Jambura Geo Education Journal
Volume 7 Number 1, March 2026, 58-69
DOI: https://doi.org/10.37905/jgej.v7i1.34164

Safeguarding Historical Heritage Amid Environmental and Human-Induced Threats: A Spatial Risk Management Study of the Muaro Jambi Temple Compound

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ARTICLE INFO

Article History:
Received: 2025-08-29
Accepted: 2025-12-26
Published: 2026-03-30

Keywords:
heritage conservation;
hiradc;
muaro jambi temple compound;
risk management;

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DOI: 10.37905/jgej.v7i1.34164

ABSTRACT

The Muaro Jambi Temple Compound, recognized as one of the most extensive cultural heritage sites in Southeast Asia, faces numerous threats stemming from both natural phenomena and anthropogenic activities. This study aims to systematically identify and assess potential risks, determine their severity and probability, and propose effective risk management strategies to support the site's long-term conservation. Utilizing the HIRADC (Hazard Identification, Risk Assessment, and Determining Control) framework, the research adopts a mixed-methods approach, combining qualitative and quantitative analyses supported by Geographic Information Systems (GIS) and SPSS-based statistical tools. The findings highlight five major risks: coal dust pollution, climate-induced flooding, artifact theft, vandalism, and inadequate conservation funding. Among these, coal dust pollution is identified as the most critical threat due to its high frequency and substantial impact on both the structural integrity of the temple complex and surrounding community health. The study proposes mitigation strategies including strengthened industrial regulations, improved drainage infrastructure, and active community engagement in heritage preservation efforts. This research underscores the necessity of an integrated and collaborative risk management approach to safeguard cultural heritage assets like the Muaro Jambi Temple Compound in the face of escalating environmental and socio-economic pressures.

How to cite: Gunawan, H., Yulistian, S., & Cahaya, C. (2026). Safeguarding Historical Heritage Amid Environmental and Human-Induced Threats: A Spatial Risk Management Study of the Muaro Jambi Temple Compound. *Jambura Geo Education Journal*, *7*(1), 58–69. https://doi.org/10.37905/jgej.v7i1.34164

1. Introduction

The perspective on cultural heritage preservation has undergone significant transformation in recent decades (Jigyasu & Chmutina, 2023; Aplin, 2002). While earlier conservation efforts largely emphasized the physical integrity of architectural structures, current approaches increasingly address broader heritage landscapes, including their ecological settings and socio-economic interactions (Durrant et al., 2023). This development reflects a more comprehensive paradigm in responding to the complex dynamics of heritage conservation, especially amid accelerating modernization and development pressures (Permanasari, 2021; Rössler & Lin, 2018). Globally, heritage sites face similar challenges. UNESCO reports that more than 60% of World Heritage Sites are now exposed to high levels of threat, while ICOMOS highlights pollution, extreme flooding, and unregulated economic activities as major sources of degradation (Falk & Hagsten, 2023; Labadi et al., 2021). These global trends demonstrate that the vulnerability of heritage sites is no longer a localized issue but a universal concern that requires systematic risk management approaches.

Cultural heritage sites experiencing structural degradation, material weathering, or the loss of essential elements face increasingly complex challenges in ensuring long-term preservation (Arifin, 2018). Empirical evidence worldwide illustrates this growing vulnerability. For example, Angkor Wat has undergone accelerated erosion due to extreme rainfall events (Unesco, 2023; Chen et al., 2019), Petra has been repeatedly threatened by seasonal flash floods (Al Kuisi et al., 2024; Yin, 2025), and Machu Picchu has suffered structural stress from overtourism and transport-induced vibrations (Larson, 2012; UNESCO, 2025). These cases underscore that heritage degradation is a tangible and measurable phenomenon affecting sites at a global scale.

Given these escalating threats, numerous studies have emphasized the importance of risk-based approaches in heritage management. However, existing works exhibit several limitations. Durrant et al., (2023) explored disaster risks for European World Heritage Sites but focused primarily on physical hazards without integrating socio-environmental dimensions. Alshweiky & Zeynep Gül Ünal, (2016) examined risks in multi-identity heritage sites but did not incorporate spatial modeling tools. Meanwhile, GIS-based analyses often focus solely on environmental hazards without addressing the socio-cultural vulnerabilities that shape heritage risk profiles (Graham et al., 2016). These shortcomings reveal a clear research gap: the need for an integrative, multi-dimensional, and spatially informed risk assessment framework tailored for cultural heritage preservation.

