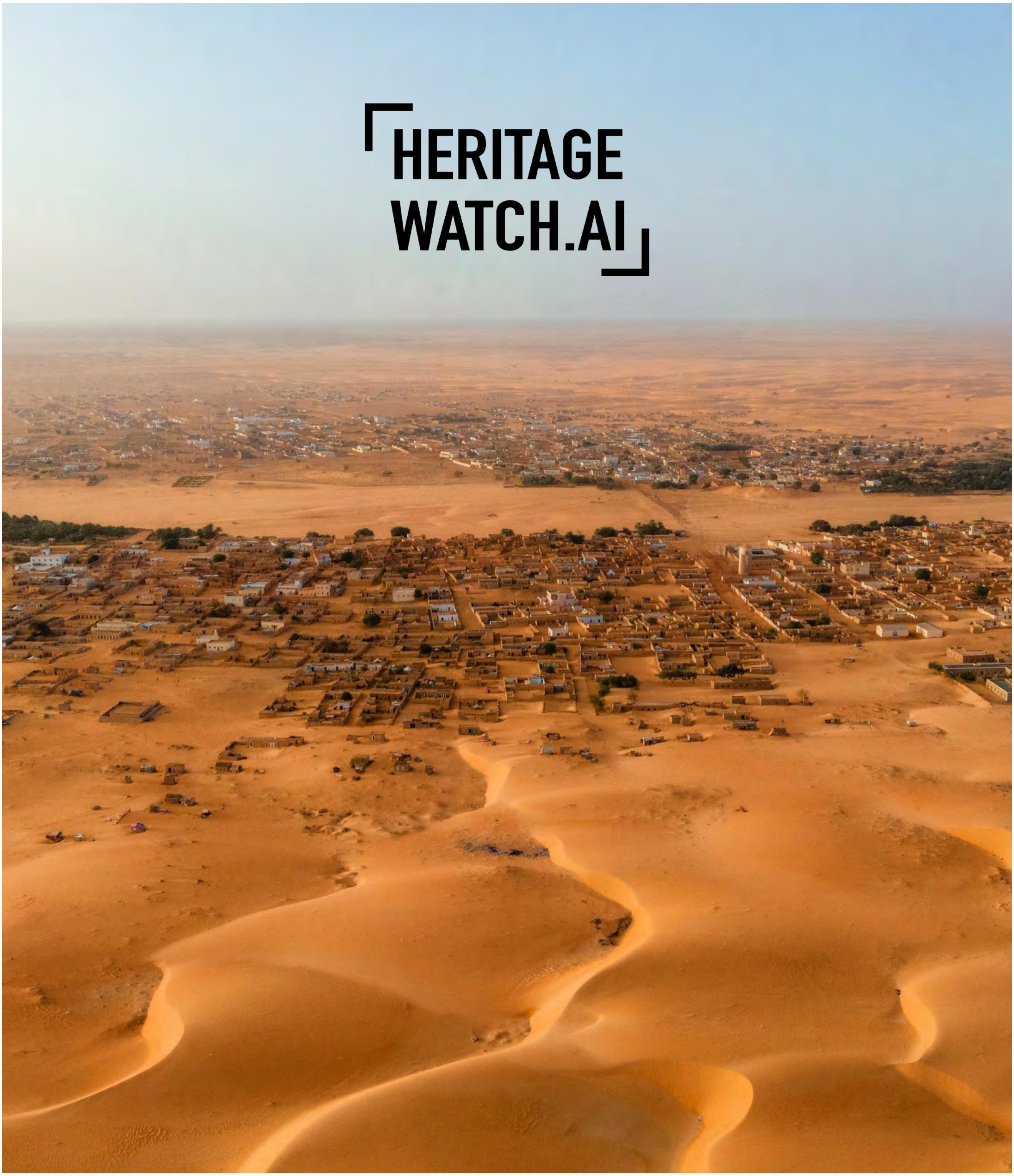

DESERTIFICATION AND CULTURAL HERITAGE IN THE SAHEL

Desertification and the Protection of Cultural Heritage in the Sahel
With Case Studies from Chinguetti, Agadez, Bandiagara, Timbuktu, and Gao

Prepared by Heritage Watch AI

Date of Publication: June 2025
Place of Publication: Paris, France
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The views expressed in this report are those of the author(s) and do not necessarily re lect any partner institutions. This report is intended for research, policy, and educational purposes only.

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ABSTRACT

This study investigates the long-term environmental and anthropological factors that threaten cultural heritage sites in the Sahel region, with a particular focus on the impacts of desertification.

By leveraging satellite imagery, we identify evolving trends related to land degradation and assess their implications for both UNESCO World Heritage Sites and nationally recognised heritage sites. Five areas of interest within the Sahel region were selected as case studies.

For each site, a comprehensive dataset was compiled, including UNESCO and national heritage documentation, state of conservation reports, global environmental statistics, scientific literature, multispectral satellite imagery (both visual and non-visual), soil typologies, architectural classifications, and relevant historical records encompassing major events and conservation or restoration interventions. Cross-referencing this diverse range of data enabled comparative analysis and the identification of current and emerging threats to cultural heritage assets.

1.1. Desertification and Its Implications on Cultural Heritage

Desertification is the process by which land turns into desert, where the soil becomes more arid, leading to barren terrain. Desertification is actively endangering centuries-old architectural heritage across the Sahel region. Defined as the degradation of land in arid, semi-arid, and dry sub-humid areas, desertification results from a combination of climatic variations and human pressures such as deforestation, overgrazing, and unsustainable land use. This process leads to a persistent decline in the biological and economic productivity of the land, often converting once-productive environments into barren, degraded zones.

In this context, architectural and cultural heritage, particularly structures made from traditional earthen materials, faces intensifying threats. This report investigates how desertification, through mechanisms such as sand movement, extreme weather events, and vegetation loss, compromises the structural integrity and long-term viability of built heritage in the Sahel. It aims to assess these threats using geospatial analysis, with a focus on historically significant urban centers. Desertification manifests most visibly through

1.2. Environmental and Climatic Dynamics

sand movement — a dynamic environmental process that alters landscapes, displaces communities, and damages historic structures. Dune migration, sediment accumulation, and wind-driven erosion contribute to the burial, abrasion, or collapse of heritage architecture. These impacts are especially pronounced in unmaintained or abandoned sites.

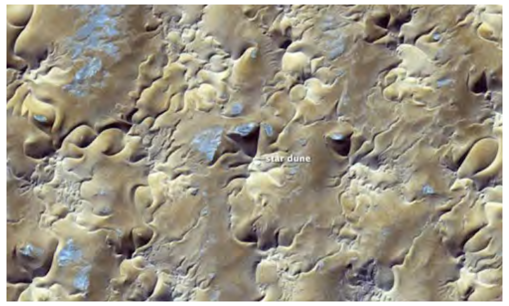
Wind patterns shape a variety of dune forms across the region, including:

Barkhane dunes (crescent-shaped)

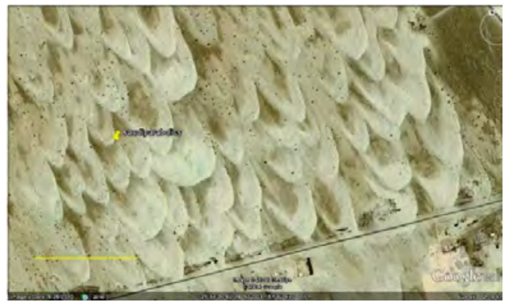
- Linear dunes
- Star dunes (ghourds)
- Parabolic dunes
- Dome-shaped dunes

a. Asymmetric barchans near Doha, Qatar. Tsoar and Parteli, 2016

b. Linear dunes, Great Sand Sea, Egypt. NASA



c. Star dunes, Algeria. NASA



d. Parabolic dunes in eastern Saudi Arabia. Andrew S. Goudie, 2014

e. Giant dome dunes in northern Taklamakan desert, China. Gao, Gadal, Rozier, Narteau.

Desertification in the Sahel is not solely a result of sand movement. It is driven by a wider set of climatic and human-induced pressures that interact with and often amplify one another, affecting both the surface and subsurface dynamics in the region.

- Irregular rainfall pattens: shorter rainy seasons, higher evaporation rates, more frequent droughts.
- Soil crusting; raindrops hit a barren soil, creating a crust that blocks water infiltration, and seals the surface, preventing vegetation regrowth & increasing runoff.
- Human pressure: bush burning for pasture management increases wind and water erosion, & deplete soil nutrients. Land overuse and urban sprawl lead to drying out shallow groundwater
- “Harmattan” winds: a dust laden wind that causes a significant drop in humidity and extreme dryness between December and March in West Africa, and thus erosion of fine topsoil particles.

Climate change intensifies these processes. Reduced vegetation weakens soil cohesion, while declining rainfall and higher evaporation rates reduce soil permeability. As a result, the land becomes less able to absorb water, increasing the frequency and severity of flash floods — which further erode historic sites and damage architectural elements.

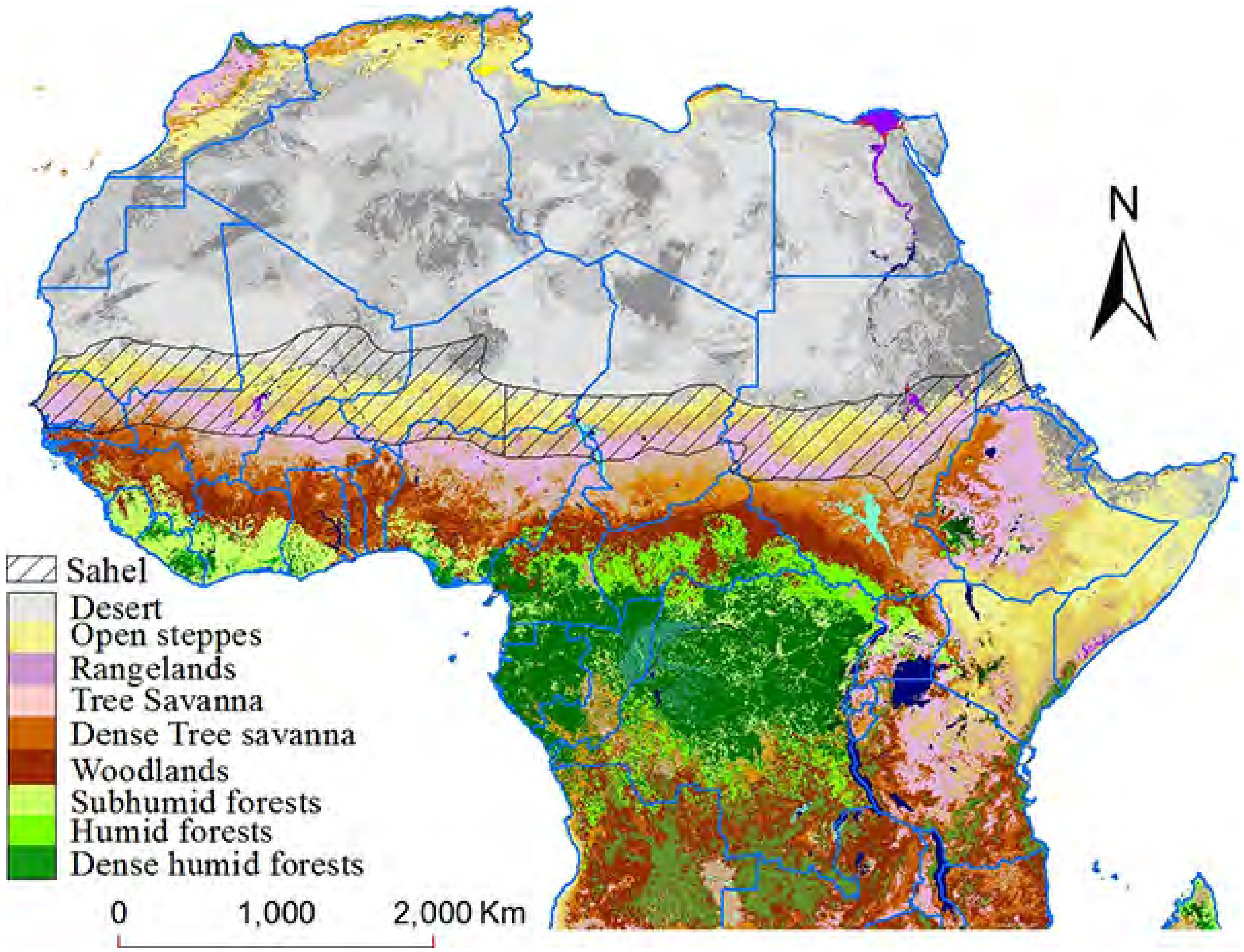
Bush burning, Matt Mwason, corbis, 2022

Soil Crusting, public domain

Floods in Djenné,Mopti regions 2022, Gouvernorat Région de Mopti

Harmattan winds, Philippe Lissac, GODONG

1.3. African Context and Regional Relevance



The great green wall in the Sahel, 2017, Cheikh Mbow

The Sahel is a biogeographical region in Africa. It sits in a transitional zone between an Arid and a Semi Arid climate, along the southern edge of the Sahara Desert. Its historic cities, once thriving hubs of trans-Saharan trade and theological knowledge, feature a distinctive vernacular architecture built from earth, stone, and palm materials, all of which are highly sensitive to environmental conditions.

