic aquifers, contributing to its long-term water balance."

3.2. Hypothesis II: Impact-Modified Basalt as a Preferential Groundwater Conduit

Proposition

The meteorite impact that formed the Lonar crater significantly modified the physical properties of the underlying basalt, enhancing its capacity to transmit groundwater.

Rationale

Impact processes are known to generate brecciation, micro-fracturing, and structural weakening within target rocks. Over time, weathering of these zones may further increase permeability relative to surrounding, unshocked basalt. Such impact-modified zones may act as preferential conduits for groundwater flow toward the crater basin.

Hypothesis Statement

"Impact-induced fracturing and subsequent weathering of Deccan basalt beneath Lonar have created zones of enhanced permeability that facilitate subsurface groundwater movement toward the crater."

3.3. Hypothesis III: Lonar Dhar as an Expression of a Deeper Aquifer System

Proposition

The feature commonly referred to as the Lonar Dhar may represent a pressure-driven discharge from a deeper, integrated groundwater system rather than a purely local surface phenomenon.

Rationale

The persistence and discharge characteristics of Lonar Dhar suggest a source beyond shallow surface runoff. In fractured basaltic terrains, similar features are often associated with confined or semi-confined aquifers releasing water along structural weaknesses or topographic breaks.

Hypothesis Statement

"Lonar Dhar and the groundwater beneath Lonar Lake are surface

expressions of a connected subsurface aquifer system operating under regional hydraulic gradients."

3.4. Hypothesis IV: Influence of Historical Water Reservoirs on Subsurface Flow

Proposition

Historical water-management structures within the broader Lonar region may have contributed to long-term modification of subsurface groundwater pathways.

Rationale

Ancient reservoirs and water-harvesting systems were often designed to promote infiltration and groundwater storage, particularly in hard-rock terrains. Even where surface features are degraded, subsurface components such as foundations, channels, and recharge zones may persist and influence groundwater movement over extended periods.

Hypothesis Statement

"Legacy water-management structures may continue to influence groundwater storage and flow patterns within the Lonar basin through enduring subsurface modifications."

3.5. Hypothesis V: Role of Long-Term Irrigation in Groundwater Recharge

Proposition

Sustained irrigation practices in the surrounding agricultural landscape may have increased groundwater recharge toward the Lonar basin over time.

Rationale

Irrigation is known to enhance deep percolation and raise groundwater levels, particularly in basaltic terrains where fractures facilitate downward movement of water. Over multiple decades, such recharge may alter natural hydraulic gradients, directing groundwater toward structurally low basins such as impact craters.

Hypothesis Statement

"Anthropogenic recharge associated with long-term irrigation has contributed to increased subsurface inflow toward Lonar Lake."

3.6. **Hypothesis VI:** Modification of Subsurface Flow by Modern Hydraulic Structures

Proposition

The construction of modern hydraulic infrastructure, including dams in the surrounding region, may have altered pre-existing groundwater flow regimes.

Rationale

Dams and water-retention structures can modify both surface and subsurface hydrological processes by changing pressure conditions and recharge patterns. In fractured basaltic settings, such modifications may propagate laterally, potentially redirecting groundwater toward adjacent basins.

Hypothesis Statement

"Modern hydraulic structures have modified regional groundwater gradients, potentially enhancing groundwater accumulation within the Lonar crater system."

3.7. Integrated Hypothesis and Interpretation

Taken together, these hypotheses suggest that the recent hydrological behaviour of Lonar Lake may reflect the cumulative influence of:

- Impact-modified basaltic geology
- Natural fracture-controlled ground water systems
- Long-term irrigation-driven recharge
- Modern hydraulic interventions

Rather than being governed solely by short-term climatic variability, Lonar Lake may function as a terminal accumulation zone within a dynamically evolving subsurface hydrological network.

These processes, if validated, have direct implications for the conservation of culturally significant structures such as *the Kamalja Mata Temple* and for the ecological stability of the Lonar crater system.

Boundary Statement

"All hypotheses presented in this section are conceptual and intended to guide future geological, hydrological, and archaeological investigations. No individual hypothesis is presented as a verified explanation."

The conceptual relationships among geological structure, subsurface groundwater flow, and anthropogenic influences proposed in this section are illustrated in Figure 1.

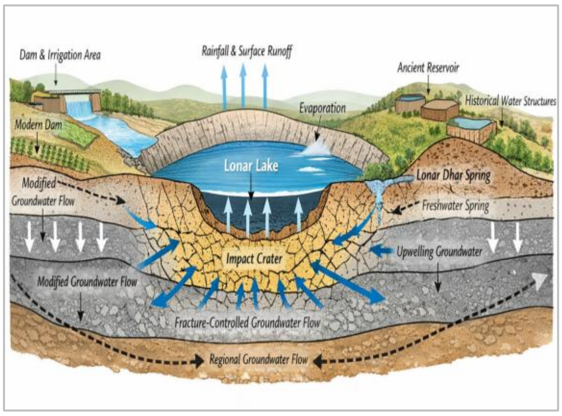

***Figure 1.**: Conceptual Model of Subsurface Hydrological Connectivity in the Lonar Crater System (AI generated & not to scale).*

Figure 1 presents a conceptual cross-sectional model of the Lonar crater and its surrounding geological setting. The model illustrates the meteorite impact structure excavated within layered Deccan basalt flows, highlighting zones of enhanced fracturing and brecciation generated during impact and subsequent geological processes. These impact-modified zones are hypothesised to exhibit higher permeability relative to surrounding unshocked basalt, thereby facilitating preferential subsurface groundwater movement toward the crater basin.