Within this context, the HIRADC (Hazard Identification, Risk Assessment, and Determining Control) framework offers a systematic method for assessing multi-layered risk by combining analyses of hazards, vulnerabilities, and capacities. Although HIRADC has been applied effectively in industrial and environmental risk assessments (Rotinsulu et al., 2023), its application in cultural heritage contexts remains highly limited. Therefore, the use of HIRADC in this study is not a replication of previous work but an expansion of its methodological potential, especially when combined with spatial analysis and quantitative techniques. Integrating HIRADC with GIS and SPSS-based statistical analysis enables more comprehensive mapping of risk levels across different zones, providing both qualitative and quantitative insights that previous studies have not sufficiently addressed. The current state of the art in heritage risk management is moving toward the integration of spatial technologies, environmental data, and socio-cultural assessments (Jigyasu & Chmutina, 2023). Yet most existing studies examine these components separately, resulting in fragmented understandings of heritage risk. This study advances the field by offering a holistic risk assessment model that synthesizes spatial, environmental, and socio-economic parameters. Such an integrative approach is essential for developing targeted, evidence-based conservation policies that reflect the multifaceted challenges faced by heritage sites today.

The novelty of this research is threefold. First, it represents the first application of the HIRADC framework to the Muaro Jambi Temple Compound, one of the largest archaeological complexes in Southeast Asia. Second, it integrates HIRADC, GIS, and SPSS to generate spatially explicit and quantitatively robust risk assessments. Third, it develops a three-dimensional classification of risk environmental, structural, and socio-economic and formulates multi-tiered mitigation strategies that incorporate technical, ecological, and community-based perspectives. These contributions not only fill existing methodological gaps but also offer a replicable model for heritage risk management in other vulnerable cultural sites.

2. Method

2.1. Research Design

This study employed a mixed-methods design that integrates spatial analysis, qualitative assessment, and quantitative risk evaluation. Such a design is widely recommended in contemporary cultural heritage risk studies because heritage vulnerability is influenced simultaneously by environmental, structural, and socio-economic factors (Jigyasu & Chmutina, 2023; Durrant et al., 2023). The HIRADC (Hazard Identification, Risk Assessment, and Determining Control) framework was selected as the core analytical tool because of its systematic and replicable procedure for identifying hazards, assessing vulnerabilities, and evaluating management capacity (Rotinsulu et al., 2023).

2.2. Data Types and Selection

Two types of data were used: spatial and non-spatial. Data selection followed the principle of relevance to the three major components of HIRADC hazard, vulnerability, and capacity. Spatial data, processed through GIS, included: Digital Elevation Model (DEM) for flood and topographical analysis; Land cover and vegetation maps to assess environmental conditions and anthropogenic pressures; Hydrology layers to identify drainage systems and erosion-prone zones; GPS hazard points collected during fieldwork to geolocate observed threats. Spatial datasets were obtained from the Indonesian Geospatial Information Agency (BIG), satellite imagery, and direct field measurements. Such spatial data are commonly used to map heritage risk patterns and landscape dynamics (Musyawarah et al, 2020;

Graham et al., 2016). Non-spatial data consisted of: Field observation notes and photographs; Semi-structured interviews with heritage managers, communities, and local authorities; Conservation reports from BPCB Jambi; HIRADC scoring sheets for quantitative classification. These datasets were selected because they collectively represent physical conditions, environmental processes, and socio-cultural interactions factors recognized as critical in cultural heritage vulnerability assessment (Aplin, 2002; Permanasari, 2021).

2.3. Data Collection Procedures

Data collection followed four structured stages to ensure replicability: Stage 1 Preliminary Review: A review of conservation reports, historical documentation, and prior studies was conducted to identify initial hazard indicators and understand the site's management context; Stage 2 Field Survey: Systematic field observations were carried out across major clusters of the Muaro Jambi Temple Compound. Structural conditions, vegetation encroachment, signs of vandalism, flooding traces, and erosion were recorded. GPS points and photographic documentation were collected to spatially reference each hazard. Stage 3 Interviews: Semi-structured interviews with heritage stakeholders, including local residents and site managers, were conducted to obtain information on socio-economic pressures, community engagement, and site management capacity. This approach is consistent with qualitative methods in heritage risk studies (Alshweiky & Zeynep Gül Ünal, 2016). Stage 4 Triangulation: Field findings, interview data, and documentary evidence were cross-checked to ensure data consistency and reduce observational bias. These stages were chosen because triangulated methods strengthen the reliability of risk assessment and reflect real on-site conditions (Khalid et al., 2021).

Qualitative data in this study were obtained through semi-structured interviews conducted with key stakeholders directly involved in the management, preservation, and daily interaction with the Muaro Jambi Temple Compound. A total of twelve (12) informants were selected using purposive sampling to ensure that the data reflected diverse perspectives relevant to heritage risk conditions. The informants included site managers from the Cultural Heritage Preservation Office (BPCB Jambi), local government officials, security personnel, community leaders, and residents living in close proximity to the temple area. These informants were selected based on their roles, experience, and direct engagement with heritage conservation activities, site monitoring, and community–heritage interactions.

