Climate Change and Cultural Heritage: Impacts and Management Strategies from a Comparative Perspective

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Abstract. Climate change poses a severe threat to the sustainability of global cultural heritage in the 21st century. This study adopts a comparative perspective, selecting three representative cases: Venice (coastal city), Egypt's Karak Oasis (arid region), and Peru's Machu Picchu (high-altitude site), to investigate the differential impacts of climate change on cultural heritage and comprehensive governance pathways. The findings reveal that heritage sites in different geographical environments face distinct climate threats: coastal areas are primarily affected by sea-level rise and salt erosion, arid regions are vulnerable to wind erosion and water scarcity, while high-altitude sites are endangered by rainfall-induced landslides and fluctuations in temperature and humidity. More importantly, these climate risks often interact with human activities such as tourism development and over-exploitation of resources, forming complex "compound risks" that significantly increase the vulnerability of heritage. The case comparisons confirm that standalone technical protection measures are often insufficient; effective management strategies must rely on the deep integration of engineering solutions, long-term monitoring, and community engagement, within an interdisciplinary governance framework. Through cross-case comparison, this study highlights the region-specific and complex nature of climate change impacts on cultural heritage, underscoring the necessity of integrating natural sciences, social sciences, and humanities perspectives. The research outcomes not only provide differentiated strategic references for protecting heritage across various environmental types but also offer a theoretical basis and practical insights for building more adaptive and sustainable global cultural heritage conservation frameworks.

Keywords: Climate Change; Cultural Heritage; Vulnerability; Comparative Study; Compound Risk.

1 Introduction

Climate change is profoundly reshaping the global environmental landscape. Over the past decades, rising sea levels, frequent extreme weather events, and persistent fluctuations in temperature and humidity have not only threatened ecosystems and human

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livelihoods but also subjected cultural heritage to unprecedented pressures. As tangible witnesses to human history and carriers of social and cultural identity, cultural heritage possesses irreplaceable value. Globally, numerous heritage sites—such as coastal ancient cities, desert oasis ruins, and high-altitude ancient settlements—are situated in climate-sensitive regions, making them frontline indicators of climate change impacts.

Research indicates that climate change threatens heritage preservation through multiple pathways [1,2]. For instance, intensified seawater erosion is accelerating the disappearance of coastal sites. Furthermore, drought and wind erosion persistently undermines the stability of desert heritage, while torrential rains and landslides severely jeopardize high-altitude historical structures. However, existing research predominantly focuses on single case studies or analyses of specific climate factors, with insufficient systematic comparative studies addressing heritage across different environmental types. Additionally, many response strategies remain centered on technical restoration and engineering protection, while discussions on comprehensive aspects such as social adaptation, cultural continuity, and governance mechanisms require further deepening.

A recent systematic review further indicates that while studies on climate factors affecting heritage degradation continue to increase, most remain case-based, lacking an integrated research framework combining multiple climate stresses with social governance [3]. Existing regional climate modeling studies indicate that distinct geographical environments (e.g., coastal, arid, mountainous) exhibit significant differences and compounding effects when subjected to stresses such as sea-level rise, salinization, extreme rainfall, and drought, underscoring the importance of cross-regional comparative research [4].

Therefore, this study selects three representative cases—the coastal region of Venice, Italy; the arid Karak Oasis in Egypt; and the high-altitude Machu Picchu site in Peru—to explore the diverse pathways through which climate change impacts cultural heritage preservation and management from a cross-regional comparative perspective. This research not only examines the degradation mechanisms of heritage artifacts themselves but also incorporates social participation and governance systems into the analytical framework. It seeks to reveal the complex interactions between climate risks and human responses, thereby providing theoretical insights and practical references for constructing more adaptive and sustainable cultural heritage protection frameworks.