Desertification in the Sahel is accelerating due to a combination of rising temperatures, erratic rainfall patterns, shrinking vegetation cover, and intensifying wind dynamics. These trends are exacerbating the fragility of already marginal environments, threatening ecosystems, livelihoods, and tangible expressions of cultural identity rooted in place.

This research highlights the shortcomings in terms of Heritage site representation in the Sahel and Africa in general, it aligns with the goals of UNESCO's "Priority Africa" initiative, which promotes heritage protection, climate resilience, and sustainable development across the continent. It also supports the broader aims of the United Nations Convention to Combat Desertification (UNCCD) by emphasizing the cultural dimensions of land degradation.

By providing geospatial evidence of environmental stress at culturally significant locations, this report contributes to filling critical data gaps in one of the world's most climate-sensitive heritage regions. The findings aim to inform conservation planning, support early warning systems, and integrate cultural heritage more effectively into resilience and land management strategies.

This study investigates the dynamics of desertification across the Sahel, with a particular focus on five historically significant urban centers: Agadez (Niger), Timbuktu and Gao (Mali), Chinguetti (Mauritania), and Bandiagara (Mali). These cities, some of which are designated UNESCO World Heritage Sites, represent not only enduring hubs of trans-Saharan trade, Islamic scholarship, and vernacular architecture, but also communities acutely vulnerable to the effects of land degradation and climatic stress.

The Sahel Region and Focus Countries in West Africa HW.ai

Regional Disaster History Across Mali, Niger, and Mauritania: Major Floods, Droughts, and Wildfires (2014–2024)

This page presents a synthesis of major natural disasters that have affected Mauritania, Mali, and Senegal over the past ten years, including floods, droughts, and wildfires. Data has been compiled from the Global Disaster Alert and Coordination System (GDACS) for wildfires and floods, and the EM-DAT International Disaster Database for floods and droughts, ensuring a comprehensive and cross-verified dataset. The aim is to contextualize environmental risks at a regional scale and highlight recurring vulnerabilities and crisis patterns across national boundaries.

Mali

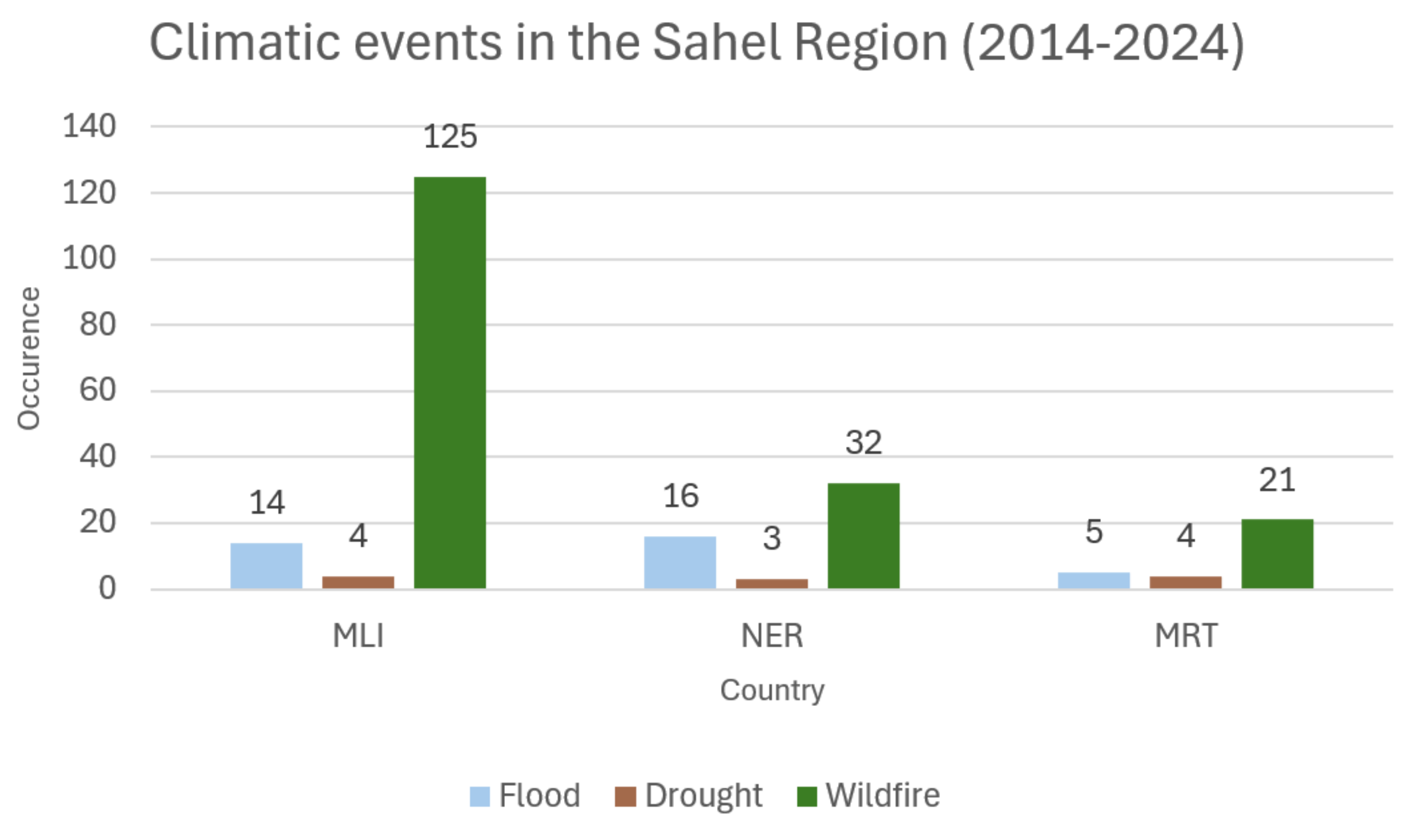
Mali is a landlocked country in West Africa, bordered by Algeria, Niger, Burkina Faso, Côte d'Ivoire, Guinea, Senegal, and Mauritania. It has a hot desert climate in the north and central regions, transitioning to semi-arid in the south. Mali experiences two seasons: a hot, dry season (March-May) and a rainy season (June-September), with scarce rainfall in the north and more precipitation in the south, though droughts are common. Desertification, driven by unsustainable farming, deforestation, and climate change, is a major concern, especially in the Sahel region. The country faces frequent droughts, floods, and wildfires, which worsen land degradation, soil erosion, and water scarcity, threatening food security and livelihoods.

Niger

Niger is a landlocked country in West Africa, bordered by Algeria, Libya, Chad, Nigeria, Benin, Burkina Faso, and Mali. It has a hot desert climate in the north and a semi-arid climate in the south, with irregular rainfall making agriculture highly dependent on seasonal rains. Niger is one of the most vulnerable countries to desertification, with the desert advancing southward each year. The Sahel region suffers from land degradation, overgrazing, and deforestation. Prolonged droughts and wildfires, along with soil erosion, contribute to severe food insecurity, water scarcity, and loss of arable land.

Mauritania

Mauritania, located in the western Sahara Desert, is bordered by the Atlantic Ocean, Western Sahara, Algeria, Mali, and Senegal. It has a desert climate, with the northern regions being extremely arid and the southern areas semi-arid. Rainfall is sparse and erratic, and the country faces extreme heat, particularly in summer. Mauritania is experiencing rapid desertification, with the Sahara advancing at a significant rate, threatening its agricultural and livestock-based economy. Water scarcity, soil erosion, deforestation, and biodiversity loss further exacerbate desertification's impact on the country.



Occurrence of Floods, Droughts and Wildfires – 2014 to 2024 HW.ai

This graph shows the occurences of floods, droughts, and wildfires the three selected countries of our studies, over a ten year period (2014-2024). The chosen parametres were compiled from the Centre for Research on the Epidemiology of Disasters (CRED), and the Global Disaster Alert and Coordination System (GDACS), and have a direct influence on the desertification process on the Sahelian region.

Floods are a key parameter for understanding climate change's impact on arid regions. Desertification degrades soil, reducing its ability to absorb water, leading to flash floods during intense rainfall. These floods, in turn, accelerate land erosion and further degrade the environment. Tracking floods provides insights into how desertification is contributing to the region's vulnerability to extreme weather events.

As desertification progresses, droughts become more frequent and severe, the reduction in rainfall and water availability lead to crop failures, and food insecurity. Monitoring drought events is essential for understanding how climate change and desertification are exacerbating environmental and socio-economic challenges in the Sahel.

Wildfires are both a result of and a contributing factor to desertification. Drier conditions from desertification increase the likelihood of wildfires, which in turn degrade ecosystems, reduce biodiversity, and accelerate soil erosion. Wildfires are indicative of the region's growing vulnerability to environmental degradation. Tracking their occurrence helps assess the broader impacts of desertification on ecosystems and human communities.

Tracking these parametres allows for a better understanding of the evolving environmental conditions in Mali, Niger, and Mauritania. The data collected over the past decade highlights the need for targeted interventions and policies to mitigate the impact of desertification and build climate resilience in the region.

1.4. Approach and Methodology

Overview

This study analyzes desertification trends from 2014 to 2024 in selected Areas of Interest (AOIs) in the Sahel, using advanced remote sensing techniques and open-source environmental and disaster data. The goal is to assess vulnerability through the analysis of:

- Land cover changes
- Vegetation dynamics
- Exposure to natural disasters

The approach supports evidence-based decision-making in land degradation monitoring, climate adaptation, and cultural heritage preservation.

1. Disaster Exposure Assessment

Including historical disaster data helps contextualize environmental stress by linking observed degradation to acute events like droughts, floods, and wildfires. This supports a risk-informed interpretation of vulnerability patterns across the AOIs.

The EM-DAT database compiles global disaster events (1988–2024) based on criteria such as:

- ≥10 fatalities
- ≥100 people affected
- Declared state of emergency
- Request for international assistance

For this study, we extracted drought, flood, and wildfire events (2014–2024) in the Sahel to contextualize environmental stress within a risk management framework.

2. Fractional Cover Index (FCI)

Indicators of Bare Soil and Vegetation Exposure
We selected the FCI because it offers a detailed, sub-pixel analysis of land cover composition—especially the extent of bare soil versus vegetation. This allows us to detect early signs of land degradation and pinpoint areas most exposed to erosion or desertification risk.

The FCI uses machine learning to estimate the proportion of land cover types at a 30-meter resolution:

- Green vegetation
- Non-photosynthetic vegetation
- Bare soil

We focus on two key metrics:

- 90th Percentile of Bare Soil (January, annually)

→ Indicates maximum soil exposure in each AOI
→ Identifies zones at risk of erosion, instability, and desertification

- 10th Percentile of Green Vegetation

→ Highlights minimum vegetation cover
→ Reflects ecological stress or degradation
Focusing on extremes (percentiles) rather than seasonal averages emphasizes long-term degradation and filters out short-term variability.

3. NDVI Analysis

Vegetative Health and Ecosystem Productivity
NDVI was chosen for its proven reliability in tracking vegetation health and productivity over time. By focusing on the peak growing season, we can assess ecosystem resilience and identify shifts in vegetation density that reflect long-term ecological trends.

NDVI values (–1 to +1) reflect vegetation health based on reflectance patterns:

- Higher values = denser, healthier vegetation
- Lower values = degraded or bare areas

Methodology:

- Source: Digital Earth Africa NDVI climatology (1984–2020)
- Focus Period: August (2017–2024) — peak rainy season in the Sahel

NDVI Histograms:

- X-axis: NDVI value range (~0 to ~0.7)
- Y-axis: Pixel frequency (spatial density distribution)

Changes in histogram shape, skewness, or spread over time signal trends in recovery, degradation, or fragmentation.

