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ORIGINAL RESEARCH PAPER

Climate crisis and cultural heritage management

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ABSTRACT

BACKGROUND AND OBJECTIVES: Climate change poses significant threats to cultural heritage sites, particularly coastal regions. This study focused on the Side Ancient City in Antalya, Türkiye, examining the impacts of sea-level rise, coastal erosion, extreme temperatures, construction, and earthquakes on its historical and archaeological integrity. Unlike previous studies, this study employed a holistic risk analysis framework.
METHODS: The study integrated a literature review, field observations, GIS-based spatial analysis, and comparative case studies to assess Sides' vulnerability to climate-induced hazards. This multi-method approach enabled a more precise evaluation of risks affecting key historical structures.
FINDINGS: Sid has experienced magnitude 5-6 earthquakes in the last 120 years, a 4.45% loss of green areas in 15 years, and a 20-fold increase in built-up area, rising from 0.84% in 1953 to 16.8% in 2010 over 57 years. The average temperature increased from 17.1°C (1979) to 18.5°C (2023).
Climate change is projected to raise the sea level on the Side coast by 2-2.2 meters. Despite its tourism significance, local-scale visitor data is lacking.
CONCLUSION: The study proposed a multi-faceted adaptation strategy to mitigate risks, including coastal defence measures, improved drainage systems, climate-resilient restoration materials, and seismic retrofitting of vulnerable structures. Additionally, it recommended policy reforms and tourism management strategies to support conservation efforts. The research offered a transferable model for protecting coastal archaeological sites from climate-induced and seismic hazards by aligning site preservation with broader climate adaptation frameworks. The study contributed to global heritage conservation by highlighting the urgent need for proactive and interdisciplinary approaches to safeguard cultural landmarks against accelerating environmental change.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
68	11	5

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INTRODUCTION

Cultural heritage sites symbolize human history and identity, yet they face escalating threats from environmental and human-induced stressors. Among these, the climate crisis has emerged as a dominant force, reshaping landscapes, destabilizing ecosystems, and accelerating the deterioration of ancient structures. The growing complexity and unpredictability of environmental conditions now demand a rethinking of how we assess, protect, and manage these fragile heritage landscapes, particularly in vulnerable coastal zones. The planet's climate has changed over time, but the 0.6°C rise in global temperature during the 20th century marks the most significant increase in the last 1,000 years. According to the IPCC, human activities especially greenhouse gas emissions and land use changes are the main drivers of warming over the past 50 years. The current rate of emissions is unprecedented in 20,000 years and is fuelled by unequal, unsustainable consumption and production patterns across regions and populations (UNESCO, 2007; IPCC, 2023a). Climate change impacts natural, societal, and cultural systems, including World Heritage sites, by causing physical damage such as soil degradation, deterioration of archaeological remains, moisture damage to historic buildings, and biological infestations. Extreme weather events like floods, storms, erosion, and desertification further threaten the long-term preservation of these heritage sites (Vyshkvarkova & Sukhonos, 2023; UNESCO, 2007). Fig. 1 shows some impacts of climate change on cultural heritage.

Fig. 1 illustrates how climate change threatens cultural heritage through environmental and biological risks, including moisture and temperature shifts, sea-level rise, wind, pollution, desertification, and biological impacts. These lead to flooding, heatwaves, material decay, and invasive species, ultimately endangering the structural integrity and preservation of heritage sites. Table 1 lists climate change impacts on cultural heritage according to researchers.

Climate change threats such as sea-level rise, coastal erosion, acidification, and salt weathering endanger coastal heritage sites by causing corrosion, material degradation, and structural weakening. Biodeterioration, freeze-thaw cycles, and soil temperature changes accelerate decay, while extreme weather events inflict severe damage. These risks underscore the urgent need for climate-adaptive strategies to protect vulnerable heritage sites. Table 2 shows some historic areas in danger and developed

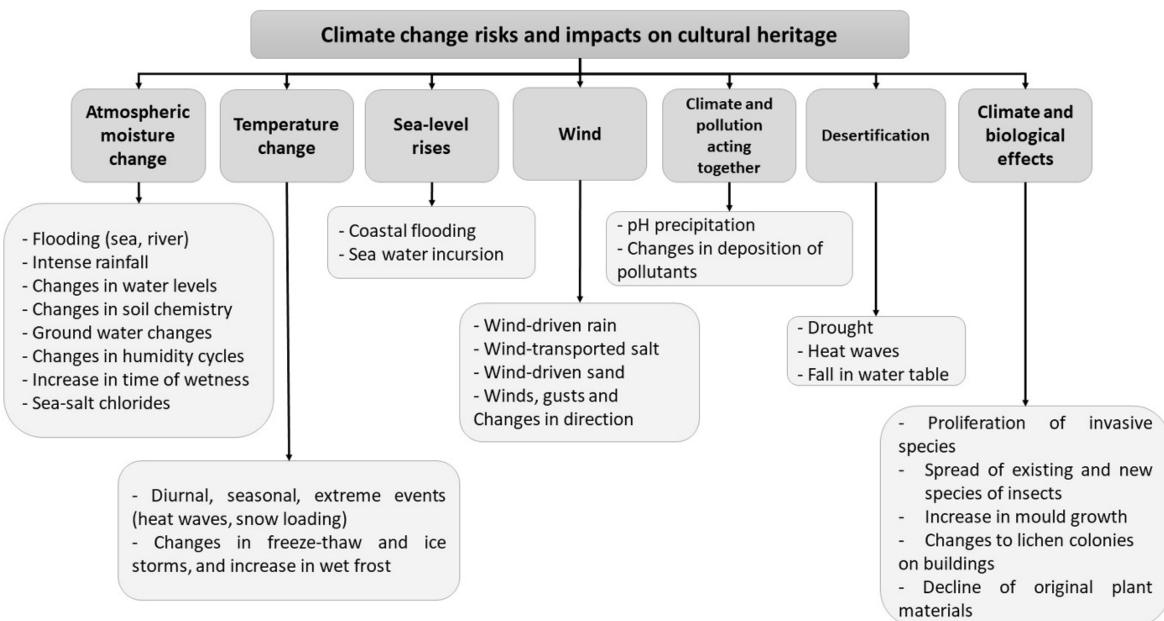

Fig. 1: Impacts of climate change on cultural heritage (UNESCO, 2007).