2 Literature Review

2.1 Impacts of Climate Change on Cultural Heritage

In terms of the impacts of climate change on cultural heritage, the threats exhibit multidimensional characteristics [5,6]. First, with the global sea-level rise trend, coastal heritage sites such as Venice and coastal monuments in Bangladesh are facing the risks of submersion and erosion, and some archaeological sites along the Mediterranean coast and in Southeast Asia have shown obvious signs of damage. Second, extreme weather events are increasing. Floods, storms, droughts and other disasters directly damage the structure of heritage sites. As evidenced by the floods in the UK, which destroyed me-

dieval relics, these events also alter the surrounding ecological and hydrological conditions. Just like the long-term erosion of archaeological sites by drought in the Middle East, they indirectly increase the vulnerability of cultural heritage. Third, fluctuations in temperature and humidity accelerate the deterioration of building materials such as stone weathering and wood decay and affect the preservation of museum collections. Furthermore, these threats are not isolated; they can interact and amplify each other, such as sea-level rise exacerbating the impact of storm surges on coastal structures, creating compound effects that are more severe than individual threats [7]. These facts highlight the systematic and compound challenges posed by climate change to cultural heritage.

2.2 Methods for Climate Change Impacts

In terms of research methodologies, a multifaceted framework blending natural sciences, humanities, and interdisciplinary approaches has developed. Methods from natural sciences employ a range of techniques for risk assessment. These include climate data analysis, remote sensing, Geographic Information Systems (GIS) monitoring, modeling, and simulation [7,8]. A clear example is the use of remote sensing to evaluate flood threats to archaeological sites in the Nile River basin. Meanwhile, humanities-based approaches draw on historical documents, archaeological evidence, and oral traditions to examine the relationship between climate and cultural heritage. For instance, African oral histories offer valuable perspectives on traditional adaptation strategies. Interdisciplinary approaches synthesize expertise from diverse domains, such as combining material science testing, climate modeling, and historical archive analysis to estimate the service life of ancient structures. Furthermore, interdisciplinary integration is increasingly becoming a central research direction, with future efforts expected to advance toward a holistic framework that incorporates technological, humanistic, and social dimensions.

2.3 Research Gaps and Shortcomings

Nevertheless, existing research has obvious shortcomings. The research objects are narrow, focusing mostly on world heritage sites and well-known relics such as the Great Wall and Angkor Wat, while paying insufficient attention to ordinary local heritage, vernacular heritage and industrial heritage. Risk analysis is limited to single climate factors, lacking systematic analysis of the superimposed effects of multiple risks. For example, the accelerated effect of the combination of floods and temperature fluctuations on the degradation of heritage sites has not been deeply explored. Protection countermeasures focus more on engineering and technical means, while research on community participation, local knowledge and adaptive governance is still limited. Based on this, future research needs to explore more comprehensive and localized response paths through cross-regional case comparisons to provide more comprehensive references for cultural heritage protection.

3 Research Methodology

This study establishes a systematic interdisciplinary comparative methodological framework to delve into the differential impacts of climate change on cultural heritage and the corresponding governance pathways. This framework directly addresses the research gaps identified in the literature review – primarily the limitations of existing studies focusing on single cases or isolated climate factors, lacking systematic examination of compounded risks and socio-institutional dimensions. The core of this methodology lies in integrating environmental monitoring techniques from natural sciences, institutional analysis from social sciences, and historical contextualization from the humanities, forming a multi-evidentiary chain. Specifically, for heritage sites across diverse geographical contexts such as coastal, arid, and high-altitude areas, the research employs tailored data collection strategies: for instance, utilizing remote sensing imagery and GIS spatial analysis to quantify erosion rates of Venetian stone structures due to sea-level rise; combining geological surveys and historical climate data to reconstruct hydrological changes and wind erosion patterns in the Kharga Oasis; and applying geological hazard modeling coupled with tourist flow statistics to assess landslide risks and anthropogenic pressures at Machu Picchu. Crucially, the framework incorporates a "social-ecological resilience" perspective, intertwining engineering protection measures (e.g., seawalls, stone conservation techniques) with community engagement mechanisms and traditional adaptation knowledge. This integrated approach not only enhances the rigor of cross-case comparison but also provides methodological support for understanding the formation pathways of compound risks, highlighting the essential role of multidisciplinary collaboration in heritage conservation.