4. Climatic Context

Rainfall and Temperature Anomalies
Rainfall and temperature anomalies provide crucial climatic context for interpreting changes in vegetation and soil exposure. These indicators help isolate the influence of broader climate patterns from local or anthropogenic drivers of degradation.

Regional-scale anomalies are sourced from gridded datasets (~100 km² resolution):

- Rainfall anomalies → From GPCC
- Temperature anomalies → From Berkeley Earth

These help contextualize NDVI and FCI trends:

- Below-average rainfall → Limits vegetation growth, increases bare soil
- High temperatures → Intensify evapotranspiration and land desiccation

While not precise at the site level, these anomalies are key to understanding broader environmental pressures.

5. Analytical Framework

By integrating FCI, NDVI, and climate anomalies, the study enables:

- Detection of persistent land degradation
- Identification of areas with regenerative potential
- Correlation with disaster events and climate stressors

6. Application of Results

The insights from this study support:

- Site-level vulnerability assessments for cultural heritage
- Regional land degradation mapping
- Policy recommendations for climate adaptation and disaster risk reduction

This integrative method empowers stakeholders to prioritize interventions based on ecological stress and heritage significance supporting more effective responses to desertification.
Data Sources and Integration

The analysis integrates multiple data sources:

- Disaster Records

From:
→ EM-DAT (Emergency Events Database, CRED)
→ GDACS (Global Disaster Alert and Coordination System)
Covering: Floods, droughts, and wildfires

- Remote Sensing Indices

→ Fractional Cover Index (FCI)
→ Normalized Difference Vegetation Index (NDVI)
Sourced via: Digital Earth Africa, based on Landsat imagery
→ Climatic Data
From: Africa Data Hub's Climate Observer
Includes:
→ Rainfall anomalies (GPCC)
→ Temperature anomalies (Berkeley Earth)
→ Contextual Validation
→ High-resolution satellite imagery
→ Conservation records
→ Archival and scientific documentation

2. SITE-LEVEL RISK AND SPATIAL ANALYSIS

2.1 CHINGUETTI, MAURITANIA

An abandoned house sits in sand near Chinguetti, Mauritania. Moulay, K. (2025, January 13). Associated Press.

I. General Overview

Chinguetti, Mauritania. HW.ai

Desert surrounding the old city in Chinguetti, Mauritania. (2023, March 20). Longari, M. The Washington Post.

Site Name: Chinguetti

Country: Mauritania

Status: UNESCO World Heritage Site (1996)

UNESCO ID: 750

Coordinates:20° 27′ 27″N, 12° 21′ 44″W

Historical Context:

Chinguetti was founded in the 11th century and flourished between the 13th and 17th centuries as a prominent Islamic and trading center along trans-Saharan caravan routes. It is known for its Great Mosque and historic manuscript libraries, many of which are privately maintained to this day. The city is part of the UNESCO-listed «Ancient Ksour» of Mauritania. In recent decades, desertification and abandonment have severely threatened its built heritage and social fabric.

Regional & Environmental Context:

Climate	Hot desert climate (BWh)
Avg. Annual Temperature	30°C
Avg. Annual Rainfall	<50 mm
Soil Type	Sandy soil with shifty dunes, rocky plateaus.
Recent Climate Anomalies	Advancing sand dunes, declining vegetation, flooding linked to impermeable soils

Social & Demographic Context:

Despite population decline (approx. 4,800 in 2013), Chinguetti remains inhabited. It holds symbolic importance as one of Islam's historic intellectual centers and retains living cultural traditions linked to manuscript preservation and religious practice.

Architecture & Construction:

The town's historic core is built primarily from locally sourced stone, banco (mudbrick), and palm wood. Its architectural style features clustered homes around courtyards and narrow streets adapted to desert conditions. Key vulnerabilities include:

- Structural erosion from wind-driven sand
- Partial burial of lower-level buildings and alleys
- Loss of traditional maintenance cycles and knowledge transmission

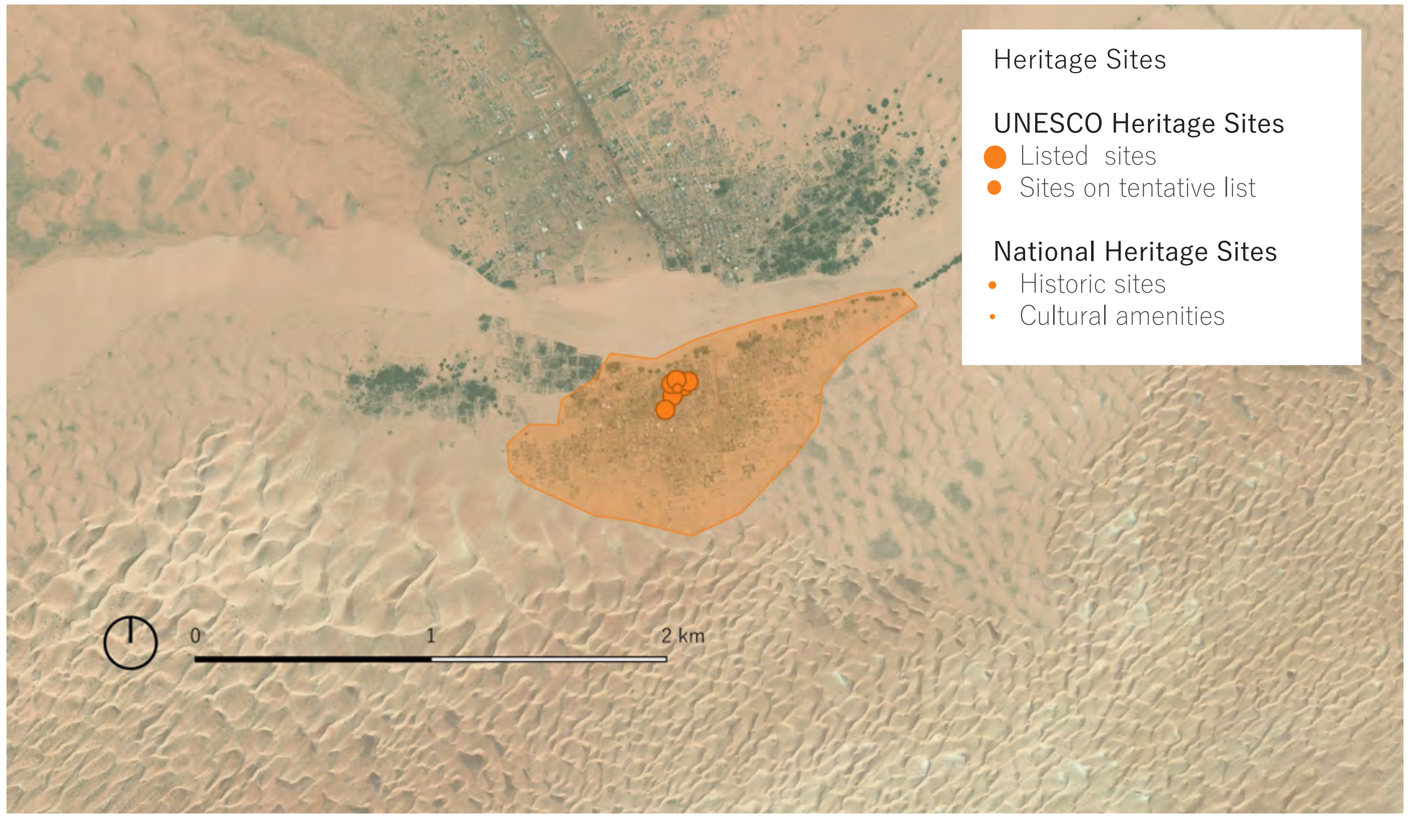
Environmental risks:

Chinguetti faces escalating environmental threats, most notably the encroachment of mobile sand dunes, which are progressively damaging the city's outer quarters and key access routes. This phenomenon, driven by regional desertification and declining vegetative cover, has intensified over recent decades and now poses a direct threat to both the livability of the site and the preservation of its historic urban fabric. The movement of sand has disrupted transport infrastructure, isolated parts of the settlement, and increased the vulnerability of earthen structures to abrasion and partial burial. The city's exposure to these processes underscores the broader environmental instability affecting Saharan settlements and the urgent need for sustainable land and heritage management

Conservation efforts:

While conservation efforts have been initiated in Chinguetti, they remain largely piecemeal, underfunded, and inconsistently applied. A protected buffer zone has been proposed to slow the advance of dunes and reduce direct environmental impacts on the heritage core (UNEP, 2024), yet its implementation remains limited due to both financial constraints and insufficient technical infrastructure. Given the site's outstanding historical and architectural significance, Chinguetti constitutes a high-priority case for integrated preservation strategies that address both cultural continuity and environmental resilience. Future efforts must adopt a multidisciplinary approach that combines traditional knowledge, modern conservation science, and regional climate adaptation measures.

II. Heritage Context



Localised Map of Chinguetti with heritage sites.

HW.ai

This section presents a spatial and visual overview of cultural heritage features in the historic town of Chinguetti. The accompanying map displays the distribution and categorization of sites based on their architectural typology, historical relevance, and current use. These include structures formally recognized as UNESCO World Heritage Sites, as well as nationally protected landmarks and locally significant elements such as communal spaces and vernacular housing clusters.

The imagery on the next page captures defining architectural characteristics, material practices, and spatial relationships within the urban landscape. Together, the map and photographs offer insight into the cultural layering of Chinguetti, while also revealing the site's vulnerability to environmental degradation and demographic change.

République islamique de Mauritanie – Chinguetti. ECPAD. (1969). ImagesDéfense.

Ancient Ksour of Ouadane, Chinguetti, Tichitt and Oualata (Mauritania) (n.d.). Gelbart, J.-J. © Editions Gelbart.

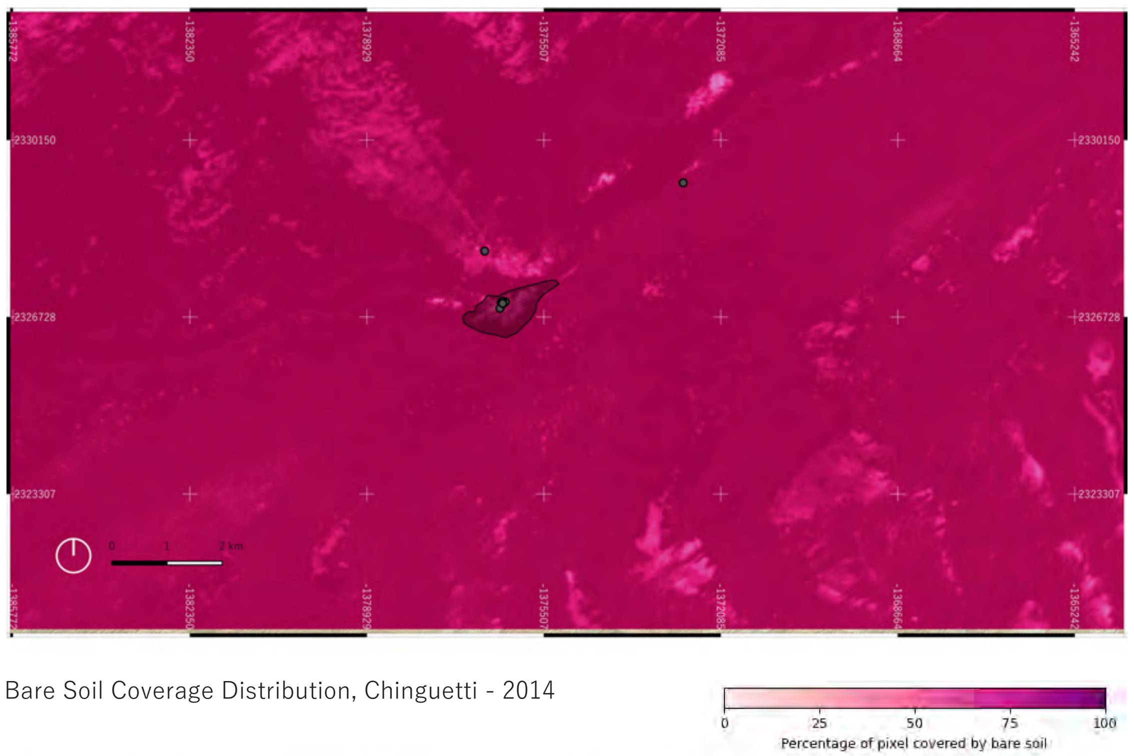
Ancient Ksour of Ouadane, Chinguetti, (n.d.). Tichitt and Oualata Spooner, J. (Mauritania) © John Spooner.

