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Environmental Threats to Prehistoric Treasures: Tassili n'Ajjer and Hoggar Facing Climatic Disruptions

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Abstract

In Tassili n'Ajjer, a UNESCO World Heritage property, and the Hoggar Mountains prehistoric rupestrian (rock) art reveals a critical narrative of environmental transformation. Dating from 10,000 BC to approximately the first millennium AD, these paintings document a once-verdant Sahara, contrasting sharply with today's arid landscape. These archaeological treasures now face an existential threat from contemporary climate change. Unpredictable rainfall, increased humidity and temperature fluctuations are systematically degrading the delicate art. As climate change intensifies, the study emphasizes the need for integrated conservation approaches that combine advanced monitoring, community-based stewardship and international collaboration.

Policy Recommendations

- The preservation of Tassili n'Ajjer–Hoggar's rupestrian art represents both a cultural imperative and a test case for heritage conservation in the Anthropocene. Algeria has an opportunity to offer global leadership in developing climate-resilient preservation strategies, which could benefit vulnerable heritage sites worldwide. However, the time for action is now – each passing season of extreme weather events increases the risk of irreversible damage. Implementing a climate resilience strategy for this unique heritage site allows us to fulfil our collective responsibility to preserve human heritage for future generations and to advance scientific knowledge of conservation in the context of climate change. The alternative – passive acceptance of incremental loss – would constitute an unforgivable failure of stewardship for one of civilization's most remarkable artistic achievements.

KEYWORDS

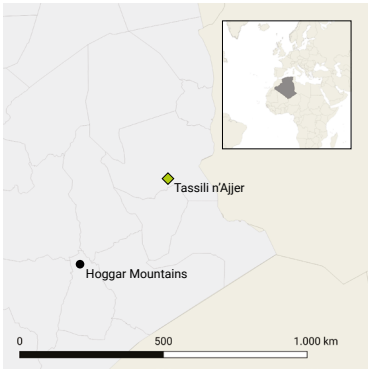
UNESCO World Heritage
Tassili n'Ajjer and Hoggar
climate change
water management
QGIS

WATER ICONS

CLIMATE

A **B** C D E

BWh: Hot desert climate



< Fig. 1 Zoomorphic cave paintings located at Tanzoumaitak in Tassili n'Ajjer park in Djanet, Algeria (Source: IssamBarhoumi, 2023. CC BY-SA 4.0, via Wikimedia Commons).

Introduction

The Algerian Sahara holds a rich history of human settlement and cultural development. It is home to some of the world's oldest rupestrian art, dating back to the Neolithic period. The region has also been shaped by the migration of nomadic peoples, who brought with them a vast array of cultural traditions and practices. This unique history is traced in the region's rupestrian (rock) art. This profound climate variability is further evidenced by Tassili n'Ajjer, which has fluctuated between aridity and wetness for millennia (Soukopova 2012), as well as the Hoggar region, characterized by green ravines and occasional snowfall (McColl 2014). However, this heritage is now under threat. The rupestrian art, which traces the region's ancient climate history, is endangered by the increasing intensity of unusual precipitation caused by modern climate change. This risk could damage the vulnerable engravings and paintings of Tassili n'Ajjer and Hoggar (Soleilhavoup 2004).

This article examines the growing climate threats to the Tassili n'Ajjer plateau (a UNESCO World Heritage property) and Hoggar Mountains in southern Algeria. Both are celebrated for their prehistoric rupestrian art but are also increasingly vulnerable to environmental change. Unusual weather events, such as the intense rainfall and flooding recorded in mid-summer 2024, highlight the urgent challenges to preserving these fragile cultural landscapes. By analyzing these weather events and their ecological impacts, this study seeks to inform adaptive strategies to safeguard the region's irreplaceable rupestrian art.