Table 1: Climate change and cultural heritage

Impacts	Literature
Sea-level rise, Coastal Erosion, and Flooding	(Carbognin *et al.*, 2010; P. Daly *et al.*, 2022; García Sánchez *et al.*, 2020; Maragno *et al.*, 2023; Marzeion & Levermann, 2014; Reimann *et al.*, 2018)
Changing of Sea Temperature	(Harkin & Westley, 2020; Isaak *et al.*, 2012; Willems & Schaik, 2017)
Acidification of Sea Water	(Harkin & Westley, 2020; Willems & Schaik, 2017)
Crystallization and Salt weathering	(Charlo, 2000; Menéndez, 2018; Ruiz-Agudo *et al.*, 2011; Vyshkvarkova & Sukhonos, 2023)
Biodeterioration and Architectural Impacts	(Bienvenido-Huertas *et al.*, 2021; Dias *et al.*, 2023; Hedayatnia *et al.*, 2021; Pires *et al.*, 2022; Prieto *et al.*, 2020; Silva *et al.*, 2020; Sitzia *et al.*, 2023)
Freeze-Thaw Cycle	(Sesana *et al.*, 2018, 2021; Vyshkvarkova & Sukhonos, 2023)
Soil Temperature	(Asano *et al.*, 2023; Bradford *et al.*, 2019; Menberg *et al.*, 2014)
Archaeological Sites	(C. Daly, 2011; Grossi *et al.*, 2007; Heilen *et al.*, 2018; Hollesen, 2022, 2023)
Severe Climate Events	(Sesana *et al.*, 2018, 2021)

adaptation-mitigation strategies to protect them.

Kapsomenakis *et al.,* (2023) warn that climate change and seismic activity increasingly threaten 244 UNESCO heritage sites in the Mediterranean. Their study reports a sharp rise in extreme heat-up to 50 additional hot days annually, and identifies Italy, Greece, and Türkiye as high-risk seismic zones. Coastal sites in these countries, including Cyprus, are particularly vulnerable, prompting the development of a Mediterranean-wide protection plan to address these escalating risks. (Kapsomenakis *et al.*, 2023). To protect heritage sites, key measures include coastal defences like sea walls, natural barriers, and erosion control to counter rising sea levels. Enhanced conservation through regular maintenance, monitoring, and climate-resilient materials is also crucial (Sabbioni *et al.*, 2010; Sesana *et al.*, 2021). According to recent research, vegetation greening has a cooling influence on air temperature both locally and globally (Liu *et al.*, 2022; Yu *et al.*, 2022). Policy and decision-makers require quantitative data on heritage risks to set risk thresholds and develop adaptation strategies. A coherent assessment methodology is needed to evaluate tangible and intangible heritage damage. Filling these gaps enables prioritized interventions, effective planning, and resource allocation (Bonazza & Sardella, 2023). While recent studies have examined the vulnerability of cultural heritage sites like Venice (Faranda *et al*., 2024) and Petra (Abdalhaleem *et al.,* 2024), there remains a lack of integrated, site-specific, and data-driven assessments that account for both environmental and anthropogenic pressures on heritage sites. There is a lack of integrated, site-specific climate risk analyses, particularly for complex conservation sites like Side Ancient City, where archaeological, natural, and urban conservation sites. This study addresses that gap by proposing a holistic approach combining comparative analysis with similar examples, field observation inputs, GIS, and risk assessment. The findings aim to support climate-resilient conservation not only for Side but also as an interdisciplinary and transferable model for other vulnerable heritage sites. By emphasizing interdisciplinary risk modelling and policy integration, this research contributes to the emerging field of climate-resilient heritage management, offering both methodological innovation and practical relevance. This study aims to develop a holistic climate risk assessment framework for Side Ancient City by integrating comparative site analysis, field observations, GIS-based spatial analysis, and risk modelling, and answer the following questions:

1. *What are the primary climate-induced threats to the Site Ancient City?*
2. *How do these threats compare with similar sites?*
3. *What integrated conservation strategies can enhance the site's resilience?*

The methodology includes a literature review, field analysis at Side, examination of similar sites under risk, and a detailed risk analysis. This study examines the climate change risks threatening the Side Ancient City in Türkiye in 2024, focusing on material decay, structural vulnerabilities, and natural hazards like floods and storms. Using a site-specific, probabilistic risk assessment, it integrates

Table 2: Historic sites in danger and developed adaptation-mitigation strategies

Risks & Impacts	Adaptation & Mitigation Strategies
Venice, Italy	
Venice faces significant risks from rising sea levels and increased flooding, exacerbated by climate change. The frequency of "Acqua Alta" (high water) events has increased, threatening the city's unique architecture and historic buildings (Faranda *et al.*, 2024).	Faranda *et al.* (2024) examine the MoSE system's effectiveness in reducing Acqua Alta flooding in Venice, analyzing its impact on sea levels and economic damage. Comparing past floods (1966, 2008, 2019), it finds that while MoSE provides protection, additional measures are needed for unprecedented floods, requiring further research and adaptation strategies (Faranda *et al.*, 2024).
Machu Picchu, Peru	
Peru has significant tourist potential due to its landscapes, culture, and geomorphological features. This diversity creates a responsibility for preservation, especially given the risks posed by even moderate climate change scenarios.	The study evaluated solar and wind energy use for a historic site and museums in Peru, finding strong renewable potential but a lack of specific sustainability laws. It emphasized the environmental benefits of renewables and recommended policy enhancements to support sustainable tourism (Calderón-Vargas *et al.*, 2021).
City of Chan Chan, Peru	
The Chan Chan Archaeological Zone is highly susceptible to the impacts of climate change, particularly the extreme climatic events associated with the El Niño phenomenon that affect the northern coast of Peru (UNESCO, n.d).	Following its designation as a World Heritage site in danger, Chan Chan implemented a Master Plan supported by the World Heritage Fund, focusing on El Niño mitigation, water table control, and structural stabilization using both traditional and modern methods. The plan also prioritized documentation, training artisans, and public education. The Ministry of Culture's ENSO program introduced preventive actions, including wall stabilization, protective roofing, and water management (UNESCO, n.d.).
Djenné, Mali	
Djenné, Mali, faces climate-induced threats to its mudbrick architecture, including flooding, material deterioration, and loss of craftsmanship. Economic pressures drive the use of modern, unsustainable materials, while climate change accelerates urbanization and challenges restrictive conservation policies (Brooks *et al.*, 2020).	The study highlights the importance of preserving both tangible and intangible heritage, noting that cultural practices are as vulnerable as physical sites to climate change. It calls for greater awareness and the integration of heritage preservation into climate policy to prevent irreversible cultural loss (Brooks *et al.*, 2020).
Stonehenge and Avebury, United Kingdom	
Murphy *et al.*, (2013) identify 22 risks to heritage sites, including erosion from tourism, livestock, and extreme weather, flooding at Avebury, vegetation changes affecting conservation, wildfire threats, and damage to species like lichens on monuments *(Murphy et* , 2013).	The report underscores the need for regular monitoring, strategic responses, and adaptive measures to protect sites' Outstanding Universal Value. It advises incorporating these actions into updated World Heritage Site Management Plans, with ongoing reviews to address changing climate conditions (Murphy *et al.*, 2013).
Petra, Jordan	
Petra faces major climate risks such as flash floods, drought, and storms, which endanger its archaeological structures and the local economy reliant on tourism and agriculture (Abdalhaleem *et al.*, 2024)	The study advocates combining local knowledge with scientific data to strengthen Petra's resilience to climate change. Under a moderate emissions scenario, it projects moderate risk by 2060, highlighting the need for proactive and sustainable adaptation measures to safeguard its cultural and natural heritage (Abdalhaleem *et al.*, 2024)
Pyramids of Giza, Egypt	
The Giza pyramid complex, including the Great Pyramids and the Sphinx, faces structural damage and material decay from natural aging, human activity, and rising groundwater levels linked to urbanization and irrigation, increasing the risk of limestone deterioration (Hemeda & Sonbol, 2020).	The research emphasized the need for structural interventions and effective management to conserve the Giza site. It also discovered a large original hill beneath the pyramids and stressed controlling urbanization's impact on rising groundwater levels (Hemeda & Sonbol, 2020).
Greek Theatre of Dionysus in Athens	
The Ancient Greek Theatre of Dionysus in Athens faces climate change threats, including material degradation from humidity, corrosion, and vegetation growth, as well as structural damage from soil erosion, landslides, heatwaves, and heavy storms (Nastou & Zerefos, 2021).	Suggested strategies focus on energy efficiency, humidity control, and resilience enhancement, integrating climate adaptation into heritage management. The approach emphasizes proactive conservation, continuous monitoring, community involvement, and a sustainable framework to protect cultural heritage from climate change (Nastou & Zerefos, 2021)

