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# ASSESSING THE CLIMATE CHANGE RELATED RISK OF CULTURAL HERITAGE SITES

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## ABSTRACT

Climate change, already evident in current global conditions, is increasingly affecting cultural heritage sites. To address the climate-related risks these sites face, a methodology was developed based on the IPCC AR6 risk conceptual framework. This methodology identifies climate-driven processes that impact open archaeological sites and uses both climatic and non-climatic indicators to quantify hazard, exposure, and vulnerability to key climate risks, such as heatwaves, droughts, floods, and forest fires. Additionally, projections from climate model simulations are utilized to assess future risk scenarios. Applied to UNESCO World Heritage sites, with the archaeological site of Olympia in the Peloponnese as a case study, the methodology underscores the urgent need for place-based, site-specific adaptation strategies. These strategies are essential for protecting archaeological sites and enhancing their resilience against the increasing frequency and intensity of climate-related risks. A key strength of the methodology is its broad applicability to open archaeological sites worldwide, regardless of their geographical location. Its adaptability allows for comprehensive risk assessments across diverse climatic contexts, offering a valuable tool for safeguarding cultural heritage in the face of evolving climate risks.

**KEYWORDS:** Climate Change, Risk Assessment, Open Archaeological Sites, Climate Projections, Earth Observation, Olympia, UNESCO World Heritage Site

## 1. INTRODUCTION

UNESCO highlights that climate change poses a significant threat to the integrity of cultural heritage sites. Cultural heritage not only enriches history and aesthetics but also fosters economic growth, development, and serves as a symbol of national and social identity. Continued climate-driven deterioration of cultural heritage sites will weaken tourism and economic opportunities for communities (Markham *et al.*, 2016; Hall, 2016). The European Commission supports the preservation of cultural heritage sites while promoting sustainable tourism, acknowledging the socio-economic importance of these sites (European Commission, 2019).

Climate change risks arise from the interactions between climate-related hazards, and the exposure and vulnerability of human and ecological systems (IPCC, 2022). To assess these risks, a combination of physical and socio-economic indicators is used, representing hazard, exposure, and vulnerability (Das *et al.*, 2020). These indicators can be categorized as climatic and non-climatic, and it is essential to consider them in both current and future climates. This is achieved using observational climate records and projections from climate models, such as the IPCC's Representative Concentration Pathways (RCPs) (EEA, 2024), that use different greenhouse gas concentration scenarios for evaluating future climate risks. In addition, Earth observation (EO), the collection of information about Earth's surface and atmosphere using remote sensing technologies, primarily from satellites, has proven to be a valuable tool for analysing the physical environment (Cartalis *et al.*, 2015), providing many non-climatic indicators. The moderate to high temporal and spatial resolution of EO data enables the definition of geophysical parameters.

Several studies have documented the risks posed by climate change to cultural heritage globally (Sesana *et al.*, 2021). However, most of these studies focus on broad regions or provide generalized assessments, lacking the detail needed to assess the specific risks faced by individual heritage sites. A growing body of literature emphasizes the need for localized risk assessments that can account for the diverse environmental, historical, and cultural contexts of heritage sites (Garrote *et al.*, 2020; Nastou & Zerefos, 2023;). To facilitate research on preservation and adaptation—which can, in turn, support decision-making based on interdisciplinary approaches (Fatoric & Seekamp, 2017)—researchers, policymakers, and local and regional administrators are expected to address both short- and long-term challenges. This approach aims to enhance the preservation and adaptation of cultural heritage sites by providing systematic access to scientifically grounded knowledge and innovative tools on the impacts of climate change.

This study addresses a critical research priority by developing and applying a climate risk assessment methodology that integrates geophysical and environmental data with climate projections, providing a comprehensive vulnerability assessment for UNESCO’s World Heritage site of the archaeological site of Olympia, Greece. The methodology supports the development of place-based and site-specific adaptation strategies to protect the cultural heritage site from future climate impacts, while the use of open-access data ensures that the methodology is easily transferable and replicable to other cultural heritage sites. The study area (the archaeological site of Olympia) is introduced in Section 2. Sections 3 and 4 outline the collected data and the adopted methodology for the climate change risk assessment, respectively. Results, as presented in Section 5, focus on climatic and non-climatic indicators, examining the present conditions of the study area as well as future climatic scenarios (2046-2065).

## 2. STUDY AREA

The archaeological site of Olympia, situated on a plain at the confluence of the Alpheios and Kladeos rivers in the western Peloponnese of Greece, is one of the most significant ancient Greek sanctuaries. It is the birthplace of the Olympic Games, which were first held in 776 BC in honor of Zeus (Pleket, 2004). The site includes significant structures such as the Temple of Zeus, the Temple of Hera, the ancient stadium, the gymnasium, and the Palaistra (Figure 1). The archaeological site of Olympia was a religious, athletic, and cultural center, attracting visitors from all over the Greek world. Until today the archaeological site attracts thousands of visitors annually and since 1989, it has been recognized as a UNESCO World Heritage Site (UNESCO).