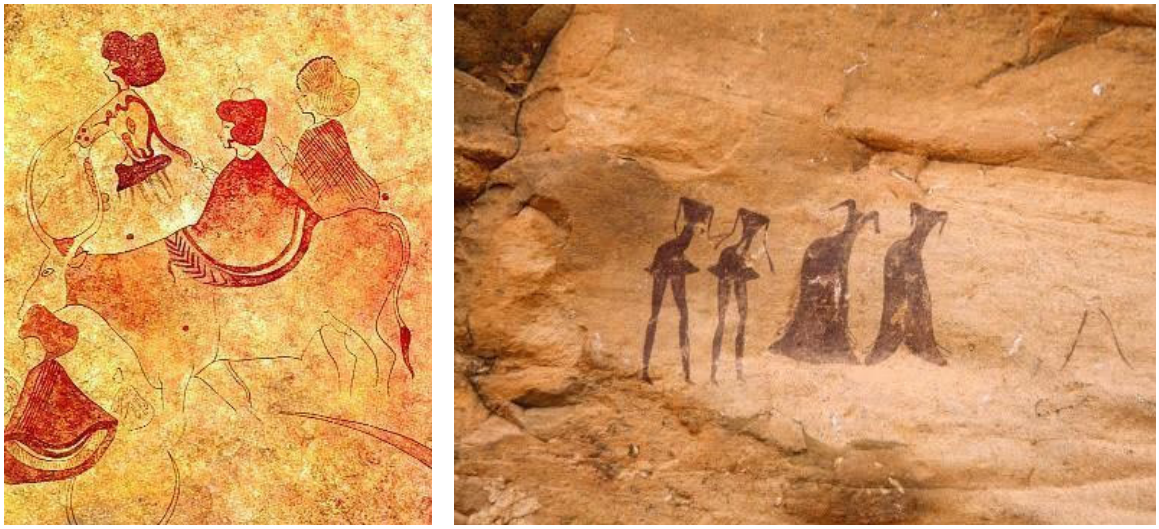
QGIS-based mapping of the Tassili n'Ajjer–Hoggar region reveals midsummer precipitation (75–150 mm, CHRS data) and associated flood risks, levels that dramatically exceed local arid norms. These findings underscore the potential for hydrological disruptions, from flash floods to microclimatic shifts, that could accelerate the degradation of millennia-old cultural heritage. As climate change intensifies, there is a pressing need for integrated conservation approaches, combining advanced monitoring, community-based stewardship and international collaboration. The research presented here contributes to broader efforts to enhance the resilience of extreme-environment heritage sites in an era of climatic uncertainty.

Rupestrian Art in the Tassili n'Ajjer–Hoggar Region

Since the third quarter of the 20th century, many European scientific missions devoted their attention to studying the region's ecological, geological and anthropological heritage. Indeed, the rupestrian art of Tassili n'Ajjer is an exceptional testimony to the interaction between humans and their environment, offering an in-depth visual chronicle of society's adaptation to drastic climate change in the Sahara.

This heritage site is renowned for its exceptional density of historic evidence with more than 15,000 paintings and engravings dating back 12,000 years, as well as many precious prehistoric remains (UNESCO 1982). For example, dwellings, burial mounds, and enclosures dating from 10,000 BC to the early centuries AD have yielded abundant lithic and ceramic materials. In addition, the rocky forests of Tassili n'Ajjer give the impression of a striking lunar landscape (Whitley 2001; Roset, 1984). Tassili n'Ajjer was listed as a UNESCO World Heritage property in 1985.

While UNESCO recognizes Tassili n'Ajjer for its rupestrian art (fig. 1–3), the Hoggar itself is not



^ Fig. 2 Rupestrian art depicting women from ancient Tassili n'Ajjer society (left), and a painting of women in long, flowing dresses with two young soldiers, in which the heads once visible in the painting have disappeared (right) (Source: Left: Toira at French, Public domain; Right: B. Salaheldine, CC BY-SA 4.0, via Wikimedia Commons).

listed on the World Heritage List. However, the histories of the two regions are closely linked as they share a parallel human history and ecosystem. The prehistoric inhabitants who created the art of Tassili n'Ajjer probably also occupied the Hoggar, which later became the heart of the Tuareg culture, which began shaping the entire region in the fifteenth century, making the Hoggar Mountains essential to address when studying this part of the Algerian Sahara (Rognon et al., 1990; Nicolaisen 1963).