field observations, GIS analysis, and comparative case studies to provide a comprehensive evaluation. The study proposes integrated adaptation and mitigation strategies, such as physical interventions, policy measures, and community-based initiatives to enhance Side's resilience. By bridging climate science and heritage conservation, it offers practical solutions and serves as a model for protecting historic urban sites from climate change. The study begins by identifying the vulnerability of the Side Ancient City to climate change, setting out its aim to develop integrated conservation strategies. It then poses key research questions about climate-induced threats, comparisons with similar sites, and resilience-enhancing solutions. The methodology includes a literature review, field analysis at Side, risk analysis, and comparison with other at-risk heritage sites. Based on this, the paper proposes adaptation and mitigation strategies such as coastal protection, improved drainage, structural resilience, protective measures, tourism management, and sustainable policies. The findings are synthesized in the results

Fig. 2: Location of Side

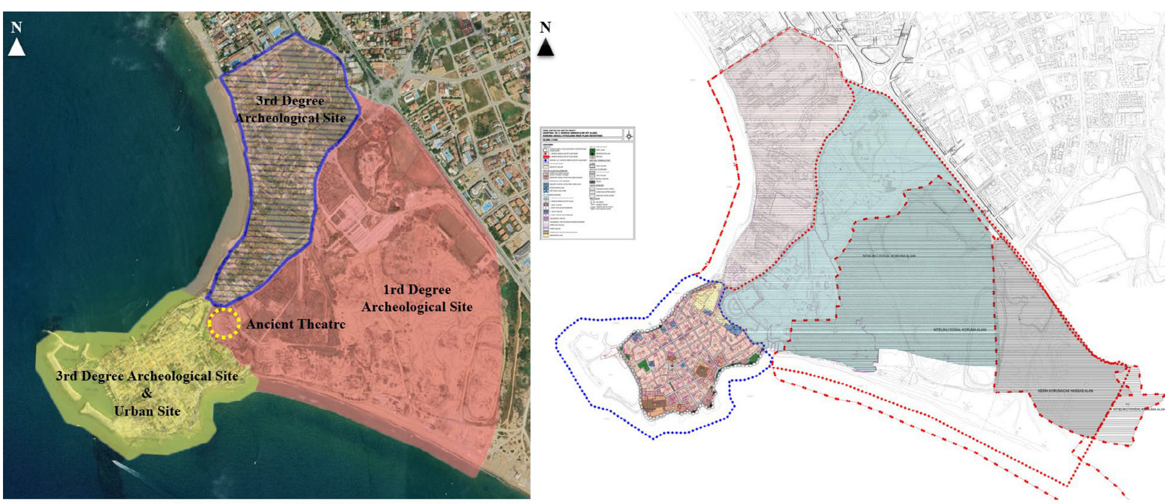

Fig. 3: 2024 Site conservation plan

and discussion sections, and practical and theoretical implications are highlighted, emphasizing similarities and differences with the literature. Finally, in the conclusion, the study's contributions, suggestions for future studies, and the study's limitations are presented.

MATERIALS AND METHODS

Side Ancient City

Asia Minor, a peninsula now largely corresponding to modern-day Türkiye, was a significant region in ancient times known as Anatolia. It played a key role in the Greek and Roman periods, particularly in Ionia along the central western coast. After the decline of Mycenaean society, Greeks, especially Ionians, began settling in the area around 1000 BC, establishing important city-states like Miletus, Samos, Chios, and Ephesus. Between 750 and 550 BD, Greek colonization expanded further, with cities positioned along major trade routes, boosting their prosperity (Sacks, 2005; 5). The Side, located in Asia Minor (modern-day Türkiye), is an archaeological treasure with a rich history that spans several civilizations. Today, Side is located in Antalya Province in the Manavgat District of southern Türkiye, near the Mediterranean coast. It lies approximately 75 kilometres east of Antalya's centre (Fig. 2).