The archaeological site of Olympia has a long history of vulnerability to various natural hazards, including seismic activity, flooding, wildfires and erosion. As one of the most seismically active regions in Greece, the archaeological site has been affected by numerous earthquakes in the past, which led to structural damage to temples and other important buildings (Alexandris *et al.*, 2014; Christaras, 2008). Flooding has also been a recurring threat, with the nearby Kladeos and Alpheus rivers periodically overflowing, causing damage to the site. Particularly in Late Antiquity, floods exacerbated by erosion from the nearby Kronios Hill led to the covering of parts of the archaeological site under thick layers of sediment (Angelakis *et al.*, 2020; Kalogeropoulos *et. al*, 2023). More recently, the devastating fires of 2007 and 2022 (Kolonia, 2008), which threatened the site's cultural heritage, underscored the need for modern fire management and prevention systems.

To assess the climate-related risks to the Olympia archaeological site, the study focuses on two geographic zones (inner and outer zones), each selected for its relevance to different scales of climate impact and management strategies (Figure 1). The protected archaeological site area (inner zone) covers 13.1 km² and represents the core area where immediate management and adaptation to climate risks are crucial. This zone is prioritized for implementing civil protection measures and urban planning strategies to safeguard the site's infrastructure and cultural heritage. The second zone, the surrounding zone termed as Effect Zone, spans 202.3 km² and forms a cohesive landscape unit functionally connected to the archaeological site. The Effect Zone (outer zone) is essential for defining the processes that affect climate hazards, such as wildfire spread or riverine flooding. Furthermore, it is well-suited for risk prevention strategies and vulnerability mitigation efforts, as interventions in the Effect Zone can reduce the severity of hazards before they reach the core of the archaeological site. However, it is important to note that defining the exact extent of such a zone may vary among cultural heritage sites. The boundaries of the Effect Zone (outer zone) in this study were defined by the authors after examining a combination of geophysical and hazard-specific factors that are unique to the archaeological site of Olympia, as there is no standardized method for defining such a key area.

***Figure 1. Study area including the archaeological site (inner zone) and the surrounding area –effect zone (outer zone)- directly influencing the archaeological site of Olympia.***

## 3. DATA COLLECTION- METHODOLOGY

To accurately assess the risk of the archaeological site of Olympia, a range of data sources was used to estimate the non-climatic indicators. These sources can be grouped into three categories based on their origin: satellite-derived, official, and survey-based data.

Regarding satellite-derived data, Normalized Difference Vegetation Index (NDVI), which is useful for detecting densely vegetated areas that may be exposed to high risk to forest fires in the event of a compound event of drought and heat wave, was calculated based on Sentinel-2 10m resolution data. To assess daytime and night-time surface temperatures which are indicative of high temperatures/heatwave sensitivity, MODIS Land Surface Temperature 8-Day (MOD11A2) satellite product at 1 km spatial resolution was used. To calculate ground slope, as steeper slopes increase sensitivity to flood risk, given that water can rapidly flow downhill, thus increasing the risk of erosion and flooding in adjacent low-lying areas, elevation data from the Copernicus program was used. Additionally, to analyse the land cover/use over the wider area around the archaeological site, Copernicus Land Monitoring Service data was used. Specifically, Corine Land Cover 2018 data at 100m spatial resolution, Forest type and Tree Cover Density layers at 10m spatial resolution, were employed to analyse the land cover/land use categories and calculate indicators such as forest density, percentage of land covered by coniferous forests, percentage of land covered by shrubs and percentage of non-forested areas.

Official data from the European Forest Fire Information System (EFFIS) was used. To detect historical fire incidents and map the burnt areas over the wider area around the archaeological site from 2000 to 2023, burnt areas data in vector format was used. Additionally, to determine the forest mass, expressed as fuel percentage, the fuel map from EFFIS (EFFIS, 2017) was used. Higher percentages of fuel reflect increased sensitivity to fire risk, as more combustible materials are present in the area. To indicate the percentage of land at high risk of flooding, data from the Flood Risk Management Plans of the Greek Ministry of Environment and Energy was used. In addition, data from the OpenStreetMap For the fire risk assessment over the area, geospatial database was used to detect watercourses. Areas with a higher percentage of watercourses are more vulnerable to flooding, as water bodies can overflow during heavy rain events, if watercourses are not properly managed.

Regarding survey-based data, the average number of visitors to museums and archaeological sites during the summer months was estimated from the Hellenic Statistical Authority annual datasets (Hellenic Statistical Authority). Sites with higher visitor numbers exhibit higher exposure to hazards such as heatwaves, as increased human exposure to extreme temperatures can affect visitor safety and site preservation.

The climatic indicators, mean air temperature during summer period, number of tropical nights (Tmin>20°C), number of warm days (Tmax>30°C), mean wind speed summer period, mean relative humidity summer period, mean soil moisture summer period, Drought Index, mean annual precipitation, number of days with very high precipitation and max precipitation height during 5 rainy days, in this study were derived from the Euro-CORDEX dynamical downscaling program, which provides high-resolution (12.5 km) regional climate projections specifically tailored for Europe. This high resolution allows for detailed, localized climate assessments, crucial for site-specific analysis. According to the dynamical downscaling procedure applied to the General Circulation Models (GCMs) using the Regional Climate Models (RCMs) specified in Table 1, each climate projection begins by inputting the outputs of the GCM into the respective RCM. This process enables a more detailed regional simulation of climate variables by refining the GCMs' coarse spatial resolution to the finer scale needed for regional assessments. Multiple regional climate model projections were used to estimate the above climatic indicators (Table 1). Furthermore, the study uses the Representative Concentration Pathway (RCP) 8.5 scenario (adopted by IPCC as the worst case scenario), which represents a high-emissions trajectory characterized by significant greenhouse gas concentrations, particularly carbon dioxide. This comprehensive use of Euro-CORDEX projections, coupled with the ensemble model approach (described in Section 4), provides a robust foundation for assessing future climate risks and developing adaptation strategies based on high-emission scenarios.