The interviews aimed to capture qualitative insights into perceived risks, management challenges, human-induced threats, and local responses to environmental pressures affecting the temple complex. Semi-structured interviews were chosen to allow flexibility in exploring site-specific issues while maintaining consistency across informants. The qualitative data generated from these interviews were used to complement spatial and quantitative analyses, particularly in interpreting socio-economic risks, management capacity, and human behavior patterns that cannot be fully explained through numerical data alone.

Table 1. Explains that Profile of Interview Informants

Informant Category	Number of Informants	Role in Heritage Context	Experience / Age Range
Heritage site managers (BPCB Jambi)	3	Site conservation, monitoring, and management	>10 years
Local government officials	2	Policy and regional cultural management	5–15 years
Site security personnel	2	Daily site supervision and security	3–10 years
Community leaders	3	Community coordination and local engagement	30–55 years
Local residents	2	Daily interaction with heritage area	25–50 years
Total	**12**		

The informants listed in Table 1 were deliberately selected to represent diverse stakeholder roles related to hazard exposure, site vulnerability, and management capacity within the HIRADC framework. Their combined perspectives provide qualitative insights into environmental pressures, structural conditions, and socio-economic dynamics influencing risk levels across the Muaro Jambi Temple Compound, thereby strengthening the triangulation and validity of the risk assessment.

2.4. Risk Identification and Analysis Using HIRADC

Risk identification was conducted by integrating spatial datasets with field observations to classify environmental, structural, and socio-economic hazards. This approach is aligned with international frameworks emphasizing multi-hazard assessment in heritage environments (Jigyasu & Chmutina, 2023; Chartres et al., 2019; Aulia & Qurtubi, 2019). Hazard identification utilized DEM, land cover, hydrology layers, and GPS points to locate threats such as flooding zones, erosion-prone areas, vegetation overgrowth, coal dust exposure, and human disturbances. Vulnerability assessment evaluated exposure and sensitivity based on structural condition, location relative to hazard sources, landscape characteristics, and community interactions. This follows the perspective that heritage vulnerability is contextual and site-specific (Durrant et al., 2023). Capacity assessment examined management readiness through interview data, institutional documentation, availability of monitoring systems, and accessibility of each temple unit. High capacity can significantly reduce overall risk even in high-hazard environments, as emphasized by UNESCO and ICOMOS (Falk & Hagsten, 2023). Each stage was included because understanding heritage risk requires evaluating not only the presence of hazards but also how exposed the site is and how capable local stakeholders are in mitigating them.

2.5. Data Processing and Visualization

Spatial and non-spatial data were processed using complementary analytical techniques. GIS Processing: DEM, land cover, hydrology, and hazard points were integrated in ArcGIS to generate thematic layers (elevation, slope, land use, hazard distribution). GIS allowed visualization of spatial patterns of risk and identification of high-priority zones. GIS-based mapping is widely used in heritage conservation because it supports spatially explicit decision-making (Kennedy M, 2009; Bahaire, 1999). Statistical Processing (SPSS): HIRADC scores for hazard, vulnerability, and capacity were analyzed using SPSS to test scoring consistency. Statistical validation minimizes subjectivity in qualitative assessments and strengthens analytical rigor (Rahardja, 2023). Integrating GIS with statistical analysis was essential for producing risk classifications that are both spatially grounded and quantitatively verifiable.

The integration of ArcGIS in this study served a critical analytical purpose rather than a purely visual function. Spatial analysis was employed to transform field-based observations into interpretable spatial patterns. Specifically, hazard points collected through GPS surveys during fieldwork were integrated into ArcGIS to generate thematic layers, including elevation, slope, land use, and hazard distribution. These layers were produced to identify spatial relationships between environmental conditions, structural vulnerability, and the distribution of risks across the Muaro Jambi Temple Compound.

The use of ArcGIS allowed the study to spatially analyze how topography, land-cover characteristics, and proximity to environmental features influence hazard occurrence and risk intensity. By overlaying hazard points with thematic layers, the analysis enabled a systematic identification of areas with concentrated risk levels. This integration was essential for supporting the HIRADC-based risk assessment, as it provided spatial evidence that complements quantitative scoring and qualitative interpretation. Consequently, GIS-based processing enhanced the accuracy of risk classification and strengthened the spatial validity of the research findings.

2.6. Risk Calculation

Risk values were calculated using the HIRADC formula:

$$R = \frac{H \times V}{C}$$

where H is hazard intensity, V is vulnerability, and C is capacity. A supplementary matrix model based on Likelihood (L) and Severity (S) was also applied to classify risks into low, moderate, high, and critical categories, following standard risk management guidelines (Serpella et al., 2014; Godfrey & Halcrow, 1996; Li, 2024). Using both models allowed the assessment to capture the interaction between probability and impact, providing a comprehensive basis for developing mitigation strategies.