Side, an ancient city in Eastern Pamphylia, is located near the Melas River. Its name, meaning "pomegranate", appears in various regions, including Pamphylia, Pontos, and Greece. Though its founding date is uncertain, ancient sources link it to Cymeans from Aeolia, while archaeological evidence suggests Late Hittite origins. Eusebius dates its establishment to 1405 BC. Unlike many ancient cities, Side experienced minimal migration or colonization, preserving its local cultural identity (Alanyalı, 2011; Alanyalı & Yurtsever, 2020). Side gained independence in the late Hellenistic period, later becoming a Roman administrative centre and naval base. It flourished in the Early Byzantine period and was eventually abandoned after the Seljuk conquest (13th century). In the late 19th century, Turkish families from Crete resettled the area, naming it Selimiye Village, and later reverted to Side. Archaeological excavations, led by Arif Müfid Mansel since 1947, uncovered key Late Antique and Byzantine monuments. Recent research focuses on the bishop's complex and urban integration during the Byzantine era, offering new insights and a conservation model for Anatolia (Altun, 2020; Elam, 2020; Soykal Alanyalı, 2017). Despite its designation as a 1st-degree archaeological site in 1990, Side faced rapid, unplanned development driven by tourism, delaying conservation and enabling illegal construction. Preservation efforts later aimed to integrate Ottoman rural architecture with archaeological heritage. The approved 2014 Conservation Plan focused on protecting traditional structures, preventing illegal building, involving the public, advancing excavations, and safeguarding both tangible and intangible heritage (Altun, 2020; Büyüksural & Sağıroğlu Demirci, 2023). To improve the 2014 Conservation Plan and better accommodate the historical area's spatial needs, revision work began in 2022. Following spatial analyses and stakeholder discussions, the updated plan was approved in 2024. Fig. 3. illustrates the 2024 Conservation Plan. Fig. 3. shows the ancient city of Side, highlighting areas with different levels of archaeological significance. The 1st Degree Archaeological Site (red area) includes key historical features like the Ancient Theatre and is under strict protection. The 3rd archaeological Sites (yellow and blue areas) are less sensitive but still hold archaeological value, with parts integrated into urban sites.

Earthquake

Side, located on Türkiye's southern coast, has historically faced natural disaster risks due to its geographical and environmental conditions. Archaeological records indicate earthquake impacts in the Antalya region, including the collapse of monumental structures in ancient cities like Termessos, Rhodiapolis, Perge, Selge, and Phaselis. Other earthquake-related effects included fires, toxic gas releases, water system failures, tsunamis, and the submersion of settlements (AFAD, 2022). Fig. 4 shows the distribution of earthquakes greater than 5 Mw from 1900 to the present.

Fig. 4 is color-coded with circles of different sizes and colors to represent the seismic activity in the Antalya province between 1900 and 2021. Blue circles for magnitudes between 5 and 6 are seen in the Manavgat district, where Side Town is located. According to the current earthquake zones of Türkiye, Side is located in the 2nd-degree earthquake zone. In these regions, ground acceleration is expected to be between 0.30 and 0.40 g. The most intense earthquakes are expected in 1st-degree regions (AFAD, 2022).

Sea level rise and coastal erosion

Side is located on the Mediterranean coast. Fig. 5 shows the risk levels of cultural heritage on the Mediterranean coast against climate change impacts. The coastal area where Side is located is shown in the red box in Fig. 5. According to the legend of this map, the Side region is at a high risk of sea rise. In possible cases, the sea level in this region may rise between 2 and 2.2 meters. This means the region is at risk from rising sea levels. The proximity of the coastal heritage like Apollo Temple to the sea presents significant challenges in the face of climate change (Fig. 6). Rising sea levels, coastal erosion, and intensified storms pose severe threats to the Apollo Temple, risking flooding, structural collapse, and accelerated material decay due to saltwater intrusion, temperature rise, and humidity changes. Shifting coastal landscapes further undermine site stability. Effective preservation requires physical barriers, better drainage, potential artifact relocation, and comprehensive risk assessment and mitigation strategies.

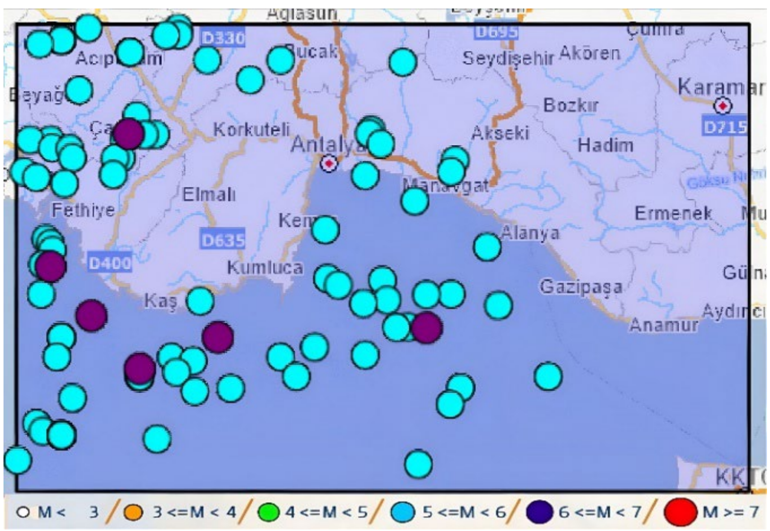

Fig. 4: Distribution of Earthquakes Greater than 5 Mw Affecting Antalya, 1900-2021 (AFAD, 2022).

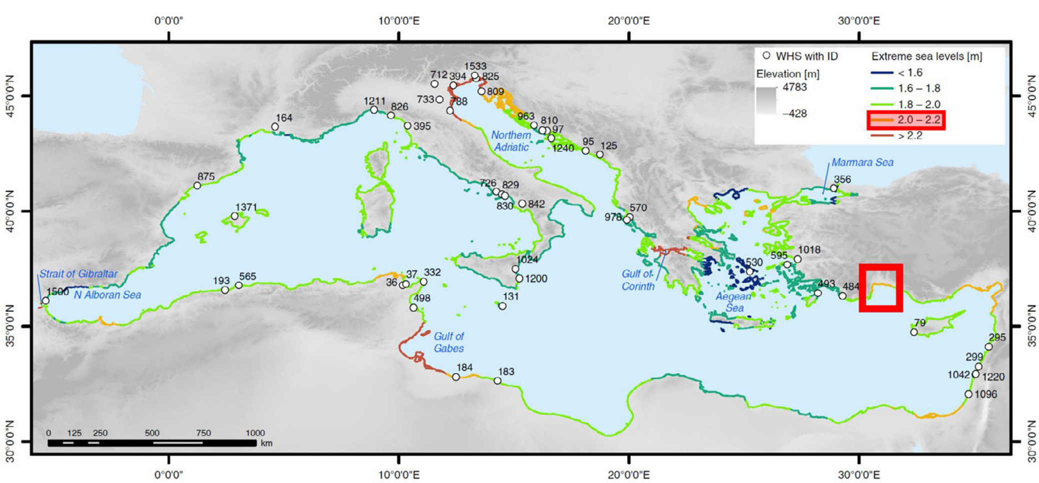

Fig. 5: Risk levels of cultural heritage on the Mediterranean coast (Reimann et al., 2018).

Vegetation

At this stage, the temporal change in the green area ratio within the section encompassing both urban and archaeological sites of the region was analysed. For this purpose, aerial photographs taken in June 2009 and June 2024 were compared (Fig. 7). Using the GIS software, green area pixels were extracted from raster data, and area calculations were performed. The analysis revealed that the green area ratio was 15.57% in 2009 and 11.12% in 2024, indicating a decrease of approximately 4.45% over the 15 years. This decline is likely attributable to multiple factors, including changes in precipitation patterns and increased drought conditions associated with climate change, as well as the implementation of inadequate urban development and environmental policies.