***Table 1. General Circulation Models and Regional Climate Models used for estimating the climatic indicators***

| General Circulation Models (GCMs) | Regional Climate Models (RCMs) |
|---|---|
| CNRM-CERFACS-CNRM-CM5 | ALADIN53 |
| ECMWF-ERAINT | ALADIN53 |
| CNRM-CERFACS-CNRM-CM5 | ALADIN63 |
| CNRM-CERFACS-CNRM-CM5 | ALARO-0 |
| ECMWF-ERAINT | ALARO-0 |
| CNRM-CERFACS-CNRM-CM5 | CCLM4-8-17 |
| ECMWF-ERAINT | CCLM4-8-17 |
| ICHEC-EC-EARTH | CCLM4-8-17 |
| MIROC-MIROC5 | CCLM4-8-17 |
| MOHC-HadGEM2-ES | CCLM4-8-17 |
| MPI-M-MPI-ESM-LR | CCLM4-8-17 |
| CNRM-CERFACS-CNRM-CM5 | HIRHAM5 |
| ECMWF-ERAINT | HIRHAM5 |
| ICHEC-EC-EARTH | HIRHAM5 |
| MOHC-HadGEM2-ES | HIRHAM5 |
| NCC-NorESM1-M | HIRHAM5 |

| | |
|---|---|
| CNRM-CERFACS-CNRM-CM5 | RACMO22E |
| ECMWF-ERAINT | RACMO22E |
| ICHEC-EC-EARTH | RACMO22E |
| MOHC-HadGEM2-ES | RACMO22E |
| MPI-M-MPI-ESM-LR | RACMO22E |
| NCC-NorESM1-M | RACMO22E |
| CNRM-CERFACS-CNRM-CM5 | RCA4 |
| ECMWF-ERAINT | RCA4 |
| ICHEC-EC-EARTH | RCA4 |
| IPSL-IPSL-CM5A-MR | RCA4 |
| MOHC-HadGEM2-ES | RCA4 |
| MPI-M-MPI-ESM-LR | RCA4 |
| NCC-NorESM1-M | RCA4 |
| ECMWF-ERAINT | REMO2009 |
| MPI-M-MPI-ESM-LR | REMO2009 |
| ECMWF-ERAINT | REMO2015 |
| ICHEC-EC-EARTH | REMO2015 |
| IPSL-IPSL-CM5A-LR | REMO2015 |
| MIROC-MIROC5 | REMO2015 |
| MOHC-HadGEM2-ES | REMO2015 |
| NCC-NorESM1-M | REMO2015 |
| NOAA-GFDL-GFDL-ESM2G | REMO2015 |
| ECMWF-ERAINT | RegCM4-2 |
| ECMWF-ERAINT | RegCM4-6 |
| ECMWF-ERAINT | WRF331F |
| MPI-M-MPI-ESM-LR | WRF361H |
| IPSL-IPSL-CM5A-MR | WRF381P |
| MOHC-HadGEM2-ES | WRF381P |

## 4. METHODOLOGY

The methodology to assess climate change-related risks for archaeological sites, was based on the IPCC AR6 risk conceptual framework (Ara *et al.*, 2022), which emphasizes that risks result from the interactions between climate-related hazards and the exposure and vulnerability of affected human and ecological systems. Additionally, the European Climate Risk Assessment (EUCRA) framework (EEA, 2024) was considered. EUCRA categorizes climate risk drivers into two types: climatic indicators, representing direct environmental changes caused by climate change and act as drivers for hazards, and non-climatic indicators, which primarily affect exposure and vulnerability and are often linked to human and socio-economic factors.

The research methodology is organized into the following five steps. First, the archaeological site is assessed to identify characteristics and interlinked systems that may be vulnerable to climate change impacts. Then, climate-related hazards, such as rising temperatures and extreme weather events, are identified for their potential to affect site's features or systems. The third step involves evaluating exposure, namely the level that the surrounding ecosystems or human systems are impacted by these hazards. Next, vulnerability is analysed by assessing the sensitivity and adaptive capacity of the ecosystems or species to withstand climate-related threats. Finally, the overall climate change-related risk is determined by comparing climatic and non-climatic indicators—representing hazards, exposure, and vulnerability—with average values that were defined at the national scale. This comparison contributes to the assessment of the system characteristics at risk and provides an overall evaluation of the site's climate-related risk.