Ancient Ksour of Ouadane, Chinguetti, Tichitt and Oualata (Mauritania) (n.d.). Gelbart, J.-J. Éditions Gelbart.

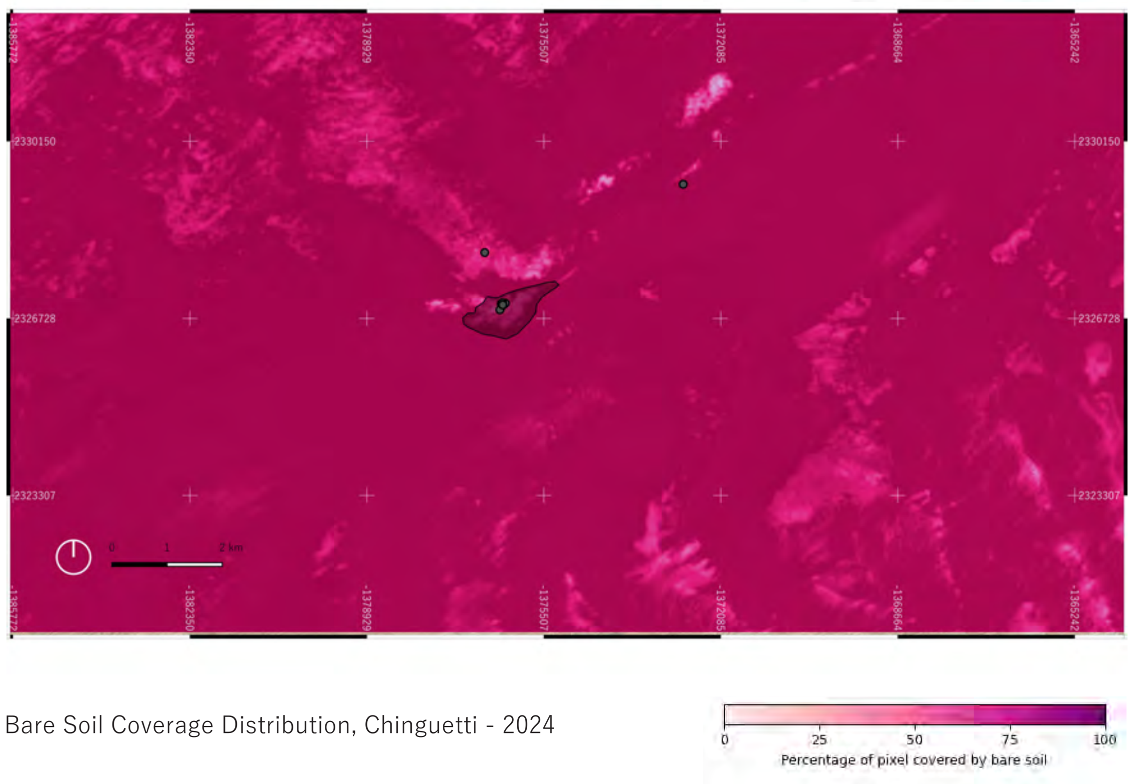
III. Risk Analyses

A- Bare Soil Exposure in Chinguetti, Mauritania (2014-2024)

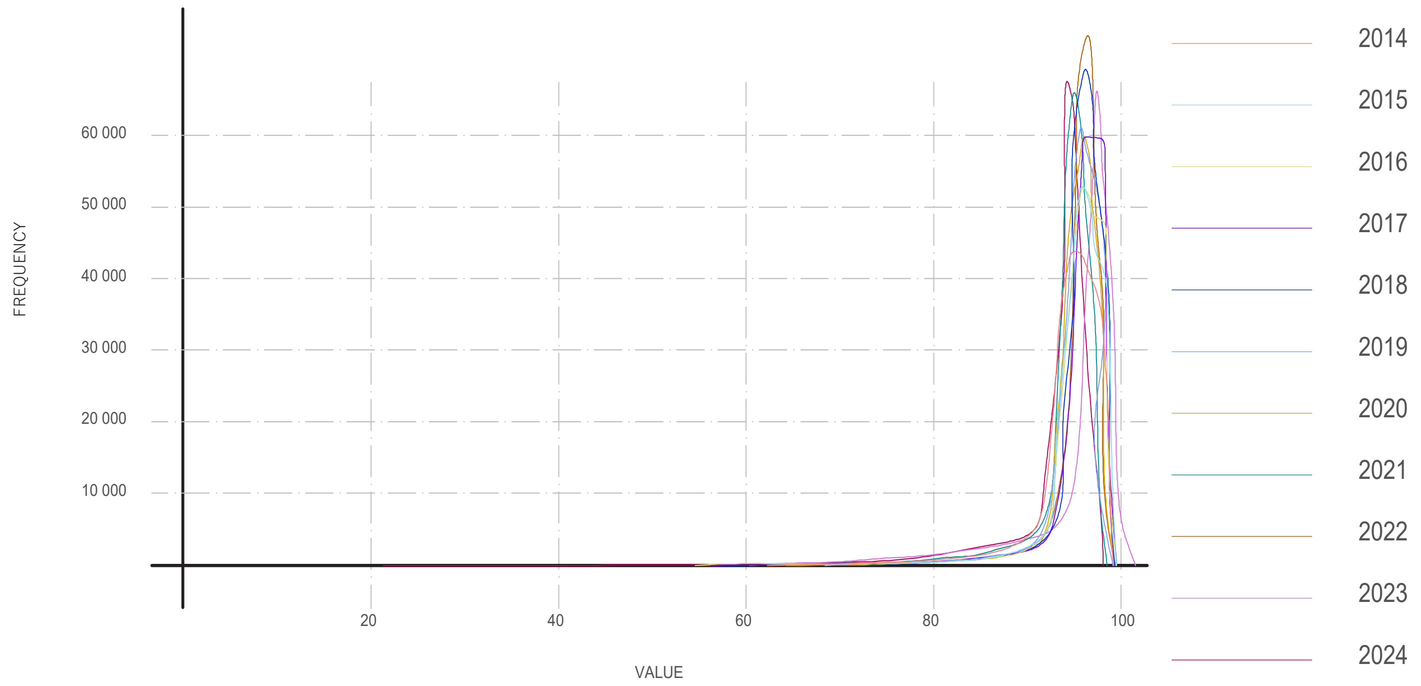
This section analyses the 90th percentile of bare soil coverage to assess the extent of exposed land surfaces and their evolution over the decade, using data derived from Landsat 5, 7, and 8 imagery processed through the CSIRO fractional cover algorithm and distributed by Digital Earth Africa.



Bare Soil Coverage Distribution, Chinguetti - 2014



Bare Soil Coverage Distribution, Chinguetti - 2024



Cumulative Bare Soil Coverage Distribution, Chinguetti – 2014-2024 HW.ai

Observations of Histogram Distributions

The histogram series across the 11-year period reveals a consistently high concentration of bare soil values above 90%. From 2014 to 2019, the distributions are already skewed toward extreme exposure, but some broadness in the curves suggests limited heterogeneity in surface conditions. From 2020 onward, the distributions become increasingly narrow and peaked around the 95–97% range. This tightening of the distribution reflects a reduction in spatial variability, with more pixels converging on very high levels of bare soil coverage.

Interpretation and Trends

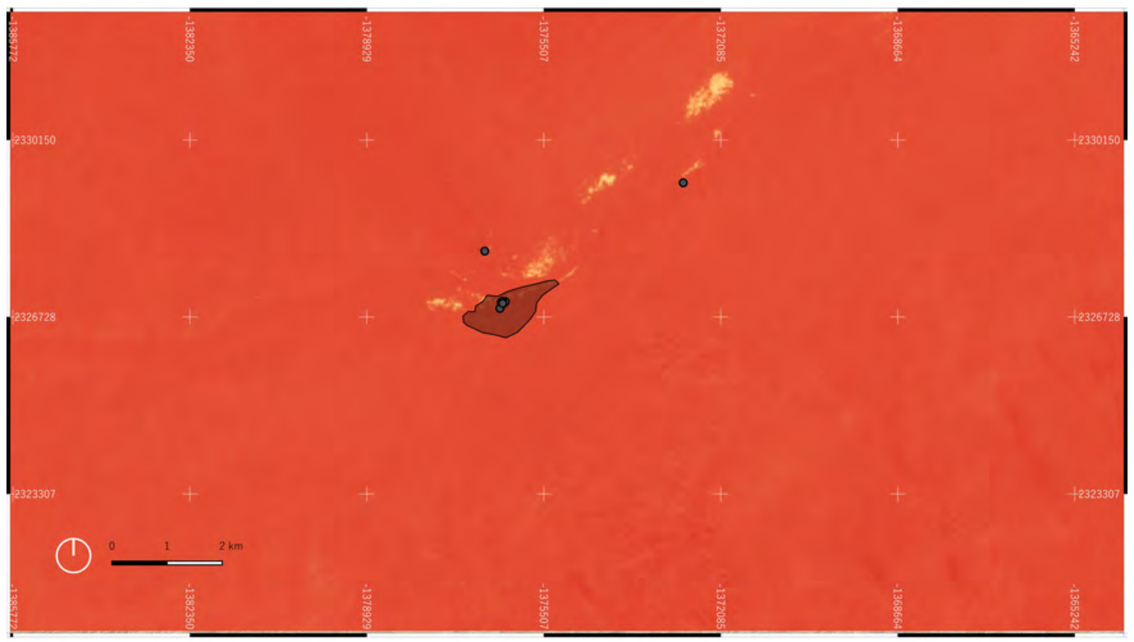
These patterns point to a progressive and spatially consolidating process of desertification. The transition from a somewhat mixed landscape to one dominated by uniform, highly exposed surfaces suggests not only the persistence of ecological stress but its intensification. The increasing sharpness of the histogram peaks over time implies that formerly semi-stable zones have crossed ecological thresholds and shifted into fully degraded states. This is not a temporary or seasonal shift, but a systemic, cumulative trend indicating reduced land resilience. Chinguetti is not merely experiencing high bare soil exposure — it is becoming ecologically homogenized under extreme aridity, reducing the landscape's capacity to recover or support diverse land uses.

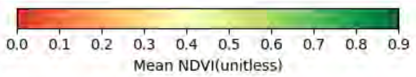
Heritge Implications

This trajectory has serious consequences for both tangible and intangible heritage. Chinguetti's historic urban core, known for its ancient adobe libraries and mosques, is increasingly exposed to wind erosion, sand abrasion, and sediment burial due to the loss of surrounding vegetative buffers. The expanding bare soil surfaces accelerate aeolian processes, undermining the physical stability of cultural structures. Simultaneously, the degradation of rangelands and croplands jeopardises the viability of agro-pastoral livelihoods that sustain the local population. As displacement pressures rise, so does the risk of losing oral traditions, land-based rituals, and custodial relationships with the sacred and historical landscape.

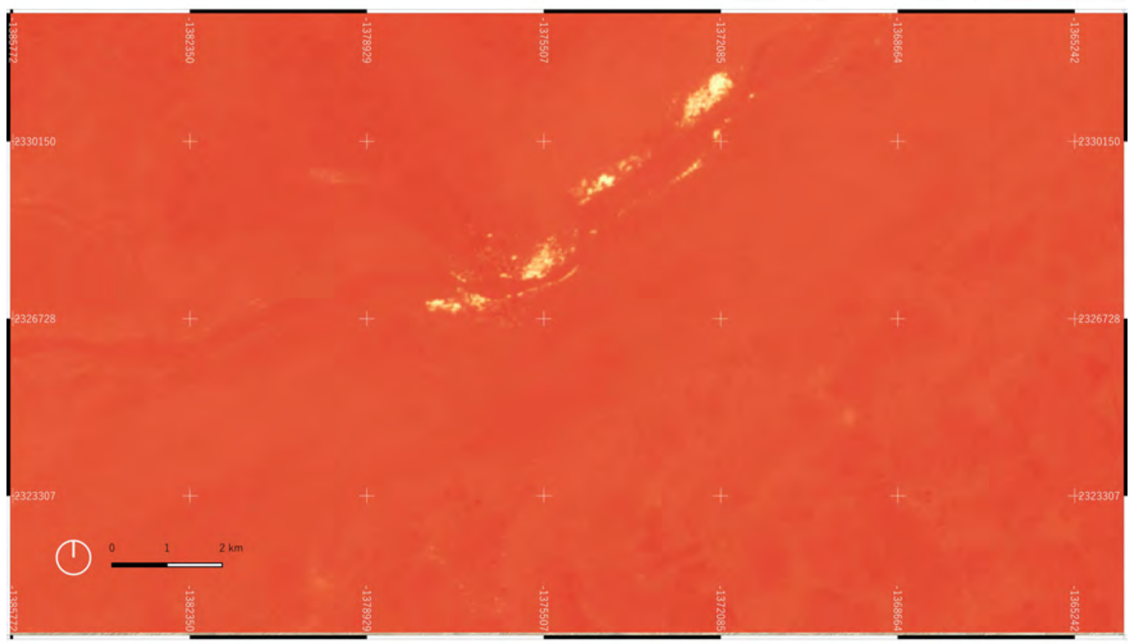
B- Vegetation Density Trends in Chinguetti, Mauritania (2017–2024)

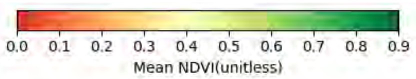
This section analyzes the August mean NDVI to assess vegetation cover and its temporal variation between 2017 and 2024, using data derived from harmonized Landsat 5, 7, and 8 imagery processed into monthly climatologies and distributed by Digital Earth Africa.