4 Case Studies

When examining the impacts of climate change on cultural heritage, case studies provide tangible insights into the diverse threats heritage sites face across different environments. This research selected three representative cases: the stone architecture of Venice, the heritage of Egypt's Qal'at al-Gharb oasis, and Peru's Machu Picchu ruins. These sites represent distinct environmental types: coastal cities, arid deserts, and high-altitude heritage. By comparing their respective climate vulnerabilities and conservation strategies, we can more comprehensively reveal the multidimensional impacts of climate change on cultural heritage and the corresponding responses. This cross-regional case analysis not only enriches the empirical foundation of climate change and cultural heritage research but also provides valuable insights for developing global heritage protection policies in the future.

4.1 Vulnerability of Venice's Architectural Stone

Venice stands as one of Italy's—and indeed Europe's—most iconic cultural heritage cities. Its historic buildings, primarily constructed from marble and Istrian stone, embody the unique architectural blend of Renaissance and medieval urban landscapes.

However, the lagoon environment in which Venice is situated renders it exceptionally vulnerable to the dual impacts of global climate change and land subsidence. Research indicates that sea-level rise has reached 2.5–3.0 mm/year, causing surface powdering and crack propagation in over 60% of historic stone structures [9]. Frequent extreme tidal events intensify seawater erosion, while salt crystallization and wet-dry cycles accelerate salt efflorescence in Istrian stone by approximately 40%. Persistent land subsidence further amplifies this degradation, leaving Venice's architectural foundations in a state of chronic instability.

Methodologically, scholars combined materials science and geological analysis with climate and environmental monitoring data to uncover the physical and chemical mechanisms of stone degradation. Laboratory simulations and long-term observations revealed that ultrasonic tests showed a 12–25% reduction in structural integrity for limestone samples at high tide level ($\geqslant$110 cm), significantly higher than ground-level samples (5–8%). μ-XRF elemental analysis further confirmed that chlorine concentration on stone surfaces at Palazzo Malipiero peaked at 38% (atomic concentration), while sulfide pollution reached 34% in downwind areas of industrial zones. This quantitative data elucidates the destructive mechanism of synergistic effects between saltwater intrusion and humidity.

To address these threats, local authorities have established a stone degradation database and implemented multiple protective measures. The MOSE barrier system, activated in 2020, reduced tide events $\geqslant$120 cm by approximately 70%, though engineering measures have also sparked academic debates on ecological impacts. The experience demonstrates that protecting coastal urban heritage requires integrating engineering solutions and cultural value assessments, enhancing climate resilience through interdisciplinary approaches.

4.2 Cultural Heritage and Climate Vulnerability in the Kharga Oasis

In stark contrast to Venice's humid water city environment, Egypt's Kharga Oasis lies within the Eastern Sahara Desert. Its unique arid setting has nurtured significant archaeological heritage, including temples, tombs, and ancient settlements. While oasis heritage has long endured under harsh natural conditions, the compounding effects of modern climate change and human activities have increasingly exposed its environmental vulnerability. Studies indicate that frequent sandstorms, rising temperatures, and abnormal rainfall patterns pose direct threats to heritage preservation. Specifically, according to Ismael et al. (2023), approximately 12,000 years ago, the oasis had a greener environment with higher rainfall, but subsequent climate shifts, such as the southward movement of the ITCZ by about 800 km, led to a rainfall decrease of 50-80%, exacerbating aridity [10]. Furthermore, overexploitation of groundwater and changes in land use have accelerated degradation in heritage zones, resulting in some sites being buried by dunes or damaged by wind erosion; for instance, wind erosion rates have increased by approximately 40% in certain areas, while groundwater extraction has caused water table declines exceeding 20 meters, further threatening heritage stability [10]. The distribution of the Egyptian settlements in the Western Desert throughout the Holocene is shown in Fig. 1.