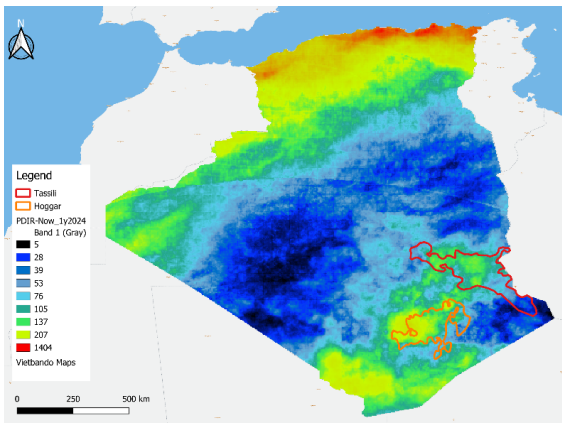
The Tuareg, have always demonstrated a remarkable ability to survive in their ultra-arid region (Hachid 1997). This cultural resilience is officially recognized; in accordance with Decision 8.COM 8.2, UNESCO (2013) has inscribed the "Practices and knowledge related to the imzad of the Tuareg communities of Algeria, Mali, and Niger" on its Representative List of the Intangible Cultural Heritage of Humanity.

The cultural heritage dimension is of crucial importance. The Tuareg. Through their millennia-old adaptation strategies, they have developed a socio-ecological system that combines highly mobile pastoralism, flexible social and land-use systems, and evolving livelihood diversification and settlement patterns in response to climatic, political and economic pressures. Tuareg communities are now facing profound socio-ecological changes and traditional nomadic practices are becoming increasingly difficult to maintain. However, the knowledge and success of this resilient community are essential for developing local adaptive strategies aimed at ensuring the sustainable preservation of the heritage of Tassili n'Ajjer and Hoggar (Badi 2024).

Climate Change and the World Heritage Property

The adverse effects of climate change pose a significant threat to hyper-arid regions, including the Algerian Sahara, a reality that persists despite increasing global recognition of the crisis. In fact, this desert is one of the major re-

^ Fig. 3 Tassili n'Ajjer rock art sequence: a visual chronicle of adaptive subsistence strategies across millennia of climatic change (Source: C. Patrick Gruban. CC BY-SA 2.0, via Wikimedia Commons; d. Alessandro Passaré. CC BY-SA 3.0, via Wikimedia Commons).



^ Fig. 4 Rainfall map of Algeria during the year of 2024 (Source: Amira Ghennaï and Said Madani, generated using QGIS, 2025).

gions in Algeria that clearly demonstrates the impact of climate change. The desert's climate has long been a key factor in the development of Saharan societies. Climate change is not a recent phenomenon in the Algerian Sahara (Williams 2014), a region marked by major changes, from the wet period of the Holocene to the transformative aridification of the mid-Holocene. This trajectory continued throughout the variability of the late Holocene, with brief wet phases, followed by further fluctuations during the Medieval Climate Anomaly and the Little Ice Age, leading to the contemporary era of anthropogenic aridification and variability in the twentieth and twenty-first centuries (Rognon 1994, Gasse 2002).

Furthermore, Algeria's heavy dependence on the hydrocarbon industry and its sensitivity to greenhouse gases exacerbates pre-existing weaknesses and generates impacts that cannot be ignored. This make its population and its priceless cultural heritage vulnerable, particularly ancient sites such as those in the Tassili n'Ajjer and Hoggar regions. As a result, Algeria is among the 24 global climate change hotspots identified by the Intergovernmental Panel on Climate Change (IPCC 2022; Bensmaine 2022).