Urbanization

An examination of Side's urbanization process reveals a rapid increase in new structures over the past years, primarily driven by tourism development (Güven Ulusoy, 2014: 75). Fig. 8 illustrates the structural changes in the ancient city of Side in recent

Fig. 6: Vulnerability of coastal heritage

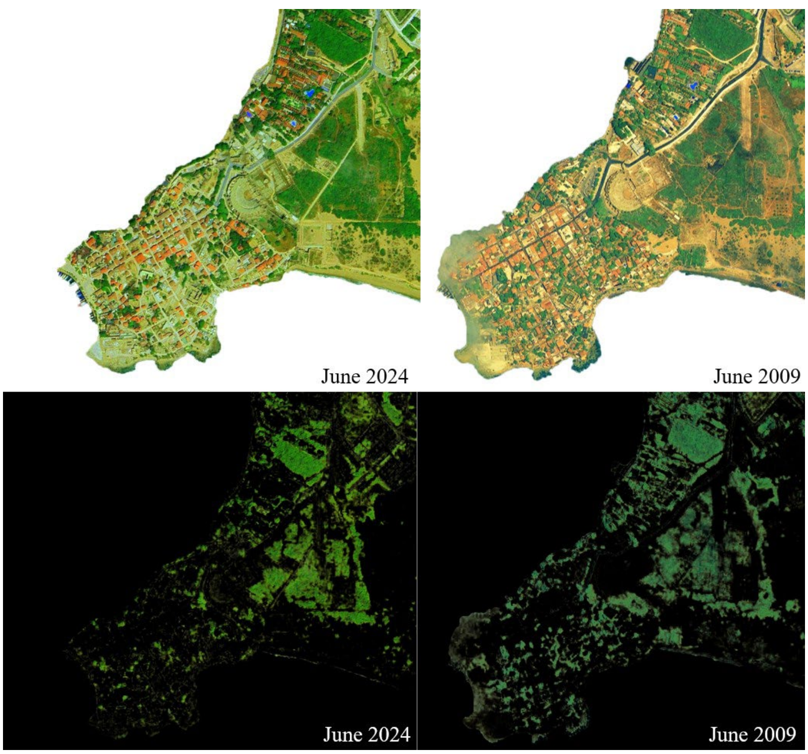

Fig. 7: Change in vegetation

years. A Void-Solid Analysis was conducted on raster data utilizing GIS software. The results indicate that the built-up area ratio was 0.84% in 1953, 4.5% in 1975, 15% in 1992, and 16.8% in 2010, demonstrating a nearly 20-fold increase in construction activity over 57 years. This rapid urban expansion has led to inevitable environmental impacts, which remain a pressing concern today.

Exposure to the sun and high temperatures

Climate change and rising temperatures are closely linked, with higher global temperatures being one of the most evident consequences of climate change. The Side Historic Site's direct exposure to the sun and high temperatures can accelerate the degradation of its ancient stone materials due to UV exposure and thermal expansion, which may lead to cracking and weakening of the structure (Fig. 9). The average temperature in Side, which was 17.1°C in 1979, has risen to 18.5°C by 2023 (meteoblue, 2023). Harsh environmental conditions deteriorate the site's microclimate, threatening its historical landscape. Protecting ruins like the Temple of Apollo requires shelters, shade structures, vegetation, and moisture control systems to reduce heat, wind, and sun exposure. Using reflective materials, regular monitoring, and adaptive management ensures long-term climate resilience in conservation.