3. Results and Discussion

3.1. Overview of Findings

The purpose of this study was to assess environmental, structural, and socio-economic risks affecting the Muaro Jambi Temple Compound using an integrated HIRADC–GIS approach. Multi-hazard and multi-dimensional assessments are widely recommended in contemporary heritage risk studies because cultural landscapes experience interacting pressures that cannot be understood through single-risk methods (Jigyasu & Chmutina, 2023; Durrant et al., 2023). Our overall findings show that the Muaro Jambi Temple Compound is exposed to three dominant categories of risk: (1) environmental hazards, (2) structural deterioration, and (3) socio-economic pressures. Among the three, environmental risks represent the highest severity, particularly related to seasonal flooding, erosion, and airborne pollution associated with coal transportation near the site. These findings align with research demonstrating that heritage sites in Southeast Asia are increasingly affected by climate-driven hydrological shifts and industrial activities (Musyawarah et al, 2020; Graham et al., 2016).

Structural risks were found to be moderate, concentrated on vulnerable brick temples with vegetation encroachment and limited routine maintenance. This pattern is comparable to studies at Angkor, Bagan, and other brick-based archaeological landscapes where biological growth and weathering processes accelerate surface loss (Shimoda et al., 2021). Socio-economic pressures arise from tourism-related disturbances, informal land use, and limited community capacity. Similar patterns have been documented in other inhabited heritage landscapes such as Petra and Lalibela, where economic activities shape risk exposure and management priorities (Falk & Hagsten, 2023; Alshweiky & Zeynep Gül Ünal, 2016). These findings suggest that the preservation challenges at Muaro Jambi are not solely rooted in the fragility of ancient structures, but also in broader landscape dynamics and human–environment interactions. This reinforces the importance of integrated, risk-based management strategies that combine technical conservation with social engagement and spatial planning (Aplin, 2002).

3.2. Environmental Risk Analysis

Our findings show that environmental pressures represent the highest category of risk across the Muaro Jambi Temple Compound. Spatial analysis using DEM, hydrology layers, and GPS-based field observations indicates that several temple clusters particularly Gumpung, Kedaton, and Kembar Batu are highly exposed to seasonal flooding and surface runoff. The overlay of elevation and drainage patterns reveals that these clusters lie within shallow depressions connected to minor waterways, which increases water accumulation during peak rainfall months. These results are consistent with studies showing that many Southeast Asian heritage sites are increasingly vulnerable to hydrological instability due to changing precipitation patterns and land conversion in surrounding areas (Durrant et al., 2023; Graham et al., 2016). Similar patterns of flood-driven deterioration have been documented at Angkor Wat and Ayutthaya, where temple foundations weaken due to prolonged water saturation (Unesco, 2023).

Vegetation encroachment also contributes significantly to environmental risk. Field observations indicate root penetration in brick joints, the presence of shrubs appearing at wall bases, and moss accumulation on temple surfaces. These biological agents heighten material weathering, particularly in brick-based structures, which are inherently porous and sensitive to moisture retention. Research from Bagan and My Son confirms that brick monuments in tropical environments deteriorate rapidly when exposed to continuous moisture and root activity (Shimoda et al., 2021; ICCROM, 2016). A third environmental threat identified in this study is airborne coal dust, which pollutes the temple environment due to truck fleets transporting coal along nearby routes. Dust accumulation was recorded on temple surfaces, vegetation leaves, and signage. Our findings align with studies showing that airborne particulate pollutants can accelerate surface abrasion and alter microclimatic conditions around heritage structures (Bahaire, 1999). While previous research has mainly focused on industrial pollutants affecting urban heritage sites, this study highlights an emerging environmental hazard for rural archaeological landscapes.

The spatial patterns indicate that environmental risks are clustered, with high-risk zones forming along water channels, low-lying temple compounds, and areas closer to coal transportation routes.

These spatialized findings are significant because they demonstrate that risk is not uniformly distributed across the landscape, but shaped by geomorphology, land use, and environmental processes. This supports the landscape-based approach to heritage risk advocated in recent literature (Jigyasu & Chmutina, 2023; Aplin, 2002). In summary, the environmental analysis suggests that the conservation of Muaro Jambi must prioritize hydrological management, vegetation control, and mitigation of industrial pollution. These environmental pressures interact dynamically, requiring integrated solutions rather than isolated interventions. The findings reinforce the argument that environmental processes are foundational drivers of heritage deterioration in open archaeological landscapes.

3.3. Structural Risk Assessment

Our findings show that structural risks across the Muaro Jambi Temple Compound are moderate but spatially concentrated in temple clusters with deteriorated brick fabric, inadequate drainage, and persistent vegetation encroachment. The HIRADC scoring indicates that Gumpung, Kedaton, and Kembar Batu exhibit higher structural vulnerability compared to other clusters, largely due to their exposure to moisture and the fragile condition of their brick masonry. Brick deterioration is one of the most prominent structural risks. Field observations recorded several indicators: surface flaking, granular disintegration, moss growth, and micro-cracks along the brick joints. These patterns are typical in ancient brick structures exposed to fluctuating moisture, acid deposition, and biological colonization. Previous studies on brick temples in Bagan and Champa regions reveal similar deterioration processes, particularly in humid tropical climates (Aplin, 2002). The porosity of laterite and baked-clay bricks accelerates water absorption, which weakens binding materials over time.