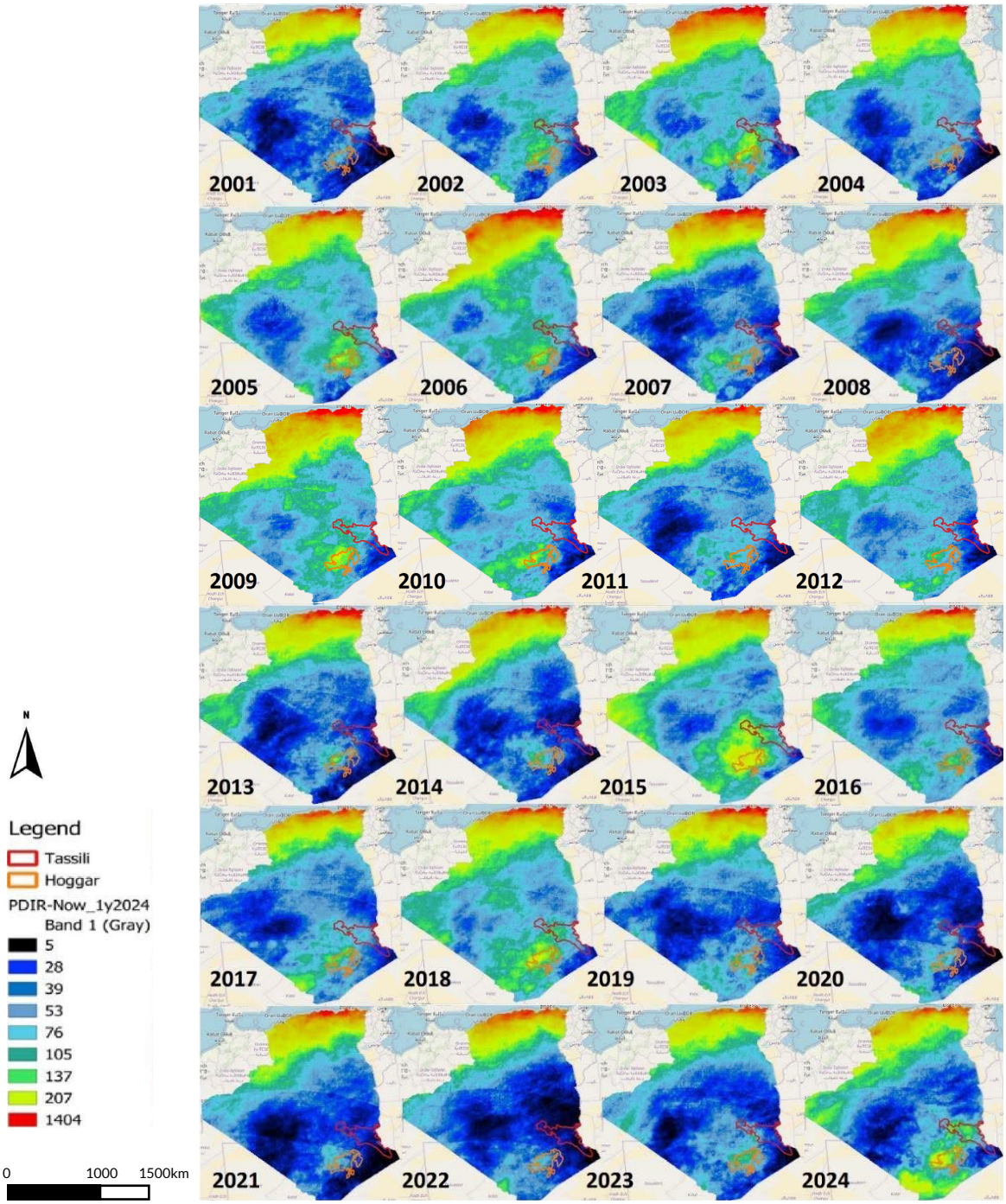
Rainfall and Flooding in the Algerian Desert

Over the last two decades, anthropogenic climate change has led to unusual weather phenomena in the Algerian desert, which is undergoing significant climatic and environmental changes. Following heavy rainfall, one of the driest and most arid regions in the world appears to be greening in certain Saharan areas of Algeria, impacting the ecosystem. According to the Algerian Press Agency, in September 2024, climate change led to unusual rainfall in the provinces of Tamanrasset, Ilizi and Djanet, leading to rising water levels and mud accumulation in Saharan villages, which caused deadly floods. Threats to World Heritage property from these events raise pressing questions about preserving heritage such as Tassili n'Ajjer (Jia et al. 2023).

The rupestrian art in the Tassili n'Ajjer and Hoggar regions is difficult to preserve due to the vulnerability of the rock surfaces and pigments. Additionally, this type of art is often damaged by tourists. Meanwhile, it is threatened by environmental factors such as climatic and microclimatic changes, as well as inappropriate lighting conditions, large temperature variations and increased rainfall, which in turn can lead to increased humidity and thus accelerate the rate of deterioration of these fragile and very ancient human traces, threatening them with extinction (Fernández-Sánchez and Gómez-Sánchez 2023; O'Hara 2014).