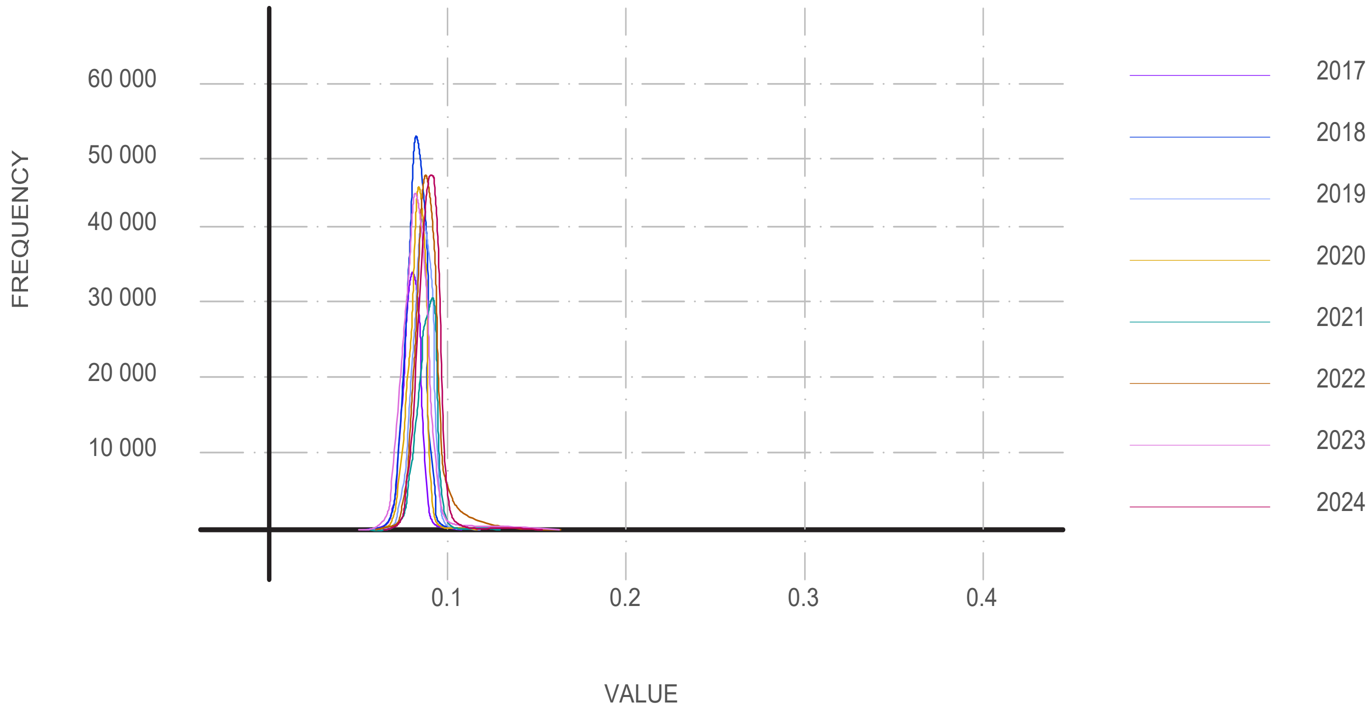


Mean NDVI Distribution, Chinguetti – August 2017





Mean NDVI Distribution, Chinguetti – August 2024



Cumulative Mean NDVI Distribution, Chinguetti – 2017-2024 HW.ai

Observations of Histogram Distributions

The NDVI histograms for Chinguetti between 2017 and 2024 consistently exhibit sharp, unimodal peaks concentrated between 0.08 and 0.10, indicating extremely low vegetation levels across the monitored area. A modest rightward shift occurs in 2022 and 2023, suggesting slight improvement in vegetative conditions, but this is not sustained: by 2024, the distribution narrows again and recenters within the original low-value range.

Interpretation and Trends

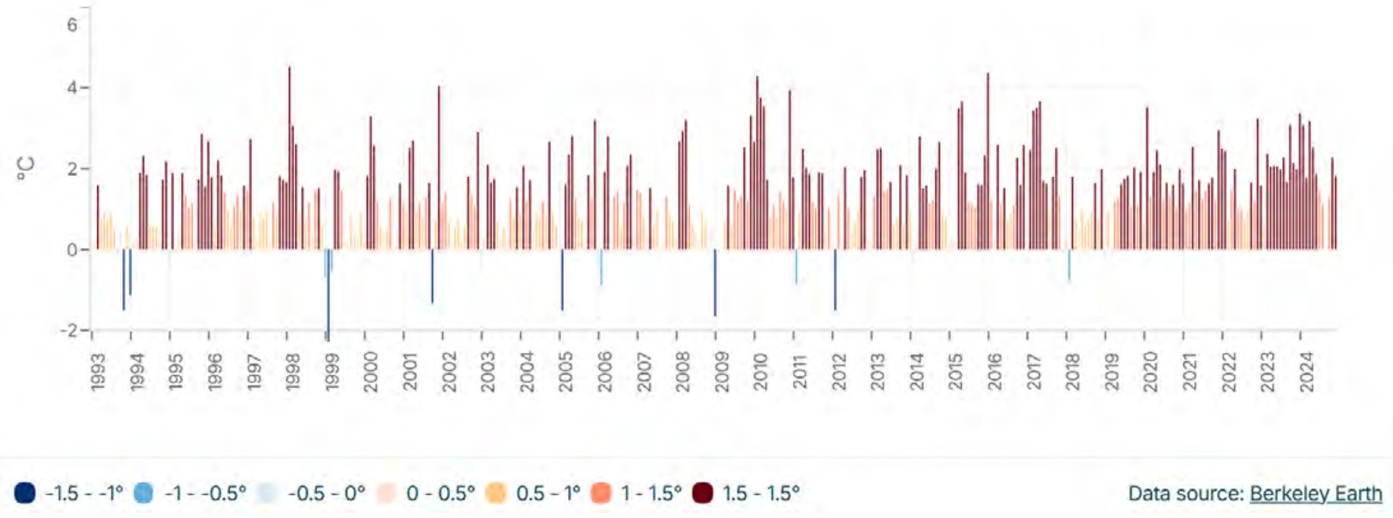
The data points to a stable yet fragile vegetative regime, with minimal photosynthetic activity and little sign of long-term ecological recovery. The brief improvement seen in the early 2020s appears to have been temporary or anomalous, rather than part of a progressive greening trend. The overall trajectory reflects a persistent and entrenched vegetative deficit, aligned with advancing desertification and constrained ecosystem resilience in this hyper-arid setting.

Heritage Implications

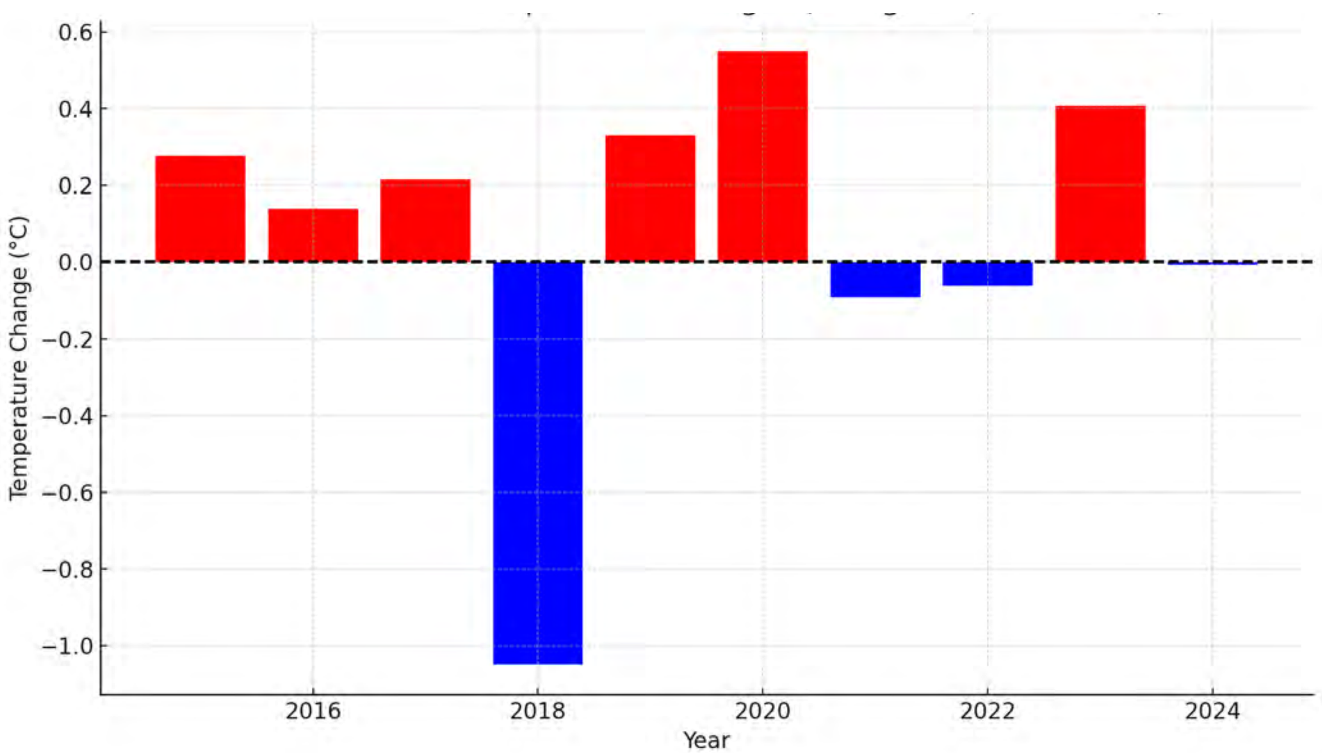
Consistently low NDVI values reaffirm the ecological vulnerability of Chinguetti's cultural landscape. The absence of substantial vegetation eliminates key buffers that traditionally mitigate wind erosion, sand encroachment, and surface instability, all of which directly threaten the integrity of historic adobe architecture and funerary sites. In addition, weak vegetative support limits the viability of seasonal pastoralism and local food systems, undermining the social and economic foundations that sustain cultural practices and landscape stewardship.

C- Climatic Context in Chinguetti; Mauritania: Temperature Trends and Rainfall (1993–2024)

This section presents monthly temperature trends and rainfall for the selected area between 1993 and 2024. The data is sourced from the Africa Data Hub's Climate Observer platform, which compiles information from the Global Precipitation Climatology Centre (GPCC) for rainfall and Berkeley Earth for temperature.