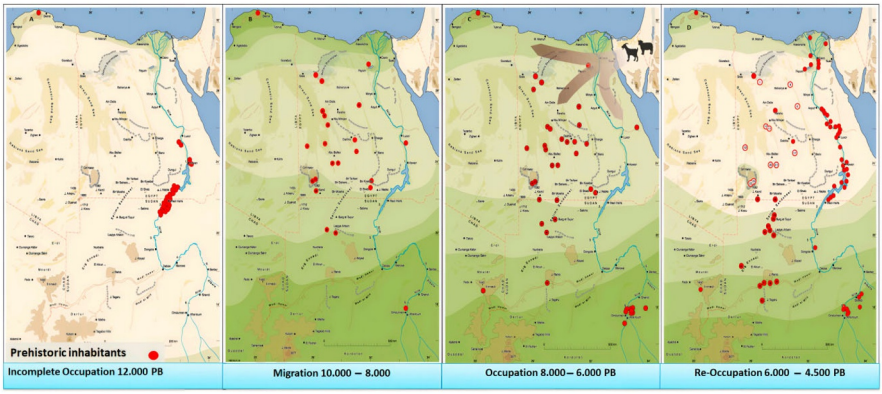

Fig. 1. Distribution of the Egyptian settlements in the Western Desert throughout the Holocene [10].

Methodologically, scholars employed an interdisciplinary approach combining remote sensing imagery, historical documents, and field archaeological surveys to reconstruct the evolution of oasis environments over millennia. Ismael et al. (2023) utilized rock art and petroglyph analysis, supplemented by radiocarbon dating (C14), to uncover paleoclimatic variations. For example, by examining 136 archaeological sites with rock art, they identified phases such as the hunting stage (around 12,000 years ago) and the shepherd stage (around 9,000 years ago), which depicted animals like giraffes and elephants, indicating a savanna-like environment with higher humidity; approximately 60% of the rock art depictions reflect the mid-Holocene humid period, while C14 dating shows intensified aridification around 7,300 BP, leading to population migration [10]. Modern extraction methods have severely depleted groundwater resources, and this resource pressure not only degrades the oasis environment but also exposes ancient sites to direct threats from wind erosion and sandstorms; remote sensing data indicate a 15% increase in dune coverage over the past 50 years, with heritage site degradation rates reaching up to 2% annually. Fig. 2 shows a selection of cultural remains carefully chosen from the Kharga Oasis.

Fig. 2. A collection of cultural remains that have been carefully chosen from the Kharga Oasis. The presented compilation exhibits a diverse array of artifacts and archaeological remnants, which function as tangible evidence of historical climate fluctuations within the given geographical area (A, B). Remains of pottery vessels (C, D). irrigation wells, (E F). cooking tools (G, H). Skeletal remains, and (I, J). security mentoring points.

Regarding conservation, Egypt's Ministry of Antiquities has established regional heritage protection zones through international collaboration in recent years. These zones restrict excessive groundwater extraction and employ remote sensing and GIS technologies for dynamic site monitoring. Simultaneously, some scholars advocate drawing on ancient hydraulic engineering expertise to restore ecological balance

through modern engineering methods, such as simulating irrigation efficiency improvements by 20% based on ancient water management systems depicted in rock art. Notably, the Kharga Oasis case highlights the compounding effects of human actions and climate risks: heritage degradation is not solely a natural process but the result of long-term interactions between social and environmental factors. This offers a critical warning for heritage conservation in arid regions worldwide.

4.3 Cultural Heritage and Climate Vulnerability of Machu Picchu

Peru's Machu Picchu, perched high in the Andes Mountains, stands as an outstanding testament to Inca civilization and is celebrated as a jewel among the world's cultural heritage sites. This archaeological complex is renowned not only for its masterful stonework and terraced fields but also for its exceptional vulnerability due to its unique mountainous geography. In recent years, climate change has increasingly threatened Machu Picchu, particularly through landslides triggered by heavy rainfall and geotechnical instability, posing severe risks to the site's foundational structures. Rising temperatures and fluctuating humidity have accelerated stone weathering, causing cracks in some walls and staircases. Meanwhile, the continuous growth of tourism activities has further intensified pressure on both the ecological and heritage environments.