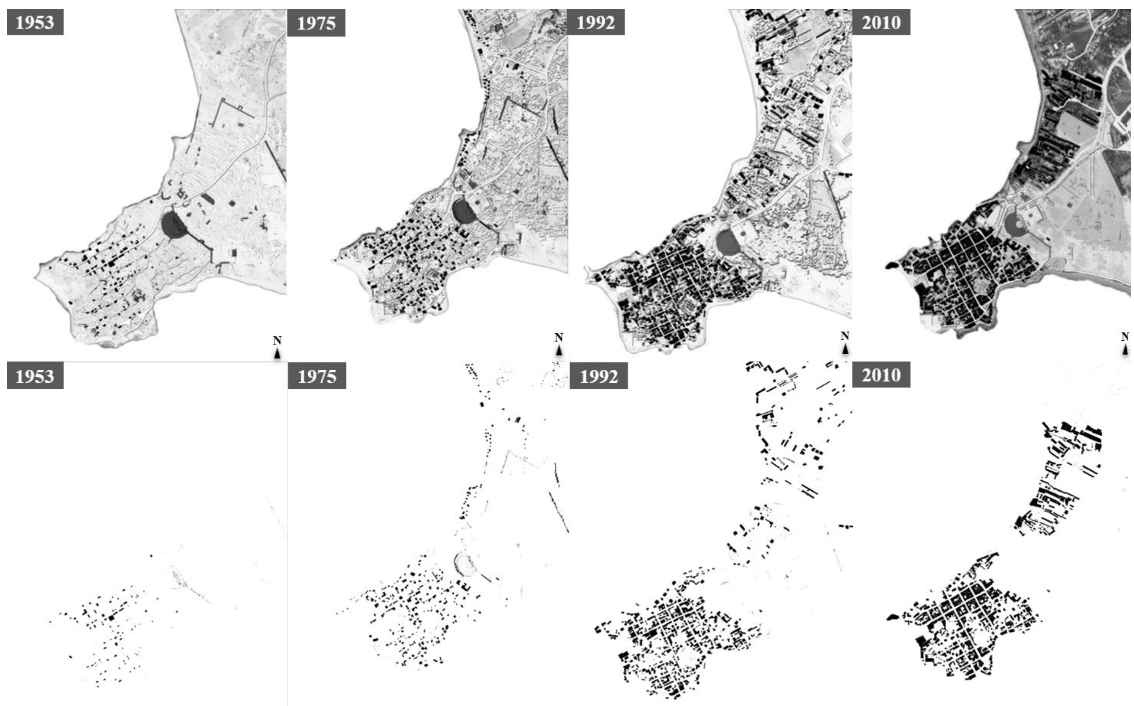

Fig. 8: Urban development of Side between 1953 and 2010

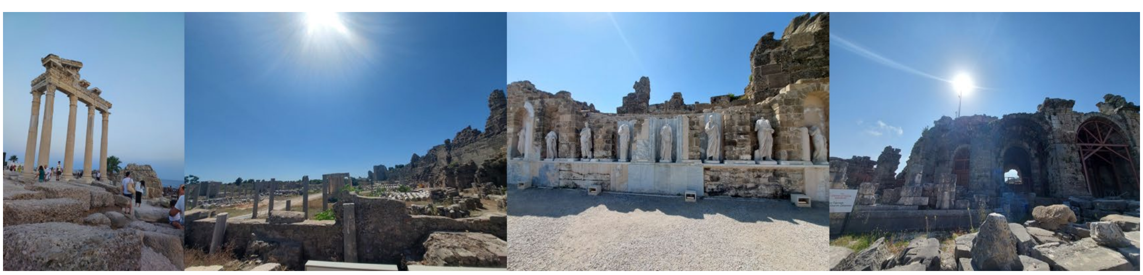

Fig. 9: Exposure to the sun

Accessibility and materials

Accessibility challenges at the site include cobblestone roads, which create instability for wheelchairs, walkers, and strollers, and a lack of ramps, smooth transitions, and handrails, making navigation difficult for individuals with mobility impairments. Narrow pathways and raised curbs further restrict movement. Improving these aspects would enhance accessibility. Environmentally, cobblestones are durable and recyclable, offering some sustainability benefits (Fig. 10). Cobblestone and brick pavements contribute to the Urban Heat Island Effect (UHIE) by absorbing and retaining heat, making cities hotter during heat waves. Their production and transportation also have a high carbon footprint, especially when not locally sourced. Additionally, their impermeability increases rainwater runoff, worsening urban flooding risks, which are escalating due to more frequent extreme weather events (Arora *et al.*, 2023; Logan, 2021). Moreover, climate change impacts like extreme heat can damage such pavements, leading to higher maintenance costs. To mitigate these issues, using cool or permeable pavements and prioritizing sustainable, low-carbon materials in construction to enhance climate resilience urban planners and designers *(Li et al.*, 2013; Santamouris, 2013).

Covering archaeological sites with glass roofs

Covering archaeological sites with glass roofs offers a way to protect them from climate change impacts, but it also comes with certain challenges (Fig. 11). Glass roofs help protect ancient structures from rain, wind, UV exposure, and temperature fluctuations while enhancing the visitor experience. However, in Side, condensation caused by trapped heat and humidity has led to concerns about accelerated degradation. To avoid the greenhouse effect, microclimate design must balance insulation, shading, and ventilation, use UV-treated, reflective glass, and regulate air exchange to maintain a stable environment (Carbonara, 2019).

Over-Tourism

Over-tourism indirectly amplifies climate change impacts through factors such as rising travel demand, air pollution, and an increased carbon footprint (Dodds & Butler, 2019; Peeters *et al.*, 2018). According to MATOB (Manavgat Tourism Hoteliers and Operators Association) 2023 data, Side hosts a total of 295 hotels, 45,211 rooms, and 102,454 beds. However, specific data on visitor numbers and tourism revenue for Side is unavailable. In 2023, Manavgat district received 7,112,462 visitors, generating $7,013,318 in tourism revenue (MATOB, 2023). The study highlights a significant gap in detailed and reliable data regarding Side Ancient City's tourist capacity, daily visitor numbers, and revenue, emphasizing the need for comprehensive tourism monitoring

Fig. 10: Accessibility and materials

Fig. 11: Covering archaeological sites with glass roofs

and reporting. Over-tourism causes overcrowding, environmental degradation, and infrastructure strain, driving loss of local identity and increased pollution. Solutions include tourist taxes, visitor caps, and tourism management strategies. Sustainable tourism management and collaboration are crucial for balancing economic benefits and environmental degradation with long-term sustainability (Dodds & Butler, 2019; Seraphin *et al.*, 2018). In places like Side, managing tourist numbers and adopting sustainable tourism practices are essential to balancing the economic and cultural benefits with the need to protect the environment and local community.

RESULTS AND DISCUSSION

Risk analysis of side effects

This section details the risk analysis of the site in Antalya, focusing on both natural and artificial factors that could threaten the site. Table 3 presents the risks, descriptions, and impacts.

Table 3: Risk analysis of side effects

Risk	Description	Impact
Sea Level Rise and Flooding	Rising sea levels, exacerbated by global climate change, pose a significant risk to low-lying areas of the site. Flooding could damage or submerge parts of the city, especially during storm surges or extreme weather events.	Physical damage to the ruins, erosion of foundational soils, and potential long-term inundation of parts of the site.
Coastal Erosion	The Side's coastal location makes it highly vulnerable to erosion from rising sea levels and increased wave action due to climate change. Over time, this erosion threatens the structural integrity of ancient ruins, especially the Temple of Apollo near the shore.	Loss of structural stability, increased risk of collapse of coastal ruins, and potential loss of archaeological artifacts.
Earthquakes	Climate change indirectly increases seismic risks by melting glaciers, thawing permafrost, and altering sea levels, which destabilize fault lines and soil structures (Turner *et al.,* 2023). Türkiye’s UNESCO heritage sites face rising threats from extreme heat, wildfires, earthquakes, and sea level rise, especially in the western and southern regions. As a high-risk seismic zone, earthquakes could worsen climate-induced damage (Kapsomenakis *et al.,* 2023). Antalya is located in a seismically active region. Earthquakes pose a significant threat to the ancient structures in Side, which were not built to withstand seismic activity.	Structural damage or collapse of buildings, loss of historical integrity, and potential endangerment of visitors and staff.
Temperature Extremes and Freeze-Thaw Cycles	Temperature extremes and fluctuations cause thermal expansion and contraction, leading to cracks and structural weaknesses in stone materials. The freeze-thaw cycle further accelerates damage to stone surfaces and mortar joints.	Cracking and fragmentation of stone structures, leading to long-term deterioration and increased need for conservation efforts.
Drought and Vegetation Loss	Prolonged droughts from climate change can reduce vegetation, destabilize soil, and increase erosion, which accelerates ruin degradation.	Increased soil erosion, loss of protective vegetation, and exposure of foundations and ruins to additional weathering.
Urban Development and Construction Activities	Urban development and construction in Antalya pose risks to the site by causing ground vibrations, pollution, and altered water drainage, potentially compromising the structural integrity of the ruins.	Structural damage from ground vibrations, pollution-related stone deterioration, and increased risk of flooding due to altered drainage patterns.
Tourism Pressure	High tourist traffic at Side accelerates wear and tear, with foot traffic, physical contact, and vandalism worsening ruin degradation. Overcrowding also increases safety risks and maintenance demands.	Physical wear on paths and structures, potential structural damage from unauthorized access, and increased maintenance and repair costs.
Inadequate Conservation and Maintenance Practices	Insufficient conservation, lack of funding, and poor restoration efforts can worsen site damage, while inadequate maintenance increases vulnerability to natural degradation and climate impacts.	Accelerated deterioration of ruins, loss of historical authenticity due to inappropriate restoration, and potential safety hazards for visitors.
Mismanaging Visitor	Poor visitor management and a lack of supervision can lead to vandalism, graffiti, and physical damage. Inadequate signage and barriers allow access to fragile areas, worsening site deterioration.	Damage to the site’s visual and structural integrity, loss of historical and cultural value, and increased costs for repairs and restoration.