Drainage failure also contributes significantly to structural vulnerability. Several temple platforms retain water after rainfall due to sediment-filled drains or absence of slope gradients. Our spatial analysis shows that clusters located near natural depressions experience slower drying times, increasing structural moisture load. Research at Angkor and Borobudur demonstrates that poor drainage is a major predictor of structural degradation, as prolonged moisture accelerates salt crystallization and microbial growth (Graham et al., 2016). Vegetation encroachment further amplifies structural risks. Root penetration was observed at wall bases and between brick joints, especially near temple perimeters with dense undergrowth. Roots exert mechanical pressure, displacing bricks and widening existing cracks. Similar impacts are reported in Southeast Asian archaeological sites, where uncontrolled vegetation is a leading cause of structural displacement (Musyawarah et al, 2020; Unesco, 2023).

Human-related structural disturbances were also identified, though at a lower frequency. These include surface abrasion from visitors touching temple walls, minor vandalism, and occasional movement of loose bricks by tourists. Such impacts reflect findings from studies on visitor-induced deterioration in heritage landscapes worldwide, including Petra and Machu Picchu, where increased human interaction introduces additional, often cumulative risk (Alshweiky & Zeynep Gül Ünal, 2016; Falk & Hagsten, 2023). Overall, the structural analysis indicates that deterioration in Muaro Jambi is driven by a combination of environmental exposure, material vulnerability, and inadequate maintenance systems. Qualitative data further elucidate why certain zones exhibit higher structural risks. According to a heritage site manager, *"several temple structures are vulnerable not only due to age, but also because repeated human contact and inadequate maintenance accelerate material deterioration"* (Interview Site Manager, 15 years experience). This insight aligns with the spatial risk classification, where zones with frequent human activity correspond to higher levels of structural vulnerability. These results reinforce the notion that structural conservation strategies must prioritize drainage improvement, vegetation control, and stabilization of weakened brick sections. This aligns with international conservation guidelines emphasizing preventive maintenance as the most cost-effective approach to safeguarding ancient masonry structures (Eze & Siegmund, 2024; Bai et al., 2024).

3.4. Socio-economic pressures and risk assessment

Our findings show that socio-economic pressures contribute significantly to the overall risk profile of the Muaro Jambi Temple Compound, particularly in areas where community activities, tourism flows, and land-use dynamics intersect with the heritage landscape. Although these pressures do not directly cause structural collapse, they intensify exposure and complicate conservation management, making them an important component of the site's risk assessment. Unregulated or semi-regulated land use around the temple area emerged as one of the most substantial socio-economic pressures. Field observations and interviews with local residents indicate that agricultural expansion, informal settlements, and community-built access paths often extend toward buffer zones of several temples. This pattern reflects broader challenges documented in other living heritage landscapes, where local economic activities intersect with heritage protection boundaries (Falk & Hagsten, 2023; Obed et al., 2024). Similar tensions have been observed in Borobudur and Ayutthaya, where residential and agricultural land use influences risk exposure and conservation priorities (Graham et al., 2016).

Tourism-related disturbances also contribute to socio-economic risk. Although tourism numbers at Muaro Jambi are not as high as major international sites, visitor behavior such as climbing fragile temple platforms, touching bricks, or leaving trash creates cumulative minor impacts. These findings align with global studies showing that even moderate visitor contact can accelerate surface degradation and disturbance to archaeological features (Alshweiky & Zeynep Gül Ünal 2016). Moreover, the absence of structured interpretation pathways and monitoring points intensifies uncontrolled visitor movement, particularly during weekends and religious holidays. Community capacity and institutional coordination were identified as crucial socio-economic factors shaping risk outcomes. These findings are further supported by qualitative insights obtained from field interviews. A site security officer highlighted that uncontrolled visitor access remains a significant challenge, stating that:

> *"monitoring visitors across such a wide area is difficult, especially during peak seasons when supervision is limited"* (Interview Security Officer, 38 years old).

Similarly, a local resident emphasized that economic pressures often lead to risky behaviors around the site, noting that

> *"some people still see the area as open land, not a protected heritage zone"*
> (Interview Local Resident, 42 years old).

These narratives help explain the high risk scores associated with human-induced threats identified in the quantitative assessment. Interview data reveal that while local communities exhibit strong attachment to the temple complex, their involvement in heritage protection remains limited by economic priorities and lack of formal training. Similar cases are discussed in community-based heritage management literature, which emphasizes that capacity gaps rather than lack of awareness often hinder conservation effectiveness (Jigyasu & Chmutina, 2023; Aplin, 2002). In Muaro Jambi, this gap manifests as inconsistent reporting of hazards, reliance on BPCB's periodic intervention, and limited integration of heritage awareness into daily land-use decisions.

