

CLIMATE EXTREMES AND ITS IMPACT ON THE CULTURAL HERITAGE OF THE REPUBLIC OF SERBIA – CONSERVATION OF MATERIALS

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Abstract. *Climate change, manifested in global warming and increasingly frequent weather extremes, represents one of the most complex contemporary challenges with far-reaching consequences for the preservation of cultural heritage. This paper systematically explores the determinants protecting architectural structures and monuments within the territory of the Republic of Serbia, analyzing their vulnerability under conditions of a disrupted climatic balance. The research focuses on the material processes of degradation resulting from climatic impacts, establishing a necessary correlation between the socio-cultural domain and exact natural sciences. The methodological framework is conceptualized as an expert synthesis and qualitative-analytical review, integrating theoretical perspectives, normative analyses of current legal regulations, and socio-legal dimensions of protection based on expert judgment. The synthesis unequivocally indicates that high environmental awareness and a radical improvement of monitoring systems within local self-government units are key factors for an effective preservation strategy and precise risk assessment. Analytical indicators emphasize the imperative for intensifying regional cooperation and the continuous innovation of the legal framework. The findings suggest the necessity of affirming a new sense of social responsibility and ecological ethics in order to ensure the long-term sustainability of identity markers through precise climate scenario modeling at both local and global levels.*

Key words: *Climate changes, Cultural heritage, Architectural buildings, Monuments, Ecology, Climate extremes.*

1. INTRODUCTION

Global climate change, accelerated by anthropogenic pressures, represents an escalating threat to the physical preservation and structural integrity of built cultural heritage worldwide. Rising temperatures, shifting hydrological cycles, and severe meteorological extremes no longer constitute distant environmental risks; rather, they act as active catalysts for material decay, structural destabilization, and the potential loss of historical memory. Consequently, modern heritage management requires a critical shift away from reactive conservation toward

proactive, interdisciplinary frameworks that bridge environmental science, public administration, and civic engagement. Within the Republic of Serbia, the contemporary protection of cultural property faces these identical systemic challenges, requiring a firm institutional and scientific response. The Law on Cultural Heritage (2021) establishes the necessary legal foundation for preventive protection and emergency interventions, formally recognizing heritage as an asset of dominant public importance that must be safeguarded from atmospheric crises and environmental degradation (Milunović, 2001). However, formal statutory regulation is inherently insufficient on its own. To translate legal mandates into sustainable field solutions, an integrated interdisciplinary approach is crucial – one that effectively links civic ecological awareness with precise engineering and conservation methods. Developing a sustainable relationship with the environment directly reflects on the preservation of both tangible and intangible heritage, thereby securing historical continuity and community identity in an era of climate instability (Cassar and Pender, 2005; ICOMOS, 2019; Stojanović, V., 2009).

The primary objective of this study is to evaluate the systemic impacts of climate extremes on immovable cultural heritage in Serbia through an expert synthesis of material degradation processes, legislative protection frameworks, and socio-ecological monitoring strategies.

2. CLIMATE CHANGE AND THE TRANSFORMATION OF SOCIAL PRACTICES

As a result of excessive consumption, the Earth's climate is changing at a significantly faster pace than its natural course. Due to a lack of adequate information and understanding of sustainable development, cultural heritage is being devastated (Jovanović, 2022; Lazić and Stanković, 2018). The issue of global climate change is a particular concern for both state and international actors. Global climate change impacts the world economy (Stern, N., 2007) and, consequently, exists in a feedback loop with the sustainability of economic policies.

Industrial production increases the amount of carbon emissions, which affects the level of environmental pollution (IPCC, 2023). The Fourth Industrial Revolution is the fundamental accelerator of climate change and threaten to the population identity (Schwab, 2017; Grubb et al., 2008). Carbon dioxide, methane, nitrogen oxides, and fluorinated gases (Solomon, et al., 2009) are most prevalent as industrial by-products. They act cyclically. Once emitted into the atmosphere, they trap heat that would otherwise be radiated into space, leading to global

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warming. Global warming increases the intensity of hydrological cycles (more precipitation, more extreme droughts) as well as the frequency of extreme weather events.