The archaeological site of Olympia, beyond its structures and monuments, is defined by a unique landscape that complements the main archaeological site, while it attracts a large number of visitors. This paper analyses the climate change risks affecting this interconnected system; the archaeological site, its landscape, and visitors/workers. Figure 2 presents the developed methodology for the archaeological site of Olympia. Climatic drivers, such as heatwaves, drought, fire weather and precipitation changes and non – climatic drivers, including population, land cover, geophysical features and fuels can influence the overall system. As shown, the interaction between these climatic and non-climatic drivers may lead to direct impacts, such as rising incident of wildfires, which in turn can result in indirect effects like irreplaceable damage of the site and loss of cultural knowledge, as well as smoke inhalation and heat stress to visitors/workers. These changes pose risks to the site itself as well as to the people visiting or working at the archaeological site

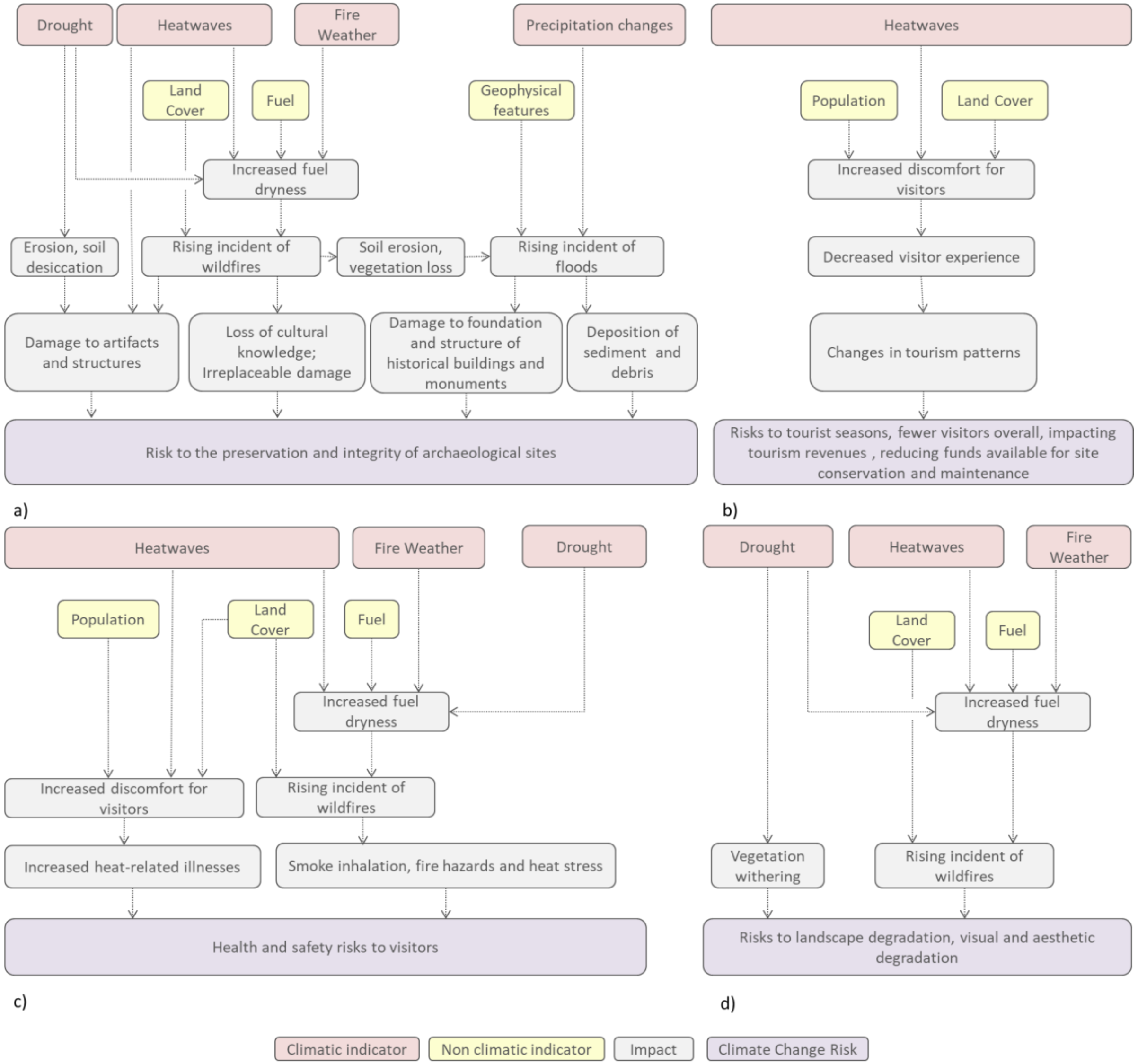


*Figure 2. Flowchart mapping the developed methodology for the four emergent risks*