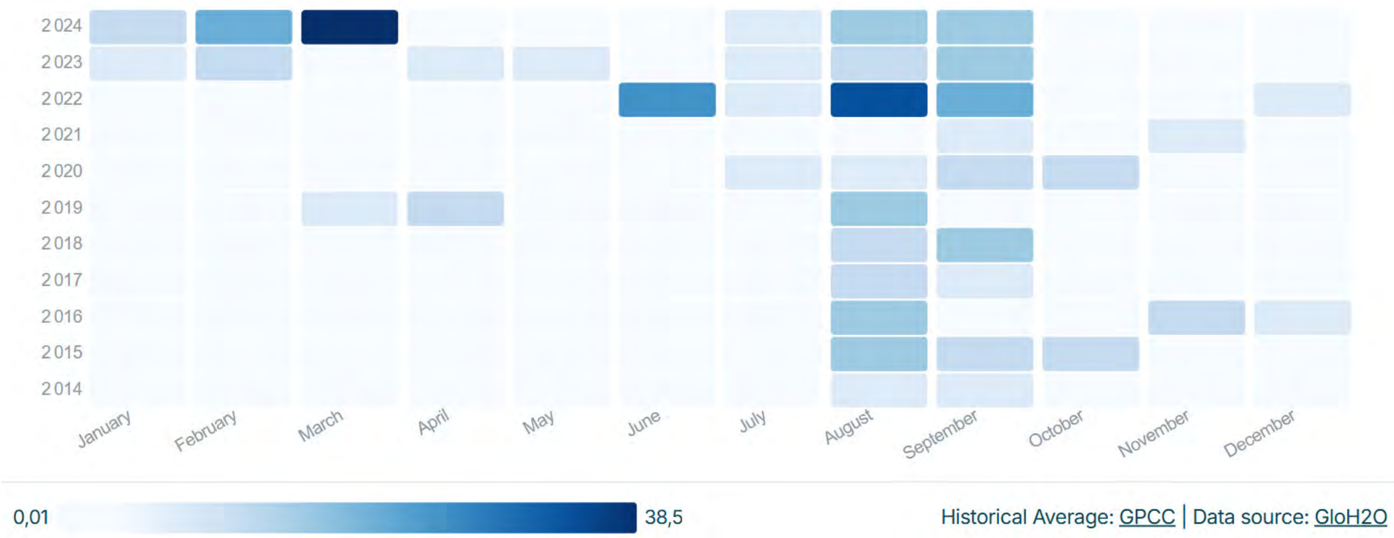


Temperature anomalies - 1993-2024



Interannual Temperature Fluctuations, Chinguetti - 2014-024

HW.ai



Average Monthly Rainfall (mm) Chinguetti – 2014-2024

Long-Term Trends (1993–2024)

Rainfall:
Chinguetti remains arid overall, with many years in the 1990s–2000s receiving under 50 mm of rain.
Recent years show more variability:
2024 saw a record 113.3 mm, more than double typical totals.
Rainfall occurred in unusual months (e.g., 38.5 mm in March 2024).
Since 2018, totals are rising — not steadily, but in erratic bursts.

Temperature:
A warming trend is evident, especially post-2014.
Most months now exceed historical averages.
April 2020 peaked at 3.8° C above normal.
Nighttime temperatures are rising, reducing diurnal relief and increasing thermal stress.

Recent Decade Focus (2014–2024)

Rainfall has grown less predictable:
Totals are higher but inconsistent, with extremes in both wet and dry years.
Rains increasingly fall outside the wet season, hinting at seasonal disruption.

Temperature anomalies are now frequent:
Both daytime and nighttime temperatures have increased.
Heatwaves and prolonged thermal stress are more common.

Interpretation

Together, these patterns indicate that Chinguetti's climate is becoming hotter, more unpredictable, and more prone to extremes. While increased rainfall might seem positive, it comes with intensified erosion risks due to sparse vegetation and poor soil cohesion. Similarly, higher temperatures can compound water loss, reduce soil fertility, and threaten traditional crops and building materials.

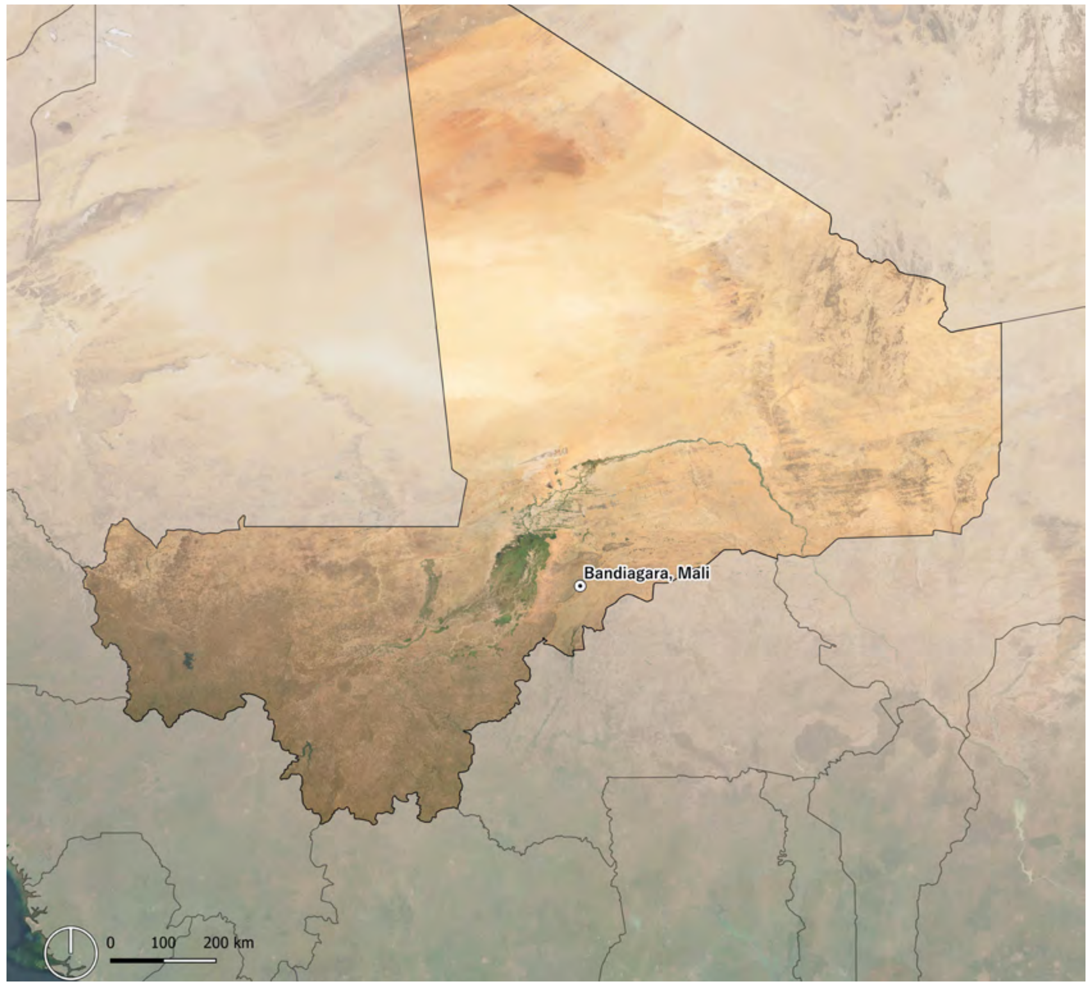
Heritage Implications

The combined pressure of heat and erratic rainfall is already impacting both tangible and intangible heritage: Historic adobe architecture is increasingly vulnerable to rain-induced erosion and drying-induced cracking. Seasonal rhythms underpinning agro-pastoral life are destabilized, weakening cultural cohesion and traditional ecological knowledge systems. More frequent out-of-season rains and intense heatwaves are likely to disrupt pilgrimage patterns, land rituals, and conservation practices. If current climate trends continue, cultural landscapes in Chinguetti may become physically and symbolically unrecognizable within a generation — unless adaptation and preservation strategies are urgently developed.

2. SITE-LEVEL RISK AND SPATIAL ANALYSIS
2.2 BANDIAGARA, MALI

Dogon village and the Bandiagara escarpment, a UNESCO World Heritage Site, Dogon country, Mali (n.d.).Lookphotos / Design Pics. Lookphotos.

I. General Overview



Bandiagara, Mali. HW.ai

Bandiagara, a Dogon village in Mali (2009, December 3). Frei, H. Flickr.

Site Name: Bandiagara

Country: Mali

Status: UNESCO World Heritage Site (1989)

UNESCO ID:516

Coordinates: N 14 19 59.988 W3 25 0.01

Historical Context:

The Bandiagara Escarpment, a landscape of cliffs and plateaus in Eastern Mali, & home to the Dogon people, contains over 289 villages of outstanding vernacular architectures. It reached cultural prominence in the 18th century, but the first human settlements date back to the Paleolithic era. The area is notable for its difficult access and dense tangible & intangible cultural heritage.

Since 2012, the region has been affected by an ongoing conflict involving armed groups and intercommunal violence, which has contributed to instability and hindered preservation efforts.

Regional & Environmental Context:

Social & Demographic Context:

Climate	Semi arid (Sahelian)
Avg. Annual Temperature	28°C
Avg. Annual Rainfall	400 - 600 mm
Soil Type	Rocky soils (lithosols) and lateritic soils, with steep escar-pments and eroded plateaus
Recent Climate Anomalies	Increased frequency of droughts and erratic rainfall, contributing to desertification and soil degradation

Until today, many Dogon cultural practices remain, including religious ceremonies, traditional dances, and (resilient) agricultural traditions. Dogon Identity is indivisible from its landscape, unfortunately, the ongoing conflict and migration have led to the depopulation of the cliff villages, threatening a disconnect in intergenerational transmission of traditional knowledge.

Architecture & Construction:

The architecture of the Dogon land has been adapted to benefit from the physical constraints of the place. The typologies found in Dogon Villages include granaries, sanctuaries, and dwellings, made of mudbricks, stone, timber, and can even be embedded into the rock. The use of mudbricks makes the constructions particularly vulnerable to rainfall and erosion; coupled with local exodus, Dogon villages have reduced maintenance.

Environmental risks:

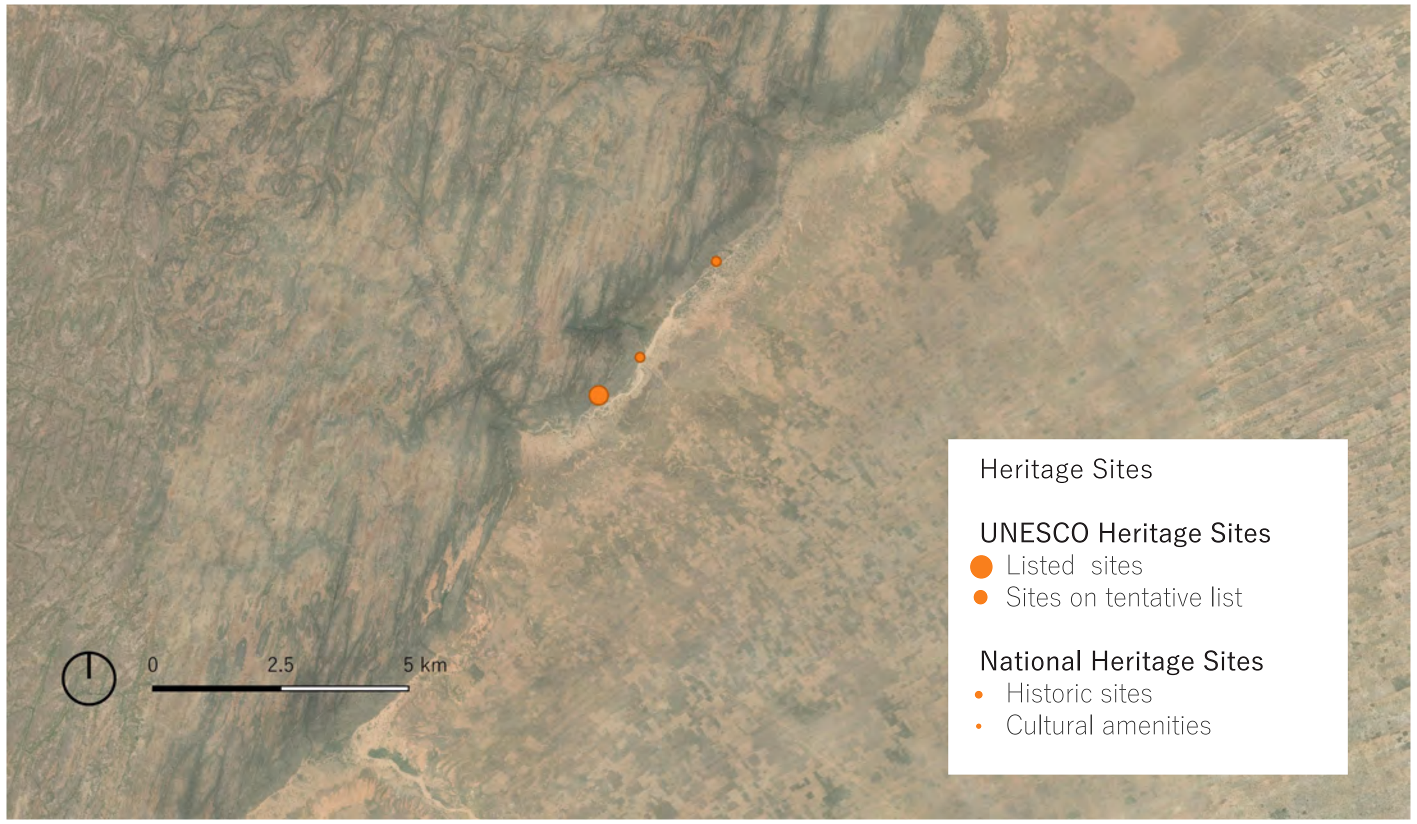
The site of Bandiagara faced several environmental and human induced threats. Desertification and more recurrent Floods pose serious risks on both built heritage and its environment. Conflict related displacement and overall insecurity have hindered community led conservation activities (both international and local).