Industrial activity near the heritage landscape introduces an emerging socio-economic risk factor. Coal transportation routes surrounding the site contribute not only to environmental hazards but also to socio-economic tensions, as residents often depend on such transportation corridors for their livelihoods. These economic dependencies complicate enforcement of protective regulations. This phenomenon is consistent with studies on heritage sites located near industrial zones, where economic dependency directly influences risk mitigation feasibility (Bahaire, 1999). Overall, the socio-economic analysis indicates that preservation challenges in Muaro Jambi are shaped by interactions between community livelihoods, tourism behavior, institutional capacity, and industrial footprints. These pressures collectively heighten vulnerability by influencing how the site is used, monitored, and managed. In line with international approaches to safeguarding cultural landscapes, addressing socio-economic risks requires community engagement strategies, capacity building, and coordinated land-use governance (Eze & Siegmund, 2024; Bai et al., 2024).

In addition to environmental and human-induced risks, the effectiveness of heritage risk mitigation in the Muaro Jambi Temple Compound is also influenced by institutional and governance-related factors.From a management perspective, institutional constraints were frequently mentioned during interviews. A local government official noted that

> *"limited funding and overlapping authority often delay preventive conservation actions"*
> (Interview Local Government Official, 10 years experience).

These qualitative findings provide contextual depth to the identified management risks and explain the persistence of moderate to high-risk levels despite existing conservation efforts.

3.5. Spatial Modeling Results

The spatial modeling conducted in this study demonstrates that risk across the Muaro Jambi Temple Compound is highly uneven and clustered in specific landscape zones. By integrating HIRADC scores for hazard, vulnerability, and capacity into a GIS framework, the research produced a single analytical output a Risk Zonation Map which visualizes the distribution of high, medium, and low risk areas across the site. This map represents the synthesis of field observations, environmental datasets, and quantitative scoring, making it the most comprehensive spatial depiction of the site's risk conditions. The Risk Zonation Map reveals that several temple clusters, particularly Gumpung, Kedaton, and Kembar Batu, fall within the high-risk category. These areas correspond to low-lying terrain, insufficient drainage, and dense vegetation, as well as locations affected by coal dust pollution and higher visitor interaction. The spatial concentration of high-risk zones indicates that deterioration pressures are not isolated but accumulate in areas where environmental and socio-economic factors intersect. This pattern aligns with findings from heritage landscapes such as Angkor and Bagan, where hydrological dynamics and human activity jointly shape deterioration (Unesco, 2023).

Conversely, clusters located on slightly elevated and better-drained ground, with clearer visibility and controlled vegetation, fall into the medium-risk category. These zones still exhibit structural and environmental pressures, but their overall vulnerability is moderated by stronger management capacity or by spatial distance from pollution and high visitor flow. Meanwhile, low-risk areas appear in sections with stable terrain, limited ground moisture, and minimal human disturbance. These results reinforce scholarship emphasizing that risk in archaeological landscapes is fundamentally spatial and shaped by the interplay between topography, land use, and management systems (Graham et al., 2016; Bahaire, 1999). The spatial patterns depicted in the map provide a clear basis for conservation priorities. High-risk zones require immediate attention, including drainage improvements, vegetation control, and mitigation of pollution, visitor impacts and education (As'ari, R, et.al., 2025; Suryana, I. G. P. E, et.al., 2025). Medium-risk zones would benefit from preventive maintenance and monitoring, while low-risk zones should be conserved through routine surveillance to prevent the emergence of new hazards. By translating HIRADC scoring into a spatial format, the model offers a practical tool for decision-makers, highlighting where limited conservation resources should be directed first.