*Table 2. Climatic and non-climatic indicators for the climate change risk assessment of Olympia archaeological site*

| | Impact driver | Indicators | | Impact driver | Indicators | Potential Impact |
|---|---|---|---|---|---|---|
| Hazard | Climatic drivers | | Exposure-Vulnerability | Non-climatic drivers | | |
| | Heatwaves | Mean air temperature during summer period<br>Number of tropical nights (Tmin>20 ∘ C)<br>Number of warm days (Tmax>30 ∘ C) | | Geophysical features<br>Land Cover<br>Population | Normalized difference vegetation index - NDVI<br>Percentage of non-forested areas<br>Number of visitors | Heatwaves have a profound impact on archaeological sites and the experience of visitors. These effects can be broadly categorized into the physical damage to heritage sites and the health and safety concerns for visitors. Prolonged exposure to extreme heat can cause materials such as stone, wood, and brick to expand and contract. This process weakens structures, leading to cracks and erosion. |
| | Fire weather | 1. Mean air temperature summer period<br>2. Mean wind speed summer period<br>3. Mean relative humidity summer period<br>4. Mean soil moisture summer period | | Land Cover<br>Fuel | 1. Percentage of land covered by forests.<br>2. Percentage of land covered by coniferous forests<br>3. Percentage of land covered by shrubs<br>4. Percentage of burnt areas<br>Fuel percentage | Wildfires present a significant and growing threat to archaeological sites and visitors. Fires can cause severe damage to structures, artifacts, and the environment, leading to the loss of cultural heritage and the degradation of historical sites. For visitors, wildfires pose health and safety risks, as well as reducing the aesthetic and experiential value of sites. |
| | Drought | 1. Drought Index<br>2. Mean annual precipitation<br>3. Mean soil moisture during summer period | | Geophysical features | Normalized difference vegetation index - NDVI | Soil erosion is a major consequence of drought, especially in areas where vegetation dies off, leaving the soil unprotected. Wind and rain erosion can rapidly wear away the protective layers over archaeological sites, exposing them to further damage. Drought often affects the natural beauty of archaeological sites, as vegetation withers and water features disappear leading to degraded landscapes. |
| | Increased precipitation | 1. Number of days with very high precipitation<br>2. Max precipitation height during 5 rainy days | | Geophysical features | 1. Slope<br>2. Percentage of areas at high risk of flooding<br>3. Presence of watercourses | Flooding has a profound impact on archaeological sites, causing erosion, waterlogging, contamination, and long-term structural damage. For visitors, floods pose significant health and safety risks, reduce access to sites, and diminish the overall experience |

The indicators representing the climatic and non-climatic drivers are presented in Table 2. To reduce uncertainty and enhance the robustness of the projections, the ensemble technique was employed. In detail, the climatic indicators were derived by averaging across multiple simulations (ensemble approach), to yield a more reliable estimation of future climate conditions. These projections focus on the period 2046–2065 and are compared with a historical baseline period of 1971–2000. Furthermore, climatic indicators are analysed across three areas: the archaeological site of Olympia (inner zone), the effect zone (outer zone), which includes the archaeological site, and the entire country of Greece. Due to the spatial resolution of the Euro-CORDEX data (12.5 km), the climatic indicator values for both zones (inner and outer) were found to be nearly identical. As a result, only the climatic indicator values for the outer zone were used to represent hazards and estimate the risk to the archaeological site. For non-climatic indicator values, data from both inner and outer zones were used to quantify vulnerability and exposure of the site and were compared to national averages to assess the climate change-related risk.

## 5. RESULTS

### 5.1. *Climatic Indicators*

Table 3 provides the arithmetic values of the climatic indicators for the archaeological site of Olympia for the periods 1971-2000 and the projected future period 2046-2065 under the RCP 8.5 scenario (a high greenhouse gas emissions scenario). The values are also compared to the Greek national average. As a conclusion, the archaeological site of Olympia has been historically warmer than the national average by nearly 1°C, and this trend continues into the future. Under the RCP 8.5 scenario, a significant temperature increase is expected for the mean air temperature, reaching 26.3°C, Furthermore, Olympia experiences higher number of warm days (annual number of days with maximum daily temperature over 30°C) compared to the current national average (57 vs. 31). This difference widens in the future, with Olympia archaeological site expected to have 93 warm days. Historically, the archaeological site of Olympia has experienced far fewer tropical nights (annual number of days with minimum temperature under 20°C) compared to the Greek average (11 vs. 35). However, the number of tropical nights in the archaeological site is expected to increase dramatically to 65 by 2046-2065, surpassing the current national average. The above indicate that the archaeological site of Olympia will experience more frequent and intense heatwaves, longer warm periods, and significantly more tropical nights, making it more vulnerable to extreme heat and forest fire risks.

The archaeological site of Olympia experiences more heavy rain days than the national average and the future scenario suggests a slight increase in heavy rain days for Olympia, from 9.7 to 11.3. This increase suggests that the intensity and concentration of rainfall events could grow, which can lead to flooding at the local scale. Additionally, higher maximum precipitation for a 5-day period is observed compared to the national average, meaning it is more likely to see short-term bursts of heavy rainfall. This value is projected to decrease slightly following the RCP 8.5 scenario but remains above the national average, indicating a continued risk of flooding during intense storms or prolonged rain events.

The archaeological site of Olympia historically has lower wind speeds than the Greek average. This trend continues into the future, with wind speeds slightly increasing in the site but still remaining lower than the current national average. Lower wind speeds and their continuation into the future suggest that wind-driven fires will be less of a concern compared to other regions, although other factors like rising temperatures and dry conditions should still be monitored for fire risk.