3. CLIMATE CHANGE AND ITS IMPACT ON IMMOVABLE CULTURAL HERITAGE

The primary combustion of fossil fuels leads to the accumulation of greenhouse gases. They trap thermal energy within the atmosphere and drive global warming. This results in damage to the cultural heritage, necessitating the urgent establishment of a legally regulated protection system. To protect architectural structures and monuments, it is essential to integrate and apply methods that encompasses research phases, legislative proposals, strategic management, and the definition of heritage' preservation through the lenses of ecology and legal regulation. The influence of immovable cultural property, that predominantly owned by churches and religious communities, is recognized worldwide and testifies to the material and spiritual culture of the most population. Ecclesiastical heritage has always been deeply rooted in the culture of society. Due to centuries of existence and the natural wear and tear of materials, immovable cultural heritage represents an exceptionally vulnerable category. Furthermore, these sites serve as indicators of social events and relationships within the community. Understanding the role of immovable property is vital for establishing cultural identity and ensuring effective conservation (Josipović et al., 2011; Langenbach, 2017; Sabbioni, et al., 2008).

4. CLIMATE CHANGE AS A DRIVER OF DEGRADATION

Climate change is no longer merely a latent threat; it has become a fundamental driver of material degradation. European cultural heritage represents an invaluable testimony to human history, encompassing an extensive assets – archaeological sites, monumental medieval churches, cathedrals to historic urban ensembles and modern cultural monuments. Built by diverse but inherently sensitive materials, cultural heritage se directly exposed to atmospheric and biochemical processes.

European and Serbian immovable heritage is directly threatened by thermal degradation and hydrological cycles (Langenbach, 2017; Sabbioni, et al., 2008). Erosion and flash floods directly jeopardize physical permanence and structural stability. To ensure effective defense

and the establishment of preventive strategies, it is necessary to integrate modern science and diverse perspectives into protection plans (Kostadinov, et al., 2022). For the long-term preservation of Serbia's heritage, it is essential to develop adaptive conservation strategies. The establishment of a dedicated fund for monitoring and emergency interventions, recognizing heritage as a key vulnerable category in the context of climate change protection, could represent a crucial step forward (UNESCO/ICCROM, 2016).

4.1. Thermal degradation

The increase in average annual temperatures and the temperatures fluctuations impose significant thermal stress. Mechanical erosion is caused by thermal stress acting on susceptible materials, thus leading to material fragmentation (Đorđević and Avramović, 2014). Extreme temperatures cause the intensive desiccation of organic materials, leading to material cracking and permanent damage (Oruc, et al., 2016).

The alteration of established hydrological regimes is a primary driver of physical and chemical degradation. Atmospheric agenses and intense precipitation cause physical erosion by washing away protective and surface layers of facades. Water penetrates the interior of a structure expands within the capillaries when the temperature drops below freezing. Upon freezing, water generates powerful pressure within cracks causing the material to crack and break. Pressure resulting from salt crystallization is also an inevitable phenomenon that devastates materials. The crystallization of salts within the interior of the object increases internal pressure, leading to fracturing (Momčilović-Petronijević et al., 2023, Mitrović, 2024).

4.3. Soil desiccation

The humidity is a critical characteristic of the soil. Prolonged periods of drought lead to the intensive shrinking clay and binding materials within the soil. The reduction in soil volume beneath building foundations causes differential settlement that results in complex cracks in walls and undermines the structural integrity of load-bearing elements in medieval and other early structures. The presence of humidity is regulated by the interaction between available precipitation and the rate at which water is released from the soil via evapotranspiration. Although the intensity of seasonal moisture changes is lower, prolonged dry periods have the greatest impact on the soil. The absence of vegetation during droughts can cause damage to the underground portions of a structure; as root growth is directed toward moister areas of the

terrain, roots may damage the foundations along their path (Berisavljević and Berisavljević, 2024; Rakić, et al., 2012).