Comparison of climate change risks: literature review and Side case study

A structured comparison of climate change risks between example heritage sites (Table 2) and sites (Table 3) is presented below (Table 4). This comparative analysis aims to contextualize the vulnerabilities of Side within the broader framework of global heritage conservation challenges.

The Side Ancient City faces severe climate and human-induced threats, including sea-level rise, erosion, seismic risk, extreme weather, and rapid urbanization. Unlike other heritage sites like Venice and Machu Picchu, it lacks adequate flood defences, visitor regulations, and strong conservation policies, making it especially vulnerable. These challenges highlight the urgent need for adaptive and mitigation strategies to ensure its long-term preservation.

Adaptation and mitigation strategies

Climate change strategies include mitigation, which reduces greenhouse gas emissions to limit impacts, and adaptation, which minimizes risks from extreme weather while leveraging potential benefits. Both approaches work together to address short-term effects and ensure long-term climate resilience (NASA, n.d.). Adaptation strategies focus on adjusting social, environmental, and economic systems to minimize the negative effects of climate change. These include enhancing infrastructure resilience to withstand extreme weather, developing drought-resistant crops, improving water conservation, and building flood defences along coastlines. Mitigation strategies aim to reduce greenhouse gas emissions by transitioning to renewable energy, improving energy efficiency, sequestering carbon, and promoting sustainable implementations and transportation reforms. Combining both adaptation and mitigation is essential for long-term climate resilience, requiring efforts from governments, businesses, and individuals (IPCC, 2023b). Table 5 shows adaptation and mitigation strategies developed in this study for the protection of Sides from climate change impacts.

Table 4: Comparison of climate change risks: similar heritage sites and Side

Category	Similar Heritage Sites (Table 2)	Side (Table 3)	Key Observations
Sea-Level Rise & Flooding	Venice, Petra, Djenné, Stonehenge and Avebury, Chan Chan	Severe risk: flooding threatens ruins and foundational erosion	Both share flooding concerns, but Side lacks large-scale flood control (e.g., Venice MoSE)
Coastal Erosion	Venice, Giza, Petra, Chan Chan	High risk due to coastal proximity (e.g., Temple of Apollo)	Similar erosion issues, but Side's unique archaeological value makes it more fragile
Earthquake Risk	Italy, Greece, and Türkiye are identified as high-risk seismic zones, where earthquakes could exacerbate climate-related damage to Mediterranean cultural heritage sites (Kapsomenakis et al., 2023). These zones need urgent adaptation strategies.	Side Ancient City is located in the south of Türkiye and the Mediterranean region, and is at risk of earthquakes.	Earthquake risk is a challenge for Side, requiring seismic-focused adaptation
Temperature Extremes & Freeze-Thaw Cycles	Greek Theatre of Dionysus	Thermal expansion and freeze-thaw cycles cause stone cracking	Both sites experience stone degradation
Drought & Vegetation Loss	Petra, Stonehenge, and Avebury	Prolonged droughts increase erosion and expose ruins	Side faces greater vegetation loss risks due to its coastal-arid environment
Urban Development & Construction	Venice (tourist-driven construction impact), Giza (construction vibrations, urban sprawl)	Urban expansion alters water drainage, and pollution effects	Both face urbanization risks
Tourism Pressure	Machu Picchu	High visitor traffic causes physical wear and structural stress	Tourism impacts are a shared concern. Side lacks controlled visitor management like Machu Picchu
Inadequate Conservation Practices	Giza (mismanagement of restoration projects), Djenné, Chan Chan	Lack of consistent conservation efforts threatens site integrity	Similar conservation challenges

Table 5 presents a comprehensive framework for climate adaptation and mitigation strategies for Side, covering coastal defence, water management, structural resilience, tourism regulation, green initiatives, and policy advocacy. While it effectively integrates nature-based solutions, technological monitoring, and sustainable tourism, several areas require improvement. Coastal defines strategies that should incorporate hybrid solutions like living shorelines to prevent erosion without disrupting natural sediment transport. Water management should address drought risks alongside flooding by incorporating rainwater harvesting and drought-resistant landscaping. Structural resilience measures should include seismic retrofitting, particularly for earthquake-prone regions such as Türkiye, Italy, and Greece. Sustainable tourism strategies need regulatory mechanisms like visitor caps and

Table 5: Adaptation & mitigation strategies

Adaptation & Mitigation Strategies		
Category	Strategy	Description
Implement Coastal Defence Mechanisms	Construct Sea Walls and Utilize Natural Defences	Develop artificial structures and enhance natural features to prevent coastal erosion
	Beach Restoration	Replenish sand and other natural materials to preserve beach areas
Upgrade Water Drainage and Management Systems	Strengthen Drainage Networks	Improve infrastructure to handle stormwater and prevent flooding
	Rainwater Collection and Control	Introduce systems for capturing and managing rainwater efficiently
Strengthen and Restore Structures	Apply Climate-Resilient Building Materials	Use durable materials that withstand climate extremes
	Routine Upkeep and Inspections	Conduct regular maintenance and checks to ensure long-term stability
Provide Protective Shelters	Temporary and Permanent Refuge Solutions	Offer shelters for immediate or long-term protection against extreme weather
	Shade and Windbreak Installations	Install coverings and barriers to guard against harsh environmental conditions
Enhance Monitoring and Early Warning Systems	Deploy Environmental and Climate Sensors	Set up devices to monitor climate changes and environmental conditions
	Install Early Warning Mechanisms for Severe Weather	Ensure communities receive timely alerts about extreme weather events
Manage Landscapes and Prevent Erosion	Apply Erosion Control Methods	Implement strategies to prevent soil erosion in vulnerable areas
	Promote Sustainable Landscaping Practices	Use eco-friendly techniques and materials to maintain landscapes and minimize environmental impact
Promotion of Sustainable Tourism	Visitor Management Plans	Implementation of strategies to reduce visitor impact and promote sustainable tourism practices.
	Educational Campaigns	Initiatives to raise awareness and educate the public on climate change impacts and sustainable actions.
Energy-Efficient Infrastructure and Practices	Renewable Energy Use	Adoption of clean energy solutions to reduce carbon emissions in energy consumption.
	Sustainable Building Practices	Application of eco-friendly construction techniques to reduce environmental impact.
Carbon Offsetting and Green Initiatives	Tree Planting and Reforestation	Initiatives to offset carbon emissions and restore natural ecosystems through tree planting.
	Green Roofs, Pavements and Walls	Installation of vegetative systems on buildings to improve insulation and reduce heat effects.
Collaboration with Climate and Heritage Organizations	Partnerships with Research Institutions	Collaborations aimed at developing innovative climate and heritage preservation strategies.
	Engagement with Local and Global Communities	Active participation in community efforts to address climate challenges.
Policy Advocacy and Integration	Advocacy for Climate-Responsive Policies	Promotion of policies aligned with climate action to protect heritage sites.
	Integration into Climate Action Plans	Inclusion of heritage preservation strategies in broader climate mitigation plans