According to Table 3, the archaeological site of Olympia receives significantly more annual rainfall than the Greek average, nearly 40% more (906 mm vs. 649 mm). However, under the RCP 8.5 scenario, rainfall in the archaeological site decreases slightly but remains higher than the national average. Furthermore, the archaeological site has a higher drought indicator than the national average, indicating more severe drought conditions. In the future, the drought index is expected to decrease slightly, but it will remain higher than the national average. Historically lower summer humidity is observed than the national average, while the trend continues in the future, with humidity slightly decreasing. Higher soil moisture levels than the national average is observed. However, in the future, both the archaeological site Olympia and Greece are expected to experience reduced soil moisture, with Olympia dropping to 708 $kg/m^2/s$. Despite a slight future decrease in the drought index, the archaeological site of Olympia will continue to face significant drought risks, with reduced soil moisture, lower summer humidity and increased air temperature intensifying the region's vulnerability to drought, leading to vegetation withering and landscape degradation, and the risk of wildfires.

***Table 3. Climatic indicator values for the archaeological site of Olympia***

| | 1971-2000 | | RCP 8.5(2046-2065) | |
|---|---|---|---|---|
| Climatic indicator | Olympia archaeological site | National average | Olympia archaeological site | National average |
| Mean air temperature summer period (°C) | 23.3 | 22.34 | 26.3 | 25.07 |
| Number of warm days (Tmax>30°C) | 57 | 31 | 93 | 65 |
| Number of tropical nights (Tmin>20°C) | 11 | 35 | 65 | 66 |
| Mean annual precipitation (mm) | 906 | 649 | 850 | 622 |
| Number of heavy rain days (>20mm) | 9.7 | 5.6 | 11.3 | 7.35 |
| Max precipitation during 5 rainy days (mm) | 54.9 | 44.8 | 50.2 | 42.3 |
| Mean wind speed summer period | 2.62 | 3.63 | 2.91 | 3.9 |
| Drought Index | 2.32 | 1.93 | 2.19 | 1.64 |
| Mean relative humidity summer period (%) | 49.7 | 53.8 | 47.2 | 54.05 |
| Mean soil moisture summer period ( kg m-2 s-1) | 838 | 776 | 708 | 653 |

Overall, the Table 3 highlights warmer and drier summers with more extreme weather events, such as increased heat days and heavy rain, as projected under climate change scenarios. In summary, climate change could severely affect the preservation of the Olympia archaeological site by increasing the rate of deterioration of its structures, creating adverse conditions for visitors, and requiring more intensive efforts to maintain its integrity. This, in turn, could reduce its appeal as a tourist destination, thus impacting the local economy.

## 5.2. *Non Climatic indicators*

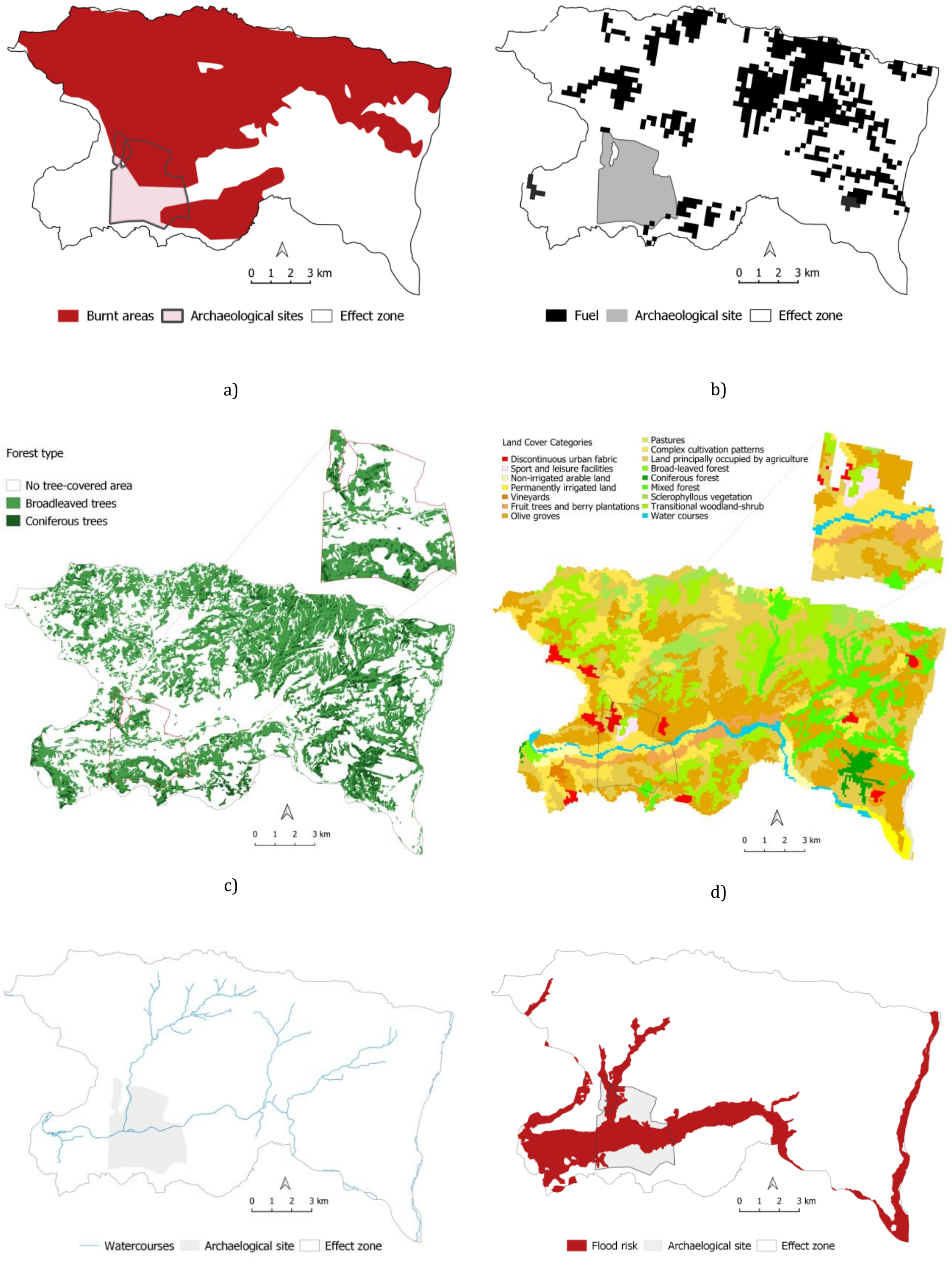
Non-climatic indicators are listed in Table 4, with selected indicators visually represented in Figure 3. Both inner and outer zones exhibit higher tree cover density compared to the national average (36.1% and 38.6% vs. 22.1%). The outer zone has a slightly greater percentage of coniferous forest and significantly more shrub coverage, which is highly flammable, increasing the risk of wildfires. This, coupled with a higher fuel percentage, makes the outer zone particularly vulnerable to wildfires, especially during dry seasons. Additionally, both zones show a much higher percentage of burnt areas than the national average, indicating a history of fire hazards, which can lead to future vulnerability.