Research methodologies primarily employ remote sensing and GIS technologies to monitor landslide risks, combined with geotechnical analyses to assess the stability of stone masonry structures. Concurrently, sociological and management approaches are applied to study the tensions between tourism and heritage preservation. Findings indicate Machu Picchu's vulnerability stems not only from natural hazards but also from human activities. Rapid tourism development has caused extensive vegetation loss, making soil structures more susceptible to erosion from heavy rainfall. The site's inclusion on the World Heritage List has compelled the Peruvian government to balance conservation with economic growth.

To address these threats, multi-tiered protective measures have been implemented locally: establishing geological hazard monitoring systems to predict landslide risks; reinforcing and restoring stone structures using materials compatible with the original stones; capping daily visitor numbers and optimizing tour routes to minimize human impact on vulnerable areas; and promoting community engagement and sustainable tourism principles to secure social support for conservation efforts and ensure long-term viability. The case of Machu Picchu demonstrates that the complexity of protecting high-altitude heritage lies not only in natural hazards but also in the tension between conservation and economic and social development objectives.

4.4 Comparative Analysis and Insights

A review of the three case studies—Venice, Oasis of Calgary, and Machu Picchu—reveals significant variations in how cultural heritage sites across different geographical environments respond to climate change. As a coastal city, Venice faces primary threats from the combined effects of sea-level rise and land subsidence, rendering its stone structures highly susceptible to moisture and salt corrosion. The Calgary Oasis, situated

in an arid desert, sees its heritage primarily impacted by wind erosion, dust storms, and water scarcity. Meanwhile, Machu Picchu, located in a high-altitude region, confronts extreme rainfall and landslides as its greatest risks, with tourism pressure further amplifying environmental fragility.

Despite these distinct threats, a shared vulnerability emerges because climate change impacts on cultural heritage are invariably complex and intertwined with human activities, which collectively amplify the risks to heritage sites. Crucially, these cases demonstrate that regionally tailored conservation approaches are essential: coastal sites require engineering solutions and technological monitoring; desert sites demand integration of traditional knowledge with regional governance; and high-altitude sites necessitate disaster early warning systems and tourism management. Moreover, these cases underscore that cultural heritage conservation is not merely a technical engineering challenge but a social and policy issue requiring multi-stakeholder engagement among governments, communities, research institutions, and international organizations.

From a global perspective, comparative analysis of these cases offers three key insights. First, the impacts of climate change on cultural heritage exhibit significant regional variations, necessitating tailored conservation measures. Second, the presence of compound risks demands interdisciplinary collaboration, integrating climate science, archaeology, materials science, and social sciences. Third, community engagement and public awareness play a vital role in safeguarding the long-term sustainability of heritage conservation. Only by adopting an integrated approach that combines technological solutions with socio-institutional governance can we effectively confront the challenges that climate change poses to cultural heritage in the coming decades.

5 Conclusion

This study adopts a cross-regional comparative perspective, focusing on cultural heritage sites in three typical environments—coastal (Venice), arid (Karak Oasis), and high-altitude (Machu Picchu)—with the core goal of revealing the differentiated impacts of climate change on heritage and integrated governance pathways. The findings indicate that heritage sites in different regions face distinct region-specific climate threats: coastal areas are impacted by sea-level rise and salt corrosion, arid regions suffer from wind erosion and water resource depletion, and high-altitude areas are endangered by rain-induced landslides and temperature-humidity fluctuations. Moreover, in all cases, climate risks interact with human activities to form compound threats. It is also confirmed that single technical protection measures are ineffective, and interdisciplinary integration and social dimension intervention are crucial. These findings provide empirical support for differentiated cultural heritage protection.

Future research should further strengthen interdisciplinary collaboration, deeply integrate achievements from climate science, materials science, sociology, and other fields, and focus on exploring the superposition mechanism of multiple climate risks and the application value of local traditional knowledge. At the practical level, an adaptive protection framework should be constructed to clarify the core role of communities

in monitoring and inheritance. Policies should promote the precise integration of mature international experience with local realities, ultimately enhancing the sustainability and resilience of global cultural heritage in responding to climate change.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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