These threats necessitate a dual approach: a better understanding of climate change impacts on the Outstanding Universal Value (UNESCO 2023) and the development of adaptive water management strategies to ensure site sustainability (Hein 2019).

By mapping summer rainfall during high-precipitation events and a subsequent numerical



^ Fig. 5 Rainfall map of Algeria from 2001 to 2024 (Source: Amira Ghennaï and Said Madani, generated using QGIS, 2025).

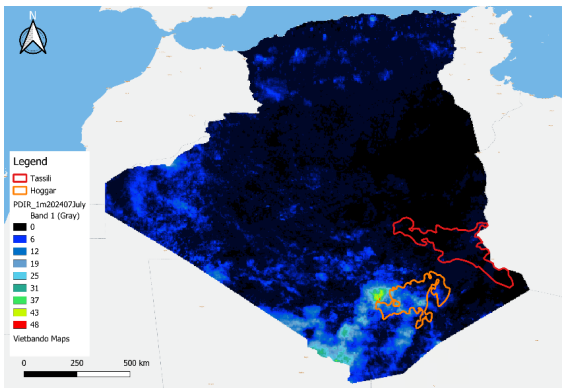
analysis of potential flooding, we have aimed to highlight the urgent need for strategies to ensure the long-term preservation of this invaluable heritage. This analysis includes the delimited study area of the Tassili n'Ajjer World Heritage property and extends to the Hoggar region (fig. 6–8). The maps visualize rainfall in millimeters using a graduated color scale. On this scale, the dark blue and lighter blue areas indicate low rainfall, while the green, yellow and red areas indicate heavier precipitation.

The process of mapping rainfall in Algeria is based on hydrometeorological data from the Centre for Hydrometeorology and Remote Sensing (CHRS). The method involves using PDIR-Now files for July, August and September 2024, a summer period marked by unusual rainfall in the country's arid regions. Importing the PDIR-Now files in TIF format into QGIS made it possible to generate three separate layers, corresponding to rainfall data for each of these three months. Using the same method, we generated an annual history of precipitation maps for Algeria from 2001 to 2024.

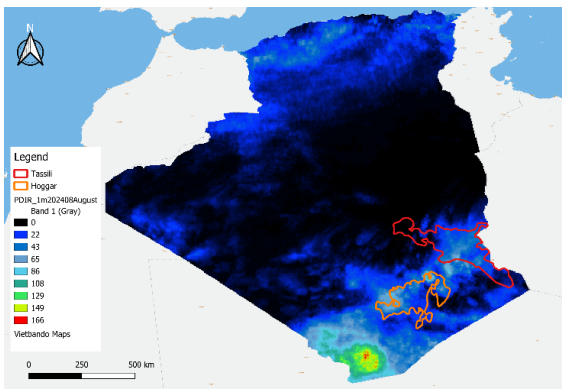
Figure 5 illustrates the rainfall history in Algeria between 2001 and 2024. It shows a continuous climatic gradation from north to south, with the northern regions receiving the highest rainfall totals. This humid zone contrasts sharply with the vast desert expanses of the south, which are generally characterized by pronounced aridity. However, there is a remarkable anomaly in the southeastern part of the Algerian desert, specifically in the Tassili n'Ajjer and Hoggar regions. This area has experienced significant rainfall, with a particularly marked peak in 2024 (fig. 4). This anomaly reflects an unusual rainfall pattern for the region, contrasting with the arid climate that prevailed there during the previous two decades.

The rainfall map for Algeria for 2024 (fig. 4) shows abundant rainfall in the northern regions in terms of annual totals, while these regions experienced almost total drought during the summer months of July and August. However, central Algeria remains consistently arid. Monthly maps reveal that the mountainous regions of southeastern Algeria, particularly the Hoggar and Tassili n'Ajjer massifs, receive isolated convective rainfall even during dry periods, which is particularly pronounced in July and August, and transitional in September, representing an abnormal deviation from the hyper-arid climate characteristic of southern Algeria over the last two decades.