Drought also alters the chemical composition of the soil, endangering artifacts made of organic materials typically sustainable in moist, anoxic environment. Changing humidity percentage damage organic materials within archaeological sites. The sudden humidity loss alters the shape and internal structure archaeological objects, resulting in cracking, deformation and many physical damages. The process of decomposition in anoxic conditions, significantly slower or completely halted as only anaerobic organisms are active, which is less efficient in biodegradation. The anoxic circumstance contains no free oxygen. For that reason, it is essentially as organic materials are exceptionally well-preserved under such conditions (Zeng et al., 2019; Franković, 2024).

4.4. Chemical and biochemical degradation

The changes in air circulation can lead to the pollutants accumulation on local. The pollutions triggered by sulfur dioxide (SO₂) and nitrogen oxides (NO_x) react with atmosphere humidity resulting with forming acid rain. These affect highly aggressive to inorganic materials. Acid rain accelerates the metals' corrosion, particularly sensitive ones (such as bronze sculptures). The process compromises not only the aesthetic appearance but also the monuments' structural stability. Similarly, limestone and marble are the most common building' elements of modern Serbian heritage and represent highly vulnerable architectural typologies . Calcium carbonate reacts with sulfuric acid, leading to form the gypsum on the building's surface. The chemical reaction product creates a hard black crust. During the time, it cracks and detaches from the surface, resulting in the permanent loss of the originally material (Malinović-Milićević and Stanojević, 2024; Mihajlov, 2010).

4.5. Geological and geomorphological degradation

Although geological and geomorphological processes are inherently slow, climate change nonetheless intensifies the risks exposed monuments. Disruptions in the rainfall regime specifically heavy rainfall as well as rapid soil thawing, directly destabilize slopes. Objects located near unstable locations are at direct risk of being destroyed by landslides and rockfalls. Intensified freeze-thaw cycles and increased thermal loads contribute the physical

disintegration of the petrographic layers, which forms the basis of many historical sites and caves (karst geomorphological forms) as sites of cultural signification (Berisavljević and Berisavljević, 2024; Antonijević and Veličković, 2016).

4.6. Biological Degradation

Increased global humidity and temperature linked to themselves climate change, creates ideal conditions for proliferation to the materials. The biological degradation of immovable cultural heritage is a complex process in which algae, lichens, and mosses collectively decompose materials through chemical and mechanical influences. *Algae* product of green and dark stains, as well as harmful biofilms that retain moisture on the surface. This facilitates penetration of other microorganisms and encourages mineral dissolution through the secretion of organic acids. Lichens play an even more aggressive role; these specific symbiotic communities of fungi and algae survive in extreme conditions. They are considered the most dangerous biological decomposers for they combine biomechanical erosion through their root-like structures with biochemical agents-via strong chelates and oxalic acid to directly dissolve the binding material in stone.

Finally, Bryophyta, although lacking a developed vascular system and possessing only rhizoids, form dense green cushions that accumulate large quantities of water. This creates constantly damp zones which, in combination with freeze-thaw cycles, lead to damaging and the permanent physical destruction objects (Handžić, 2025; Stanković et al., 2017).

5. PROTECTION AND MONITORING

The strategy on the synergy of physical landscape' stabilization and inventing advanced technologies. Primary this include biological and mechanical soil stabilization within archaeological site zones, alongside the design of drainage systems and supporting structures around historical edifices and memorial parks for the effective control of surface and groundwater. The core concept of these measures is systematic monitoring, which, through a network of embedded sensors, enables the continuous tracking of critical parameters such as humidity, temperature, and atmospheric pollution. This approach ensures the future sustainability of the structures, allowing for a timely response before permanent damage occurs (Stanković et al., 2017; Abd El-Wareth, 2024).

In addition to structural interventions, modern conservation implements innovative solutions such as the application of hydrophobic and UV-stable nano-coatings to the facades of monuments and fortresses, thereby increasing material resistance to thermal stress and chemical degradation. Simultaneously by active measures, passive adaptation focuses on the restoration of traditional ventilation systems for natural interior moisture control. The final level of protection is digital preservation through mass 3D scanning and photogrammetry. By establishing centralized digital archives and repositories, a final line of defense is created, guaranteeing the preservation of architectural details and historical insights even in cases of physical devastation (Basto et al., 2016; Bonarini et al., 2014).