controlled access to mitigate Over-Tourism impacts. The green initiatives section would benefit from incentives for sustainable practices around heritage sites, such as tax benefits for eco-friendly businesses. Additionally, policy advocacy should align with global frameworks, including UNESCO's Climate Action Plan and the Paris Agreement, ensuring international coordination in heritage conservation. Strengthening these areas will enhance the practical applicability of the strategies, making them more effective in safeguarding cultural heritage against climate and seismic threats. This study presents a comprehensive, site-specific climate risk assessment of Side Ancient City in Türkiye, integrating environmental, seismic, and anthropogenic threats. The results confirm that the Side faces complex, overlapping risks, such as sea-level rise, coastal erosion, earthquakes, extreme temperatures, drought, vegetation loss, over-tourism, and insufficient conservation measures, many of which are exacerbated by the absence of flood defences and poor tourism management. Unlike prior studies that address single threats in isolation, this research employs a layered vulnerability model combining GIS analysis, field observation, and comparative global heritage data, advancing scholarly understanding of site-specific diagnostics. A critical synthesis with existing literature reveals key parallels with heritage sites like Venice, Petra, Giza, and Machu Picchu in terms of environmental stressors and management challenges. However, Side's lack of adaptive infrastructure and controlled visitor access renders it particularly fragile. However, unlike Petra or Machu Picchu, where structured tourism management exists, Side suffers from a lack of regulated visitor flow and monitoring—a critical gap also noted in research on over-tourism's impact on heritage (Dodds & Butler, 2019; Peeters *et al.*, 2018). The study reveals a novel dimension by addressing green space loss and its implications for microclimate regulation, a factor often overlooked in heritage climate studies. Vegetation cover has declined by 4.45% in Side over the past 15 years, exacerbating urban heat island effects and increasing surface-level erosion risks. While Liu *et al.,* (2022) and Yu *et al.,* (2022) affirm the cooling and stabilizing benefits of vegetation, this study demonstrates how such loss can compound heritage vulnerability in coastal settings. Another important point of synthesis involves seismic threats. While the literature identifies Türkiye as a high-risk seismic zone (Kapsomenakis *et al.,* 2023), few studies offer integrated seismic and climate assessments at the site level. This study advances by linking probabilistic seismic data with climate-induced degradation pathways such as thermal expansion and freeze-thaw cycles (Vyshkvarkova & Sukhonos, 2023). In terms of mitigation, existing literature often proposes isolated strategies—such as protective barriers or climate-resilient materials—but lacks the integrated, site-adapted, and multi-scalar approach offered here. This research develops a model of adaptation and mitigation strategies (Table 5) that align physical interventions (e.g., drainage systems, seismic retrofitting) with policy actions (e.g., sustainable tourism management, community engagement), following the interdisciplinary calls from Bonazza & Sardella (2023) and Sesana *et al.* (2021). In conclusion, this work significantly advances the literature by:

- Providing an integrated, GIS-informed risk assessment model;
- Comparing the sides' vulnerabilities within global case studies;
- Offering a robust set of practical and policy recommendations;
- Shifting heritage conservation discourse from generalized risk awareness to proactive, site-based adaptation planning.

This work moves the discussion forward from generalized vulnerability assessments to localized, actionable frameworks, bridging the gap between theoretical models and practical heritage management.

CONCLUSION

This study presents a significant theoretical contribution by introducing an integrated, site-specific framework that assesses climate, seismic, and anthropogenic risks to heritage sites, addressing a key gap in the literature where such threats are typically examined in isolation. Unlike traditional approaches that analyse risks in isolation, this research synthesizes environmental, urban, and structural vulnerabilities into a unified model. The model combines GIS analysis, probabilistic risk assessment, and global comparisons, offering a scalable and transferable approach to understanding vulnerability and resilience in complex heritage landscapes like Side Ancient City. Managerially, the study provides actionable recommendations, such as coastal defence systems, seismic retrofitting, improved drainage infrastructure, and sustainable tourism regulation, while emphasizing the importance of community engagement and cross-sector collaboration in policy implementation. This model is particularly relevant for Mediterranean heritage zones increasingly exposed to environmental hazards. For future research, the model should be tested in other geographic contexts, integrated with real-time environmental monitoring, predictive modelling to enhance risk forecasting, and expanded to explore socio-economic aspects such as community resilience, equity in tourism, and cost-benefit analyses of intervention strategies. Lastly, future studies can test the applicability of this framework within national policy systems and international agreements (e.g., UNESCO's World Heritage Climate Action Plan or the Paris Agreement) to inform global heritage governance under accelerating environmental change. This study's main limitations include the absence of detailed visitor data for Side Ancient City, limited generalizability due to its single-site focus, lack of real-time environmental monitoring, uncertainties in long-term climate projections, and insufficient detail on seismic retrofitting measures. These constraints reduce the precision and broader applicability of the findings. Other researchers can address these limitations by collecting real-time environmental and tourism data, applying the methodology to multiple heritage sites for broader validation, using advanced climate modelling tools, and collaborating with engineers to develop site-specific retrofitting solutions.

AUTHOR CONTRIBUTIONS

L. Akbarishahabi performed the conceptualization, literature review, methodology, data collection, data analysis, manuscript preparation, and final editing.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely witnessed by the authors.

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ABBREVIATIONS (NOMENCLATURE)

BC	Before Christ
C	Celsius
ENCO	El Niño Southern Oscillation
g	Typical range of earthquake acceleration
GIS	Geographical Information Systems
IPCC	Intergovernmental Panel on Climate Change
MATOB	Manavgat Tourism Hoteliers and Operators Association
MoSE	Modulo Sperimentale Elettromeccanico
Mw	Moment Magnitude
UHIE	Urban Heat Island Effect

UNESCO	United Nations Educational, Scientific, and Cultural Organization
UV	Ultraviolet

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