Conservation efforts:

In 2020, UNESCO published a State of Conservation report detailing the restoration efforts on the site of Sessé, gin'nas (large family houses) in several villages, as well as training of young people in local construction techniques. A Reactive Monitoring mission, requested on several occasions by the Committee since 2016, has not yet been implemented due to the instable security situation.

In 2020, ALIPH granted 984 818 USD for the "Reconstruction and Rehabilitation of the Built Heritage of Bandiagara". The Association Dogon Initiative and other organisations, have undertaken actions for rehabilitation, awareness raising on cultural heritage, capacity building for women.

II. Heritage Context



Localised Map of Bandiagara with heritage sites.

HW.ai

This section offers a spatial interpretation of the cultural landscape of the Bandiagara region. The map identifies heritage elements categorized by function, architectural form, and cultural meaning—spanning sites listed as UNESCO World Heritage, locations included on Mali's Tentative List, and places of local significance preserved through oral tradition and community practice.

Photographs on the following page document architectural features, sacred sites, and settlement forms integrated into the natural terrain. The visual and spatial data work together to highlight the complex interplay between tangible heritage and the cultural systems that sustain it, as well as the growing challenges posed by erosion, climate stress, and migration pressures.

Village Dogon République du Mali, cercle de Bandiagara, Ségué, 1958. ECPAD. Images Défense.

Cliff of Bandiagara (Land of the Dogons), (n.d.) Stefansson, P. Mali. OUR PLACE The World Heritage Collection. UNESCO World Heritage Centre.

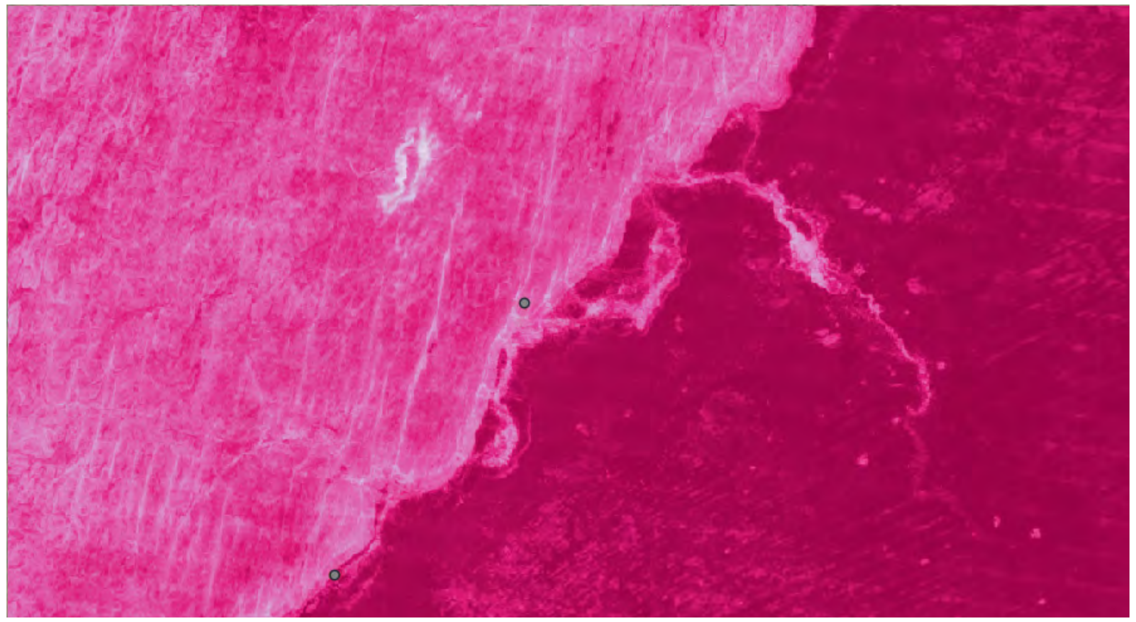
Cliff of Bandiagara (Land of the Dogons), (n.d.). Mali. Stefansson, P. UNESCO World Heritage Centre.

Grenier Dogon dans le village, au pied de la falaise. République du Mali, village d'Iréli, cercle de Bandiagara. (1958). Leroux. ImagesDéfense.

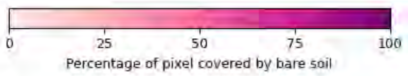
III. Risk Analyses

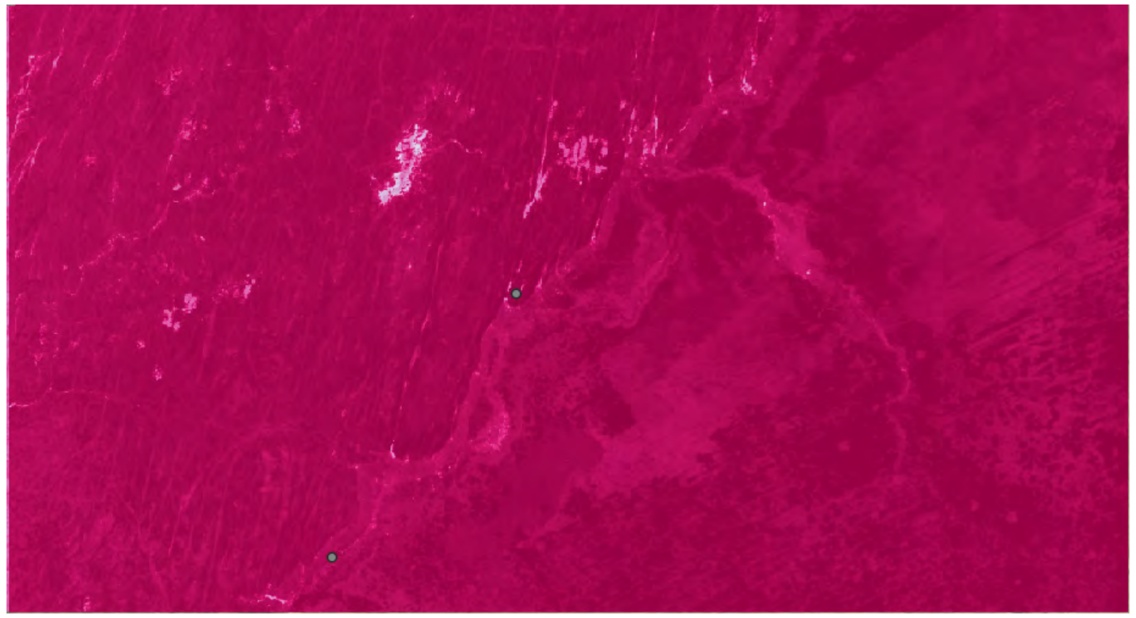
A- Bare Soil Exposure in Bandiagara, Mali (2014–2024)

This section analyses the 90th percentile of bare soil coverage to assess the extent of exposed land surfaces and their evolution over the decade, using data derived from Landsat 5, 7, and 8 imagery processed through the CSIRO fractional cover algorithm and distributed by Digital Earth Africa.

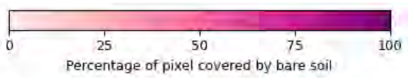


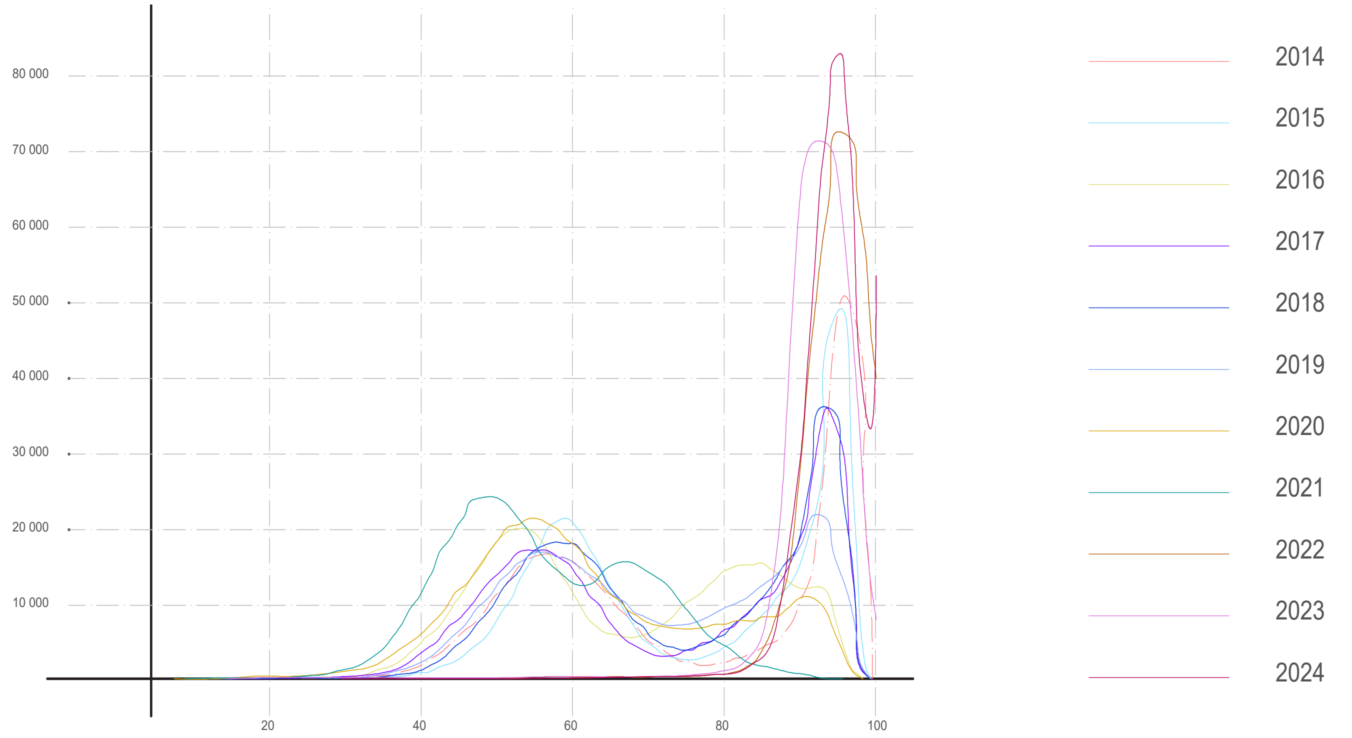
Bare Soil Coverage Distribution, Bandiagara – 2014





Bare Soil Coverage Distribution, Bandiagara – 2024





Cumulative Bare Soil Coverage Distribution, Bandiagara – 2014-2024 HW.ai

Observations of Histogram Distributions

From 2014 to 2021, the bare soil histograms for Bandiagara consistently display a bimodal distribution, with prominent peaks in two distinct ranges: moderate bare soil coverage (50–60%) and very high exposure (90–100%). This pattern suggests the coexistence of two dominant land surface conditions, some areas retaining moderate vegetation or ground cover, while others are highly degraded. However, from 2022 onward, this dual-peak structure collapses into a unimodal distribution, sharply concentrated in the 95–100% range. The histogram for 2024, in particular, shows a dense spike with minimal distributional spread, indicating the dominance of uniformly bare surfaces across the landscape.