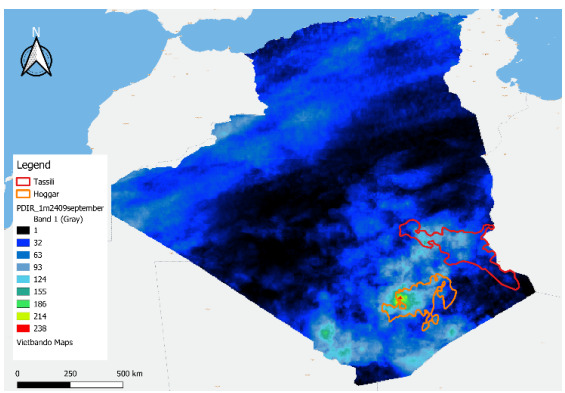
Faced with hydrological disasters, Algeria has gradually adopted a proactive risk management policy. At the national level, this approach has resulted in significant infrastructure investments – dams, retention basins, modernized drainage networks – institutional strengthening (civil protection, early warning systems) and planning tools such as urban risk zoning. However, protecting the rock art heritage of Tassili n'Ajjer and Hoggar requires a radically different strategy. In this case, public action relies less on heavy engineering and more on a legal framework (UNESCO classification, Cultural Park Office), scientific monitoring and targeted, in situ conservation interventions. This protection, which is essentially preventive and adaptive, consists of mapping vulnerabilities, monitoring sites and intervening locally rather than transforming a vast and fragile desert landscape. Thus, while the national response to flooding focuses on infrastructure and planning, the preservation of rupestrian art remains a challenge requiring patience and precision and must be constantly reassessed in the face of climate change effects.



^ Fig. 6 Rainfall map of Algeria, July 2024 (Source: Amira Ghennaï and Said Madani, generated using QGIS, 2025).



^ Fig. 7 Rainfall map of Algeria, August 2024 (Source: Amira Ghennaï and Said Madani, generated using QGIS, 2025).

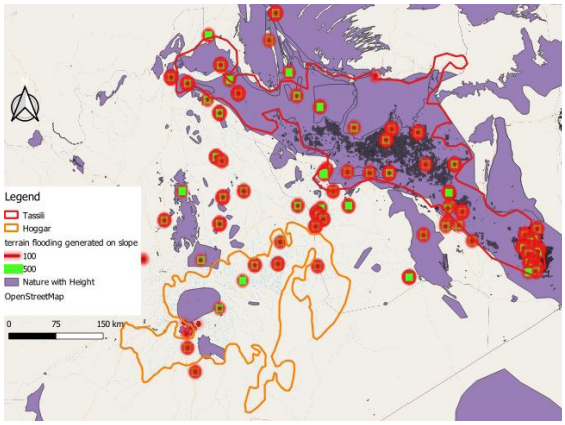


^ Fig. 8 Rainfall map of Algeria, September 2024 (Source: Amira Ghennaï and Said Madani, generated using QGIS, 2025).

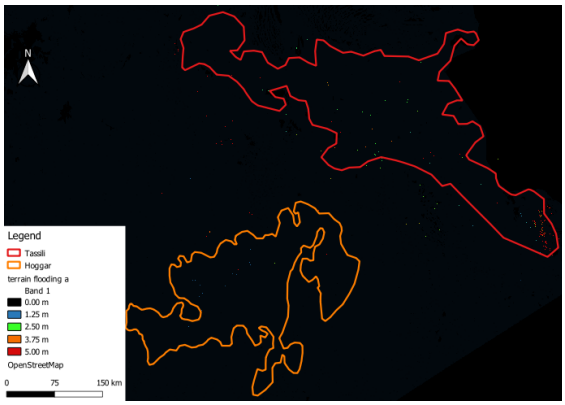
The map showcasing a simulation of potential flood risk (fig. 9–10) was generated in QGIS using the SAGA-GIS Terrain Flooding tool. This tool performs a multi-layer analysis, primarily integrating a Digital Terrain Model (DTM), a terrain slope layer and land cover data with elevation attributes. The tool's algorithm works by simulating the flooding of a digital elevation model for a specified water level. It models a constant water level propagating from a starting cell to produce a Flooding Digital Elevation Model (Flooding DEM) (Wichmann 2022). This output is critical for identifying terrain susceptible to inundation, thereby effectively illustrating flood risk across the study areas.