The inner and outer zones have a lower percentage of non-forested area compared to the national average and therefore do not experience more intense heatwaves due to increased exposure to extreme temperatures as areas with higher non-forested land do. However, both zones have higher NDVI values, indicating healthier vegetation than the national average. This healthier vegetation can help mitigate the effects of drought and lessen the severity of heatwaves.

In the outer zone, the higher maximum slope increases the potential for runoff during heavy rainfall, a fact that elevates flood risk. Steeper slopes can intensify flood hazards and accelerate erosion. The inner zone has a significantly larger percentage of areas classified as high-risk for flooding compared to the national average. These high-risk areas are more vulnerable to excessive rainfall and could experience greater impacts from climate change. Additionally, both zones contain watercourses, which, while beneficial for supporting vegetation, can contribute to localized flooding during heavy rains, if not properly managed.

***Table 4 Non-climatic indicator values for the archaeological site of Olympia***

| Non-climatic indicator | Inner Zone | Outer Zone | National average |
|---|---|---|---|
| Land Cover: Mean Tree Cover density (%) | 36.1 | 38.6 | 22.1 |
| Land Cover: Coniferous forests (area in %) | 6.9 | 7.9 | 6.9 |
| Land Cover: Non-forested area (area in %) | 57.6 | 54.4 | 69.2 |
| Land Cover: Shrubs (area in %) | 9.0 | 19.0 | 5.84 |
| NDVI (mean) | 0.58 | 0.59 | 0.53 |
| Fuel (area in %) | 0.5 | 20.6 | 47.12 |
| Burnt areas 2000-2023 (area in %) | 45.6 | 58.0 | 13.7 |
| Slope (angle in %) (min-max) | 0-40 (7.87) | 0-55 (10.08) | 10.9 |
| Areas at high risk of flooding (area in %) | 46.9 | 15.0 | 23.5 |
| Presence of watercourses | ✓ | ✓ | ✓ |
| Number of visitors | 292037 | - | 67169 |



a) b)

c) d)

e) f)

*Figure 3. Non-climatic indicators for the inner and outer zones a) Burnt areas 2000-2023, b) Fuel, c) Forest Type, d) Corine land cover, e) Watercourses and f) Areas at high risk of flooding*

In summary, while both zones have strengths in vegetation and forest cover compared to the national average, specific parameters indicate varying vulnerabilities to fire, drought, heatwaves, and floods, particularly in the outer zone, which directly influences the archaeological site.

### 5.3. *Climate change risk assessment*

The climate change-related risks for the archaeological site of Olympia are presented in Table 5, along with the contribution of climatic and non-climatic drivers. Emerging risks are complex and driven by rising temperatures, shifting precipitation patterns, and changes in land use. The risk assessment was conducted by synthesizing data after evaluating each indicator, using future climate projections and comparing them with the current national average. For example, if all indicators are projected to increase and exceed the national average, the emergent risk is considered high. If the majority of indicators meet these criteria and some remain below the national average, the emergent risk level is adjusted to moderate to high or moderate, depending on the number of indicators meeting the threshold.