The model depicts groundwater flow paths guided by fractures, joints, and weathered flow contacts within the basalt, contributing to subsurface inflow into Lonar Lake. Freshwater springs and the feature commonly referred to as Lonar Dhar are represented as pressure-driven discharge points emerging along structural or topographic weaknesses. The lake itself is conceptualised as a semi-open hydrological system receiving water from both surface inputs and subsurface sources.

Historical water-management structures are shown schematically as zones of enhanced infiltration and subsurface storage, reflecting the potential long-term influence of ancient reservoirs on groundwater pathways. Additionally, modern hydraulic interventions such as dams and irrigation infrastructure are represented as modifiers of regional hydraulic gradients, with the potential to alter recharge rates and redirect subsurface flow toward the crater.

This conceptual model integrates geological, hydrological, and anthropogenic elements to illustrate how cumulative subsurface reorganisation may influence present-day lake-level behaviour. The figure is intended solely as a hypothesis-guiding framework to support future geological, hydrogeological, and archaeological investigations, rather than as a definitive representation of subsurface conditions.

4. Methodological Framework for Testing the Proposed Hypotheses

The hypotheses proposed in this study are conceptual and interdisciplinary in nature, requiring an integrated methodological approach combining geological, hydrological, geophysical, and archaeological tools. This section outlines feasible and established methods through which the proposed hypotheses related to Lonar Lake can be systematically tested in future research.

4.1. Hydrogeological Investigations

To evaluate subsurface connectivity and groundwater inflow to the Lonar basin (Hypotheses I and V), detailed hydrogeological investigations are required.

Key approaches include:

- Mapping of groundwater levels in wells surrounding the crater to identify hydraulic gradients
- Seasonal monitoring of lake water levels in relation to regional groundwater fluctuations
- Analysis of spring discharge characteristics, including Lonar Dhar, to assess continuity and pressure-driven flow

Such investigations would help determine whether Lonar Lake behaves as a closed surface basin or as a semi-open system influenced by regional groundwater dynamics.

4.2. Geophysical Surveys

Non-invasive geophysical techniques offer critical tools for investigating subsurface structure without excavation, particularly within protected or sensitive landscapes.

Recommended methods include:

- Electrical Resistivity Tomography (ERT) to delineate saturated zones, fracture networks, and potential flow barriers
- Ground-Penetrating Radar (GPR) for shallow subsurface imaging of structural discontinuities and possible anthropogenic features
- Seismic refraction surveys to identify depth to bedrock, fractured zones, and impact-modified basalt layers

These techniques are particularly suited to testing Hypotheses II and III concerning impact-modified basalt and subsurface flow pathways.

4.3. Hydro-chemical and Isotopic Analysis

Hydro-chemical characterization provides insight into the origin, residence time, and connectivity of water sources.

Suggested analyses include:

- Comparative chemical profiling of lake water, springs, wells, and Lonar Dhar discharge
- Stable isotope analysis ($\delta^{18}O$ and $\delta^{2}H$) to distinguish between meteoric water, evaporated lake water, and groundwater sources
- Tracer-based studies to assess flow paths and recharge zones

Such methods are essential for verifying whether surface and subsurface waters share a common origin or represent distinct hydrological systems.

4.4. Integrated Archaeological and Geo-archaeological Assessment

To assess the influence of historical water-management structures (Hypothesis IV), a geoarchaeological approach is recommended.

This may include:

- Review of archaeological records, historical maps, and regional surveys
- Surface reconnaissance and shallow subsurface probing in non-protected zones
- Integration of archaeological findings with hydrogeological data to evaluate legacy hydrological modification

Importantly, this approach emphasizes documentation and correlation, not excavation-driven proof, aligning with conservation-sensitive research standards.

4.5. Assessment of Irrigation and Modern Hydraulic Infrastructure

The role of long-term irrigation and modern hydraulic structures (Hypotheses V and VI) can be evaluated through a combination of spatial and temporal analysis.

Recommended approaches include:

- Analysis of historical irrigation expansion using satellite imagery and land-use records
- Mapping of dams, canals, and recharge structures in the broader Lonar region
- Correlation of infrastructure development timelines with observed groundwater and lake-level changes

Such analyses would clarify whether anthropogenic interventions have measurably altered subsurface flow regimes toward the Lonar basin.