The rainfall distribution patterns observed in mid-2024 reveal significant climatic anomalies across southern Algeria's UNESCO World Heritage property. While July showed concentrated precipitation near the Hoggar plateau (12–43 mm) with little to no rainfall at Tassili n'Ajjer, August marked a dramatic shift with both plateaus receiving over 86 mm – an extraordinary amount for these typically hyper-arid regions during peak summer. This trend intensified further in September, when widespread rainfall exceeding 238 mm was recorded across southern Algeria, including sustained precipitation over both study areas. These figures are particularly alarming when considering the region's average annual rainfall rarely reaches 250 mm, with Hoggar receiving nearly half its typical yearly precipitation in August 2024 alone.

The contours rendering visualizes a flood model in the form of contour lines rather than colored areas: the 100 mm interval shows a red line for each 100 mm increase in water height, and the 500 mm interval, represented by a green line, highlights the main levels (500 mm, 1000 mm, etc.). Although useful for reading precise values along the isolines, this contour line representa-



^ Fig. 9 Simulation of potential flood risk (Source: Amira Ghennaï and Said Madani, generated using QGIS, 2025).



^ Fig. 10 Simulation of flood susceptibility in Tassili n'Ajjer and Hoggar areas (Source: Amira Ghennaï and Said Madani, generated using QGIS, 2025).

tion does not allow for immediate visualization of the spatial extent and intensity of the flood.

The flood susceptibility analysis identified several vulnerable zones despite the generally mountainous topography. Valley bottoms and topographic depressions, clearly marked on the flood risk map by red or green dots, show particular susceptibility to water accumulation due to their low-lying position and the effects of surrounding steep slopes that accelerate runoff. These flood-prone areas coincide with locations where increased soil saturation from repeated rainfall events could significantly alter local microclimates. Of particular concern is how these hydrological changes may affect the delicate environmental balance within the caves housing ancient rupestrian art, potentially accelerating deterioration processes through increased humidity and water infiltration.

A flood simulation model was developed for the Tassili n'Ajjer and Hoggar mountain (fig. 10) ranges based on a representative rainfall event, using a digital terrain model and hydrological processing performed in QGIS. The resulting map identifies potentially flooded areas and estimates water depth, classified from 0 to 5 m using a progressive color scale. The results highlight mainly localized flooding, with water levels reaching up to 5 m in topographical depressions and wadi beds, reflecting a varying response of the environment to rainfall.

These unprecedented rainfall patterns and associated flood risks present multiple conservation challenges for the region's irreplaceable cultural heritage. The sudden influx of moisture in typically arid environments may trigger complex ecological responses, from ephemeral vegetation growth that alters sediment stability to the formation of temporary water bodies that disrupt long-established arid-zone equilibria. For the prehistoric rupestrian art, the implications are particularly grave, as increased humidity and potential water contact could promote salt crystallization, microbial growth and surface erosion. These findings underscore the urgent need for adaptive management strategies that address both immediate flood risks and longer-term climate adaptation measures to ensure the preservation of these unique cultural landscapes in a changing environment.

The 2024 weather anomalies strongly suggest an evolving hydrological regime in the Sahara,

necessitating a fundamental reassessment of conservation approaches for arid-region heritage sites. Moving forward, protection efforts must incorporate real-time climate monitoring systems, microclimate stabilization techniques for sensitive cave environments, and community-based flood-preparedness programs. Future research should focus on developing higher-resolution predictive models to better anticipate these emerging climate threats and inform more resilient conservation strategies for these invaluable windows into human history.

Conclusion

The Tassili n'Ajjer and Hoggar plateaus represent a fragile cultural and ecological treasure of global significance. They contain some of humanity's most important prehistoric rupestrian art collections, and face threats from accelerating climate change. Our geospatial analysis has highlighted unprecedented summer rainfall events in 2024, with rain quantities that dramatically exceed historical norms for the region. These hydrological anomalies are triggering complex ecological responses, from flash flooding and ephemeral lake formation to microclimatic alterations within the caves housing ancient artworks. The resulting physical, chemical and biological degradation processes threaten to permanently damage irreplaceable cultural heritage that has survived millennia in stable desert conditions.

Likewise, the analysis of these hydrological dynamics highlights their potential impact on the sustainability of Tassili n'Ajjer's rupestrian art. Flooding promotes mechanical erosion of the walls, chemical alteration of the rock substrates and the weakening of rock shelters, particularly near drainage channels. Thus, flooding appears not only as a one-off risk, but as a structuring factor in the long-term degradation of rupestrian art heritage. The simulation map is therefore an essential decision-making tool for identifying the most vulnerable sites and guiding conservation and management strategies for the site.