The implementation of these strategic components requires collaboration among the Institutions such as: Institute for the Protection of Cultural Monuments, Geological Institutes, and scientific institutions, positioning Serbia as a model for proactive adaptation of cultural heritage to global climate change. Serbia's cultural heritage is a precious testimony to continuous development and survival, but it is simultaneously exposed to the constant influence of both nature and man (Antonijević et al., 2021) Therefore, its preservation is crucial for the sustainable development of both entity and identity.

6. TECHNOLOGICAL ADAPTATION FOR CONSERVATION

Contemporary conservation of medieval heritage in Serbia (especially those located in river valleys) in near future must orient itself towards climate modeling to define potential threats, preventive measures, and solutions.

The usage of hydrophobic materials and binders chemically compatible with original materials must technologically exist in symbiosis with nanotechnology components based on silanes and siloxanes for permanent adaptation . These compounds are characterized by moisture resistance while simultaneously maintaining vapor permeability, thereby preventing internal accumulation and effectively blocking biological and salt erosion without compromising the architectural authentic (Stepanović, et al., 2021; Momčilović-Petronijević, et al., 2022).

Furthermore, the structural strengthening and stabilization of stone masonry are carried out using materials based on ethyl-silicates or nanotechnology. These materials are resistant to

high temperatures and aeolian erosion. The substances penetrate deep into the stone structure, where they strengthen the base compounds of the original material via chemical reaction, increasing resistance to abrasion, frost erosion, and splitting caused by extreme temperatures. This achieves long-term protection while leaving the original appearance intact. This type of monitoring and modeling is vital for maintaining the integrity of cultural property (Lukić Petrović, M., 2025; Mitrović, I., Nikolić, S., 2024).

To enhance the effectiveness of renewable materials, it is necessary to implement prevention based on forecasted weather conditions for a specific period, utilizing an IoT (Internet of Things) early warning system. These wireless sensors are embedded within structures to monitor parameters such as relative air humidity, wall moisture content, and atmospheric pollutant concentrations. Such monitoring allows conservators to automatically receive alerts regarding extremes the moment measured parameters exceed critical thresholds, enabling rapid intervention before damage occurs to facades and interior walls (Basto, et al., 2016; Anđelković, et al., 2020).

7. PRESERVATION OF CULTURAL HERITAGE IN THE REPUBLIC OF SERBIA

The growing instability of global ecosystems is heavily emphasized today as a direct consequence of shifting climate patterns and anthropogenic factors. To address these challenges, it is essential to apply an integrative science approach based on synthetic-analytical methods. Such a model enables the forming of applicable solutions for the preservation of immovable cultural heritage. A sustainable approach is founded on building habits and responsibility toward the environment.

Although the climate in Serbia is moderate-continental, a warming trend has been recorded over the last two decades. These changes manifest through flash floods and long periods of drought during summer months. A particular challenge reflects by sudden temperature spikes alternate with high air humidity and frost. The temperature imbalance and smog pollution, consolidated with high humidity and frost, intensify the processes of salt erosion and material crumbling (Stanojević, et al., 2020; Langenbach, 2017).

Additional risks reflects the issue of the soil erosion; intense precipitation directly affects the movement of landslides and rockfalls, particularly prevalent on the mountainous slopes of Western Serbia. Through detailed analysis of local meteorology data and typology itself, it is

possible to accurately assess risks and define adequate adaptation measurements, relying on modern protection strategies (Knežević and Marković, 2016; Basto, 2015; Čelić, 2022).

Preserving cultural property is crucial for maintaining collective identity and prevent the loss of historical memory. Tangible heritage that form the pillar of identity, is under the exposure of climate extremes. Their protection became an imperative for sustainable social integrity (Cvetković, et al., 2024). Identity preserves the historical narrative and protects the cultural continuum, allowing generations to relate their social identity.

8. ANALYTICAL APPROACH TO REGIONAL VULNERABILITY

The analysis of regional vulnerability in Central Serbia highlights that the threat extends beyond mere material degradation, directly strike to sociocultural identity. Progressive environmental and climate monumental deterioration risks disorienting collective memory and weakening community cohesion. Preserved structures serve not only as physical artifacts but also as key symbols of stability and drivers of local continuity.