4.6. Integrated Conceptual and Numerical Modelling

An integrated modelling framework can synthesize geological, hydrological, and anthropogenic data to test the internal consistency of the proposed hypotheses.

This may involve:

- Development of a conceptual groundwater flow model incorporating crater geometry and basalt stratigraphy
- Scenario-based simulations to assess the impact of altered recharge and flow impedance
- Sensitivity analysis to identify dominant controls on lake water balance

While detailed numerical modelling may require extensive data, even simplified models can provide valuable insights into system behaviour and research priorities.

4.7. Research Ethics and Limitations

All proposed methods emphasize non-invasive and ethically responsible investigation. The Lonar region includes environmentally and culturally sensitive zones; therefore, future research should prioritize minimal disturbance and regulatory compliance.

Limitations of the proposed methodology include data availability, access constraints, and the inherent uncertainty associated with subsurface systems. Nonetheless, triangulation across multiple methods can significantly improve interpretive confidence.

Summary

This methodological framework demonstrates that the hypotheses proposed in this study are empirically testable using established scientific tools. By outlining clear pathways for investigation, this section positions the paper as a guide for future research rather than a source of definitive conclusions.

5. Discussion

The hypotheses proposed in this study collectively suggest that the recent hydrological behaviour of Lonar Lake may be governed by subsurface processes operating over geological and anthropogenic timescales rather than by surface hydrological inputs alone. This perspective offers an alternative to rainfall-centric explanations and situates the lake within a broader, dynamically evolving groundwater system.

The interpretation of Lonar Lake as a semi-open hydrological system implies that groundwater inflow may play a sustained role in regulating lake water levels. If validated, this would explain the persistence of elevated water levels even during periods that do not correspond directly with extreme precipitation events. Such behaviour is consistent with crater lakes hosted in fractured volcanic or impact-modified substrates, where subsurface connectivity can buffer short-term climatic variability.

The role of impact-modified basalt as a preferential groundwater conduit further emphasizes the importance of geological inheritance in shaping present-day hydrology. Meteorite-induced fracturing and brecciation may have permanently altered permeability patterns beneath the crater, creating subsurface pathways that continue to influence groundwater movement long after crater formation. This interpretation highlights how ancient geological events can exert lasting control over modern hydrological systems.

The conceptualization of Lonar Dhar as an expression of a deeper, pressure-driven aquifer system integrates surface observations with subsurface processes. Rather than being treated as an isolated or local feature, Lonar Dhar may represent a discharge point within a regionally connected groundwater network. This view strengthens the argument for examining lake-level change in relation to subsurface flow regimes rather than surface runoff alone.

Anthropogenic influences emerge as potentially significant modifiers of this natural system. Legacy effects of historical water-management practices may have altered subsurface storage and flow patterns in ways that persist today, even where surface structures are no longer prominent. More recently, sustained irrigation and the construction of modern hydraulic infrastructure may have further modified groundwater gradients, enhanced recharge and redirecting subsurface flow toward the structurally low Lonar basin. These influences, acting cumulatively, could contribute to progressive water accumulation within the crater.

Importantly, the proposed framework does not suggest a single dominant driver but rather a convergence of geological structure, groundwater dynamics, and human intervention. This integrated interpretation aligns with the complexity typically observed in hard-rock aquifer systems, where multiple interacting controls shape hydrological outcomes.

From a broader perspective, the implications of these interpretations extend beyond scientific understanding. If subsurface groundwater processes are indeed central to rising water levels, management strategies focused solely on surface inflows may prove insufficient. Improved understanding of subsurface connectivity would be critical for mitigating risks to culturally significant structures such as the *Kamalja Mata Temple* and for maintaining ecological balance within the crater ecosystem.

Overall, this discussion underscores the value of a hypothesis-driven, interdisciplinary approach. While the proposed interpretations require empirical validation, they provide a coherent framework for future investigations aimed at resolving the drivers of hydrological change at Lonar Lake and at informing evidence-based conservation and management efforts.

6. Conclusion

This study develops a hypothesis-driven conceptual framework to examine the rising water levels of Lonar Lake, emphasizing the role of subsurface hydrological processes operating within impact-modified Deccan basalt. By integrating geological structure, fracture-controlled groundwater flow, historical water-management practices, long-term irrigation, and modern hydraulic interventions, the framework suggests that Lonar Lake may function as a semi-open hydrological system influenced by regional groundwater connectivity.

Rather than proposing a single causal mechanism, the study highlights the likelihood of cumulative and interacting controls acting across different temporal scales. The outlined hypotheses and methodological pathways are intended to guide future interdisciplinary investigations aimed at empirically testing subsurface hydrological connectivity and its influence on lake-level behaviour.

Understanding these processes has implications beyond scientific inquiry, particularly for the conservation of culturally significant structures such as the *Kamalja Mata Temple* and for maintaining ecological stability within the crater system. The proposed framework provides a foundation for informed research, conservation planning, and sustainable management of this scientifically and culturally important landscape, with relevance to similar impact craters and hard-rock basins elsewhere.

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