This research underscores the urgent need for a paradigm shift in heritage conservation approaches. Traditional preservation methods developed for stable environments are inadequate against the accelerating pace of climate change.

The Global Environment Facility's (GEF) Small Grants Programme (SGP), implemented by the United Nations Development Programme (UNDP), supports Algeria's strategy to protect the Tassili n'Ajjer National Park. While currently focused on strengthening biodiversity management, a more comprehensive approach is needed to ensure long-term resilience. To this end, future strategies should incorporate advanced climate modelling and microclimate management to directly address the humidity and climate challenges threatening Tassili n'Ajjer–Hoggar rupestrian art (Alkadri et al. 2024). Consequently, a combination of advanced monitoring technologies, community action and integrated science is required to enhance the national program. This integrated approach will enable the creation of a robust conservation framework that not only protects biodiversity but also safeguards the quality and sustainability of the park's unparalleled cultural heritage (Barrile et al. 2024).

The strategies currently deployed to protect rupestrian art in Tassili n'Ajjer and Hoggar, although based on scientific prevention and in situ conservation, have structural shortcomings that limit their long-term effectiveness. Current action, triggered mainly after risks or signs of damage have been identified, is essentially re-

active and does not address the root causes of degradation. It does not allow for preventive action on climatic factors accelerating erosion, nor does it allow for adaptation to new hydrological regimes induced by climate change. To be truly protective, these strategies should systematically incorporate adaptive management to increasing climatic hazards, such as regular monitoring of the humidity and mechanical condition of the walls, soft and controlled channeling of runoff upstream of the sites to avoid its destructive concentration on the decorated panels, and preventive stabilization of the soil and embankments around the rock shelters. Without this shift towards more proactive, integrated and refined intervention, the conservation of this fragile heritage will remain a race against time, constantly overtaken by the natural dynamics it seeks to contain.

To operationalize this conservation vision, we recommend immediate implementation of six interconnected policy initiatives:

1. Establishing comprehensive monitoring systems represents the foundation for informed decision-making. This requires creating a dedicated climate observatory network that combines satellite remote sensing, automated weather stations and Indigenous knowledge systems. Such infrastructure should incorporate machine learning algorithms to predict extreme weather events and provide early warnings to local communities. These systems must be complemented by continuous digital documentation of rupestrian art panels using 3D laser scanning to create baseline records for condition monitoring.
2. Legal and policy frameworks require substantial strengthening to meet contemporary challenges. Algeria's cultural heritage legislation needs updating to explicitly address climate risks, including stricter controls on nearby land and water use. Heritage protection must be mainstreamed into national climate adaptation strategies and disaster risk reduction planning. Internationally, we advocate for developing UNESCO guidelines specifically addressing conservation in arid and semi-arid zones under climate stress.
3. Community engagement and sustainable tourism management offer pathways for locally grounded solutions. Tuareg communities possess generations of traditional knowledge about desert ecosystems that can inform adaptive strategies. Their involvement should be central through training programs for heritage stewards and participatory monitoring networks. Tourism management must balance preservation needs with economic benefits through carefully regulated access and digital interpretation tools.
4. Technological innovation provides crucial tools for twenty-first century conservation. Emerging solutions like IoT environmental sensors, passive ventilation systems and moisture-regulating materials show particular promise for stabilizing cave microclimates. These should be deployed in pilot projects while establishing long-term research partnerships with materials scientists and conservation technologists.
5. International cooperation mechanisms must be strengthened to mobilize resources and expertise. This includes pursuing emergency funding through UNESCO's World Heritage Centre, building regional conservation partnerships with neighboring Saharan nations, and accessing climate finance instruments like the Green Climate Fund. Knowledge exchange programs can facilitate transfer of best practices from other climate-threatened heritage sites worldwide.

Finally, adaptive governance structures are needed to ensure policies remain responsive to changing conditions. This requires implementing flexible management frameworks that can incorporate new scientific findings, conducting regular vulnerability assessments, and establishing multi-stakeholder oversight committees. Such structures should bridge traditional knowledge systems with modern scientific approaches through culturally-sensitive knowledge co-production.

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