***Table 5. Emerging climate change related risks for Olympia archaeological site***

| | Climatic driver | | | Non-climatic driver | | Emergent Risks |
|---|---|---|---|---|---|---|
| | | RCP 8.5 | | | | |
| Hazard | Heatwaves | ↑ | Exposure-Vulnerability | Geophysical features | ↓ | **Moderate to High**: Olympia archaeological site is projected to experience more frequent and intense heatwaves, with the number of warm days (Tmax > 30°C) rising from 57 to 93 days by 2046-2065, and tropical nights increasing from 11 to 65. The mean summer temperature is expected to rise to 26.3°C, which is significantly above the national average. These conditions will place stress on archaeological structures and visitors, though somewhat mitigated by the area's vegetation cover. |
| | | | | Land Cover | ↑ | |
| | | | | Population | ↑ | |
| | Fire weather | ↑ | | Land Cover | ↑ | **High**: Archaeological site of Olympia is highly vulnerable to wildfires due to both climatic and non-climatic factors. Increasing temperatures, drier conditions, and reduced soil moisture create a high risk of fires. The outer zone, in particular, has a high percentage of flammable vegetation (19% shrub cover), and a significant history of burnt areas (58% compared to the national average of 13.7%). While wind speeds are lower than the national average, the combined factors of vegetation, drought, and heatwaves make wildfire a significant concern. |
| | | | | Fuel | ↑ | |
| | Drought | ↑ | | Geophysical features | ↓ | **Moderate**: Although the drought index is slightly decreasing, Olympia archaeological site will continue to face drought risks due to declining soil moisture and reduced relative humidity in the summer. The risk is elevated by reduced vegetation health during prolonged dry periods, though healthier vegetation (higher NDVI) compared to national averages provides some mitigation. Overall, The site remains vulnerable to drought, but the risk is not as severe as other hazards like heatwaves and fire. |
| | Increased precipitation | ↑ | | Geophysical features | ↑ | **High**: The archaeological site of Olympia receives significantly more rainfall than the Greek national average and heavy rain events are projected to occur in the future, despite a slight decrease in total annual precipitation. The presence of slopes and a high percentage of areas at risk of flooding (46.9% for the inner zone) heighten flood vulnerability. The presence of watercourses and increasing heavy rain days further contribute to localized flood risks, especially during extreme weather events. |

In summary, climate change presents considerable threats to the preservation, safety, and cultural significance of Olympia. Flooding, heatwaves, drought, and wildfires can cause direct damage to the site and its surrounding environment, while also undermining visitor experience and posing significant financial challenges for long-term preservation efforts.

## 6. CONCLUSIONS

This study developed and applied a comprehensive methodology for assessing climate change-related risks to archaeological sites, using Olympia as a case study. By integrating both climatic and non-climatic indicators, the approach offers a structured framework for quantifying current vulnerability and exposure while projecting future climate hazards.

One of the methodology's key strengths lies in its adaptability and transferability. The use of open-access data allows it to be applied globally to other archaeological sites, while the integration of both climatic and non-climatic factors ensures a holistic risk assessment. Additionally, leveraging climate projections from the Euro-CORDEX program enables detailed, localized assessments of climate impacts, facilitating the development of long-term adaptation strategies by focusing on future hazard scenarios.

However, some limitations exist, particularly concerning the spatial resolution of the climate data. While the 12.5 km resolution provides valuable regional insights, it may fail to capture micro-scale climatic variations within the core archaeological site, potentially overlooking localized risks. Another challenge lies in the selection of appropriate indicators, especially for non-climatic drivers, to accurately quantify exposure and vulnerability. Identifying suitable metrics, such as single-variable indicators or compound indices, is complex. Furthermore, the available data—whether demographic, economic, or health-related—often varies in spatial resolution, frequently covering larger areas than the study site or lacking consistent quality and coverage. The methodology also assumes that such data is current, which may not always be the case. Additionally, the distinction between exposure and vulnerability indicators is not always clear-cut, as some overlap between the two exists (EEA, 2024).

To enhance future applications, incorporating higher-resolution local climate models could capture finer-scale variations, and developing a more standardized method for defining key zones, such as the "Effect Zone," would improve the consistency of the methodology across different sites. Despite these limitations, the methodology provides a valuable framework for assessing climate-related risks to archaeological sites. With continued refinement, it has the potential to deliver even more accurate, site-specific risk assessments and adaptation strategies.

In its application to the archaeological site of Olympia, the methodology effectively accounts for both climatic and non-climatic drivers, providing a comprehensive evaluation of how various factors interact to influence the site's vulnerability. Specifically, Olympia is projected to experience more frequent and intense heatwaves, which will increase thermal stress on archaeological structures and pose safety risks for visitors. The risk of localized flooding will rise due to heavy rainfall events and the area's geophysical features. Additionally, prolonged dry periods, combined with the presence of flammable vegetation, will heighten the risk of wildfires, further endangering the site. These climate-related threats could also reduce tourism, adversely affecting the local economy, which relies heavily on visitors to the archaeological site of Olympia.

The complex and interlinked nature of climatic and non-climatic drivers necessitates adaptive management strategies to enhance the resilience of archaeological sites. Collaborative efforts among stakeholders from various sectors (local authorities, tourism, etc.) will be crucial in implementing effective adaptation strategies. Continuous monitoring of climatic and non-climatic indicators is essential for understanding evolving risks and adjusting management practices accordingly.

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