Systematic integration of ecological and social disciplines demonstrates that enhancing public environmental awareness and strengthening civic participation are essential for effective risk management. Rather than viewing local populations merely as passive recipients of policy, expert synthesis underscores the necessity of engaging community awareness to foster proactive preservation. In regions like the Rasina District, aligning local ecological habits with systemic climate adaptation – such as establishing organized monitoring initiatives or localized "Eco-patrols" – provides a vital link between statutory regulations and municipal execution.

9. METHODOLOGICAL FRAMEWORK

The methodological framework of this study is conceptualized as an expert qualitative-analytical review and multidisciplinary synthesis. Instead of relying on isolated empirical sampling, the research integrates normative analysis of legal regulations, material science models of decay, and environmental policy frameworks to evaluate heritage vulnerability under climate extremes.

The primary objective is to examine the accelerating climatic stress conditions and the structural degradation of immovable cultural property in Serbia. Reach the aim of the problem solving plan, the qualitative evaluation synthesizes legislative analysis of current mechanisms such as the Law on Cultural Heritage, the physical and biochemical dynamics of material degradation across regional heritage typologies, and socio-ecological policy frameworks aimed at bridging technical conservation with local governance.

This integrative approach provides a comprehensive database for establishing long-term preservation strategies, aligning scientific risk modeling with policy-level implementation.

10. RISK SYNTHESIS AND DIAGNOSTIC RESULTS

Synthesizing meteorological data, geomorphological conditions, and material risk factors reveals that hydro-meteorological hazards, particularly flash floods and torrential inundations, represent the most immediate threat to cultural assets in Central Serbia. Consequently, regional protection strategies must prioritize proactive hydrological management, including the continuous maintenance and clearance of riverbeds adjacent to historic sites.

Among various heritage typologies, archaeological sites and exposed open-air structures emerge as the most acutely vulnerable category. Their extreme susceptibility stems primarily from fluctuating groundwater levels, soil desiccation cycles, and sub-surface moisture shifts that disrupt anaerobic preservation conditions.

Furthermore, diagnostic analysis indicates that addressing complex climate threats requires a thorough revision of existing municipal guidelines. Transitioning from reactive restoration to continuous, technology-driven monitoring (such as early-warning IoT sensor networks and non-invasive stabilization) is essential for mitigating catastrophic material loss before irreversible damage occurs.

11. Conclusion

This paper confirms the profound, systemic link between climate extremes, material degradation of immovable cultural heritage, and the potential erosion of sociocultural identity in the Republic of Serbia. Unprotected archaeological assets and exposed historical

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monuments are identified as exceptionally high-risk categories, necessitating statutory status assessments and environmental impact studies prior to major regional infrastructure projects.

Solving these complex challenges demands a fundamental integration and multidisciplinary scientific planning. On an institutional level, updating regulatory frameworks is required regulatory frameworks to explicitly incorporate climate risk modeling and establishing a dedicated Heritage Protection Fund for emergency interventions. From a technical perspective, emphasis must be placed on proactive technological adaptations, including advanced, breathable nano-coatings, non-destructive structural consolidation, and IoT-based early warning monitoring systems designed to local microclimates. Furthermore, beyond exclusive technical measures, fostering inclusive ecological education through interactive and extracurricular frameworks plays a crucial role in linking heritage preservation directly to sustainability and environmental awareness. Finally, effective long-term protection relies on participatory governance that ensures full transparency in urban planning through mandatory public consultations including local authorities, heritage experts, and civil society organizations.

Ultimately, preserving cultural heritage under conditions of global climate imbalance must not be treated as an administrative expense, but as a strategic investment in national identity, ecological resilience, and sustainable local development.

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Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the author(s) utilized generative AI tools (specifically Gemini / ChatGPT) solely for the purposes of language polishing, stylistic revision, grammar refinement, and formatting the reference list according to APA 7th edition guidelines. After using these tools, the author(s) thoroughly reviewed, edited, and verified all generated content, ensuring full accuracy, logical coherence, and academic integrity. The author(s) take full responsibility for the final content and scientific validity of the publication.