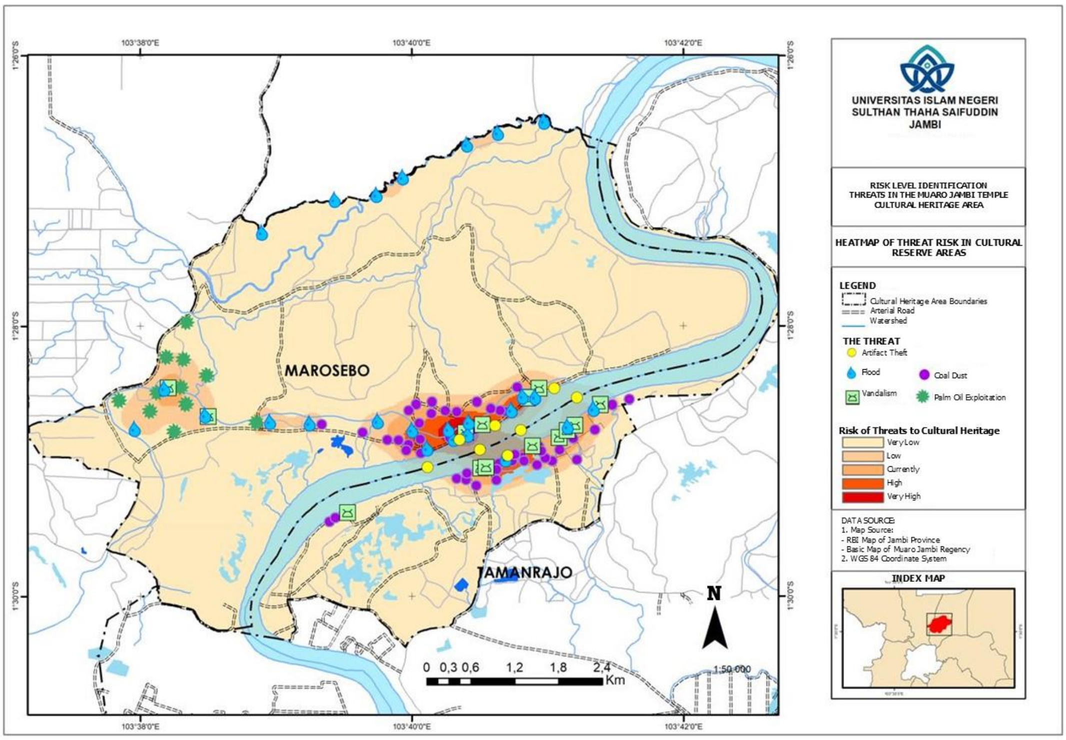

Figure 1 Explains Risk Classification Using GIS-Based Analysis

Figure 1 illustrates the spatial distribution of heritage risk levels across the Muaro Jambi Temple Compound based on the integrated HIRADC–GIS analysis. The risk zonation map synthesizes hazard intensity, site vulnerability, and management capacity scores into spatial categories of low, medium, high, and critical risk, enabling the identification of priority areas for targeted conservation and risk mitigation interventions. Overall, the spatial modeling underscores the importance of landscape-based assessment in heritage conservation. The results demonstrate that environmental pressures, structural vulnerabilities, and socio-economic activities manifest in identifiable spatial clusters, reinforcing the need for geographically targeted management strategies.

3.6. Integrated Discussion

The integrated results of this study reveal that the risks affecting the Muaro Jambi Temple Compound arise from a complex interaction between environmental processes, structural vulnerabilities, and socio-economic pressures. Rather than functioning independently, these dimensions reinforce one another, producing spatially clustered patterns of deterioration that are consistent with contemporary theoretical perspectives on cultural heritage risk. Scholars such as Jigyasu & Chmutina, (2023) and Aplin, (2002) have emphasized that heritage vulnerability is inherently multi-scalar and relational, shaped by both natural processes and human activities. The findings of this study corroborate these arguments, demonstrating that the degradation of Muaro Jambi cannot be understood without considering the broader landscape and social context in which the temples exist. Environmental conditions play a particularly dominant role in shaping structural deterioration. Hydrological instability, manifested through seasonal flooding and poor drainage, directly weakens the temple foundations and accelerates moisture-related decay. When combined with the deposition of coal dust from nearby transportation routes, these environmental pressures create a microclimatic condition conducive to biological growth, salt crystallization, and brick disintegration. Similar deterioration patterns have been documented in Angkor and Bagan, where fluctuating moisture and airborne pollutants contribute significantly to the weakening of ancient masonry (Unesco, 2023). The case of Muaro Jambi thus adds further evidence that environmental stressors not only threaten individual structures but fundamentally shape the long-term preservation trajectory of archaeological landscapes in tropical regions.

These environmental pressures are further intensified by socio-economic factors. Unregulated land use, community-driven pathways, and visitor activities create patterns of ground compaction, vegetation disturbance, and accidental abrasion that exacerbate erosion and moisture retention. Such community-related dynamics resemble issues reported in living heritage environments such as Petra and the Kathmandu Valley, where economic activities and everyday mobility influence risk exposure (Falk & Hagsten, 2023). In Muaro Jambi, the situation is complicated by the presence of industrial coal transport routes, which create both airborne pollution and economic dependencies that limit the feasibility of stringent regulatory interventions. This interplay between livelihood needs and heritage protection reflects broader global tensions within heritage management discourse and underscores the need for approaches that integrate community engagement with environmental mitigation. Spatial modeling results further strengthen these findings by showing that risks are not evenly distributed across the landscape. High-risk zones emerge at the convergence of low elevation, dense vegetation, inadequate drainage, and intensive human movement. This spatial clustering aligns with research emphasizing that heritage risk is fundamentally landscape-based and requires interventions tailored to specific geographic contexts (Graham et al., 2016). By visualizing the relationships between hazard, vulnerability, and capacity through GIS, this study provides a spatially explicit understanding of how deterioration processes accumulate and where management interventions would be most effective.

These insights have several important implications for heritage management. First, environmental mitigation must be prioritized, particularly improvements to drainage, vegetation control, and pollution monitoring. Second, socio-economic conditions especially community roles and land-use patterns must be incorporated into conservation strategies, as successful heritage protection in living landscapes depends on aligning local livelihoods with preservation goals. Third, the spatial risk maps produced in this study offer practical guidance for prioritizing areas of intervention, enabling resource allocation based on objective risk evidence. Despite its contributions, this study has limitations that should be acknowledged. The spatial datasets used, including DEM and land cover layers, rely on publicly available resolutions that may not fully capture microtopographical variations essential to temple-level analysis. HIRADC scoring, although validated statistically, still contains subjective elements inherent in expert-based assessment. Additionally, environmental and socio-economic data represent conditions at specific points in time and may not capture seasonal or annual fluctuations. Coal dust assessment, while clearly observed during fieldwork, would benefit from continuous air-quality monitoring to quantify its long-term effects.

Nevertheless, the study contributes meaningfully to the field in several ways. Methodologically, it demonstrates the value of integrating HIRADC with GIS to create a replicable model for multi-dimensional heritage risk assessment in Indonesia. Empirically, it identifies coal dust pollution as an emerging yet understudied hazard for archaeological landscapes. Practically, it provides risk zonation maps that can guide BPCB Jambi and local authorities in formulating targeted conservation interventions. Overall, this integrated discussion positions Muaro Jambi not merely as a case study of site-based deterioration but as a representative example of the complex interaction between environmental, social, and spatial factors shaping heritage vulnerability in Southeast Asia.

4. Conclusion

This study assessed the environmental, structural, and socio-economic risks affecting the Muaro Jambi Temple Compound through an integrated HIRADC–GIS approach. The findings reveal that the heritage landscape is shaped by multi-layered pressures that operate simultaneously and reinforce one another. Environmental hazards, particularly flooding, moisture retention, and coal dust pollution, represent the most critical threats. These factors accelerate biological growth and material decay, especially on porous brick structures that are highly sensitive to fluctuating moisture conditions. Structural vulnerabilities, including deteriorated masonry, inadequate drainage, and vegetation encroachment, further increase the susceptibility of several temple clusters. Socio-economic dynamics, such as unregulated land use, visitor activities, and limited community capacity, intensify these risks by influencing patterns of exposure and maintenance. By visualizing the distribution of hazards and vulnerabilities through GIS, the study demonstrates that risk is geographically clustered rather than uniformly distributed across the heritage landscape. High-risk zones emerge at the intersection of low-lying terrain, dense vegetation, and areas of human disturbance, underscoring the importance of spatially targeted conservation strategies. The results support theoretical perspectives that emphasize the relational and landscape-based nature of heritage risk in living archaeological environments.

The study contributes to the broader field of heritage risk assessment in three ways. Methodologically, it demonstrates the effectiveness of combining HIRADC scoring with spatial modeling to produce a replicable, multi-dimensional risk evaluation framework. Empirically, it identifies coal dust pollution as an emerging hazard for rural archaeological sites in Indonesia, expanding current understandings of industrial impacts on heritage landscapes. Practically, it provides risk zonation maps that can inform decision-making and help prioritize conservation interventions for BPCB Jambi and other stakeholders. While the study offers a comprehensive assessment, several limitations should be acknowledged. The spatial datasets rely on publicly available resolutions, HIRADC scoring involves inherent subjectivity, and temporal variations in environmental and socio-economic conditions were not fully captured. These limitations highlight opportunities for future research, including higher-resolution topographical surveys, continuous environmental monitoring, and longitudinal community-based studies. In conclusion, the preservation of Muaro Jambi requires integrated management that addresses environmental processes, structural conditions, and socio-economic realities. Risk-based conservation, supported by spatial evidence and community participation, will be essential to safeguard the site's cultural and archaeological significance for future generations.

5. Acknowledgments

The authors would like to express their sincere gratitude to the Directorate of Islamic Higher Education Research and Community Service (Litapdimas), Ministry of Religious Affairs of the Republic of Indonesia, and UIN Sulthan Thaha Saifuddin Jambi for their invaluable support and assistance in the implementation of this research.

Funding. This research was funded by the State Budget (DIPA) of UIN Sulthan Thaha Saifuddin Jambi under Grant No. SP DIPA-025.04.2.424188/2024.

Conflict of interest. The authors declare no conflict of interest.

Data availability. Not applicable.

AI Use Declaration. The authors used Grammarly to check grammar and spelling. No substantive content was generated by artificial intelligence. The authors reviewed and edited all AI-assisted output and are fully responsible for its content and any errors.

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