Interpretation and Trends

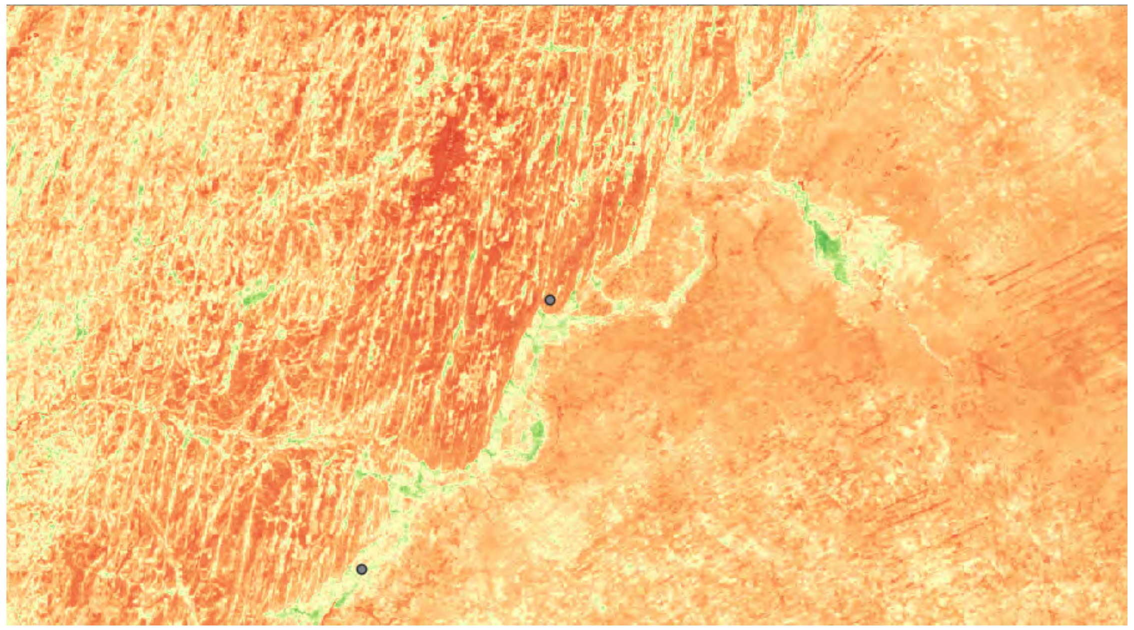
The evolution from a bimodal to a narrow unimodal distribution signals a critical ecological transition. Bandiagara's landscape has moved from partial heterogeneity, with varying degrees of land cover, to near-complete homogenization under extreme exposure. This indicates an advanced stage of desertification, where the spatial variability that once reflected pockets of vegetative resilience has disappeared. The sharpness and centralization of the recent distributions suggest that land degradation is no longer fragmentary but widespread and entrenched. The transformation implies a collapse of land recovery potential, with formerly semi-stable areas now assimilated into the desertified matrix. These trends are characteristic of a landscape that has crossed a degradation threshold, potentially entering a new ecological regime dominated by erosional forces.

Heritge Implications

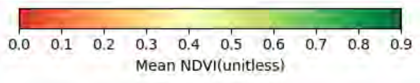
This accelerating loss of ground cover presents critical risks to Bandiagara's cultural landscape, especially the Dogon heritage zone. Many of the region's sacred and vernacular structures built into cliffs and slopes are vulnerable to geomorphic instability. The lack of vegetation removes essential protections against runoff and wind-driven erosion, increasing the likelihood of collapse or damage to earthen architecture. Moreover, the degradation of surrounding agricultural and pastoral zones places pressure on community sustainability. As arable land and grazing capacity decline, there is an increasing risk of outmigration and social fragmentation, which threatens intangible heritage including spiritual rites, seasonal festivals, and traditional ecological knowledge, all deeply tied to place and seasonal cycles.

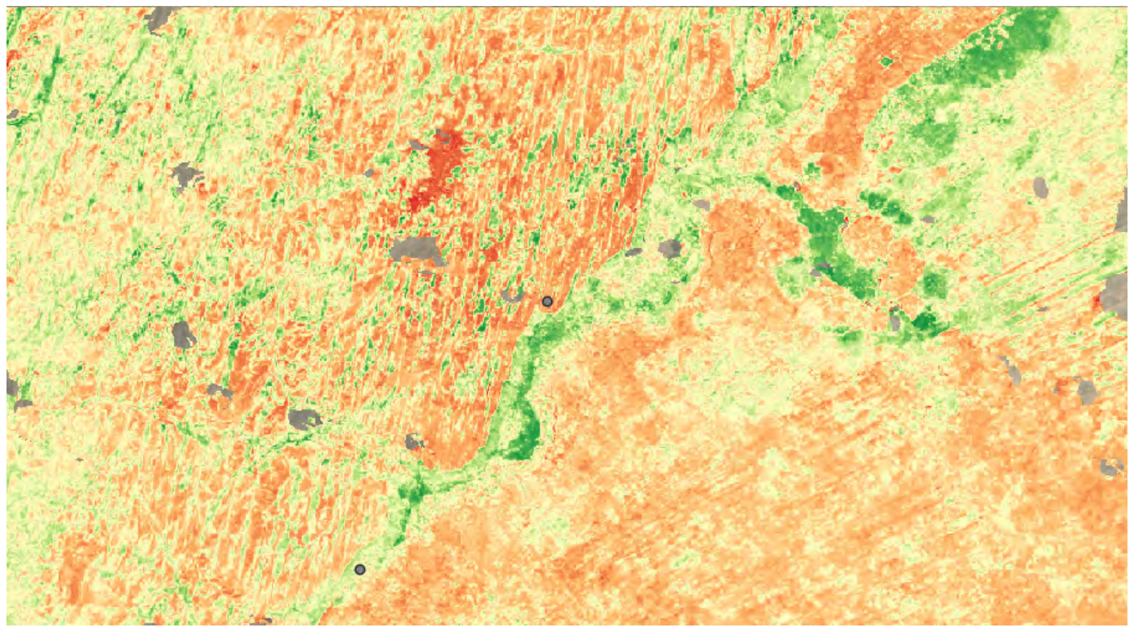
B- Vegetation Density Trends in Bandiagara, Mali (2017–2024)

This section analyzes the August mean NDVI to assess vegetation cover and its temporal variation between 2017 and 2024, using data derived from harmonized Landsat 5, 7, and 8 imagery processed into monthly climatologies and distributed by Digital Earth Africa.

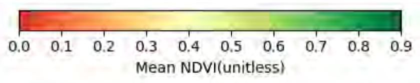


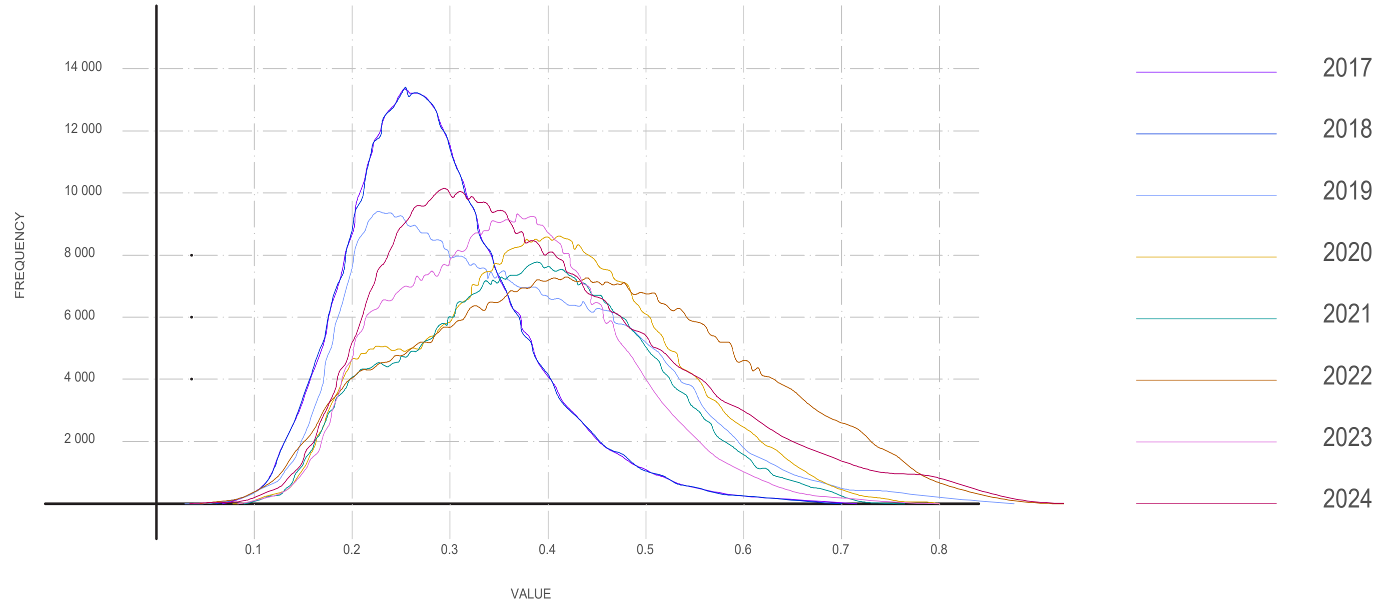
Mean NDVI Distribution – August 2017





Mean NDVI Distribution – August 2024





Cumulative Mean NDVI Distribution – 2017-2024 HW.ai

Observations of Histogram Distributions

From 2017 to 2018, Bandiagara's NDVI histograms are narrow and centered around low values (0.25–0.30), indicating relatively sparse vegetation and limited photosynthetic activity. Starting in 2019, the histograms broaden and shift to higher NDVI values, with modal peaks consistently around 0.35–0.45. Notably, tails extending into the 0.6–0.8 range become more frequent after 2020, suggesting the emergence of denser vegetative patches and improved ecological heterogeneity.

Interpretation and Trends

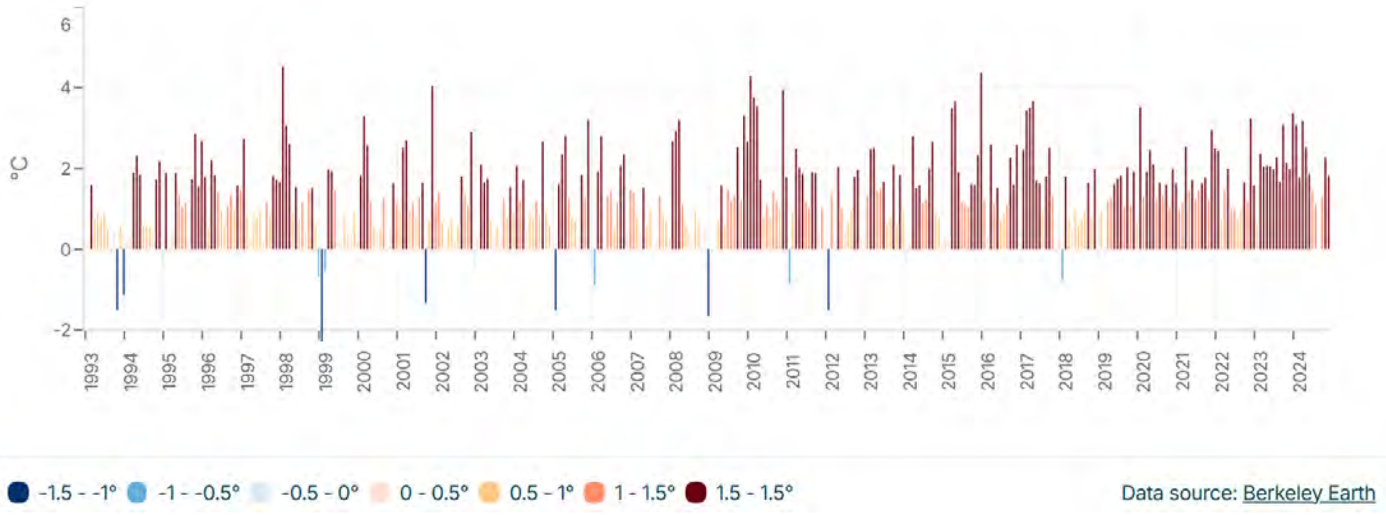
This progression reflects a gradual and consistent vegetative recovery in the Bandiagara region, marking a departure from early low-productivity states. The sustained upward shift in NDVI indicates strengthening ecosystem function, likely supported by either favorable rainfall patterns, localized restoration efforts, or changes in land-use intensity. Unlike many Sahelian regions showing static or deteriorating vegetation profiles, Bandiagara's NDVI trend stands out as a potential case of ecological resilience or rebound amid regional aridification.

Heritage Implications

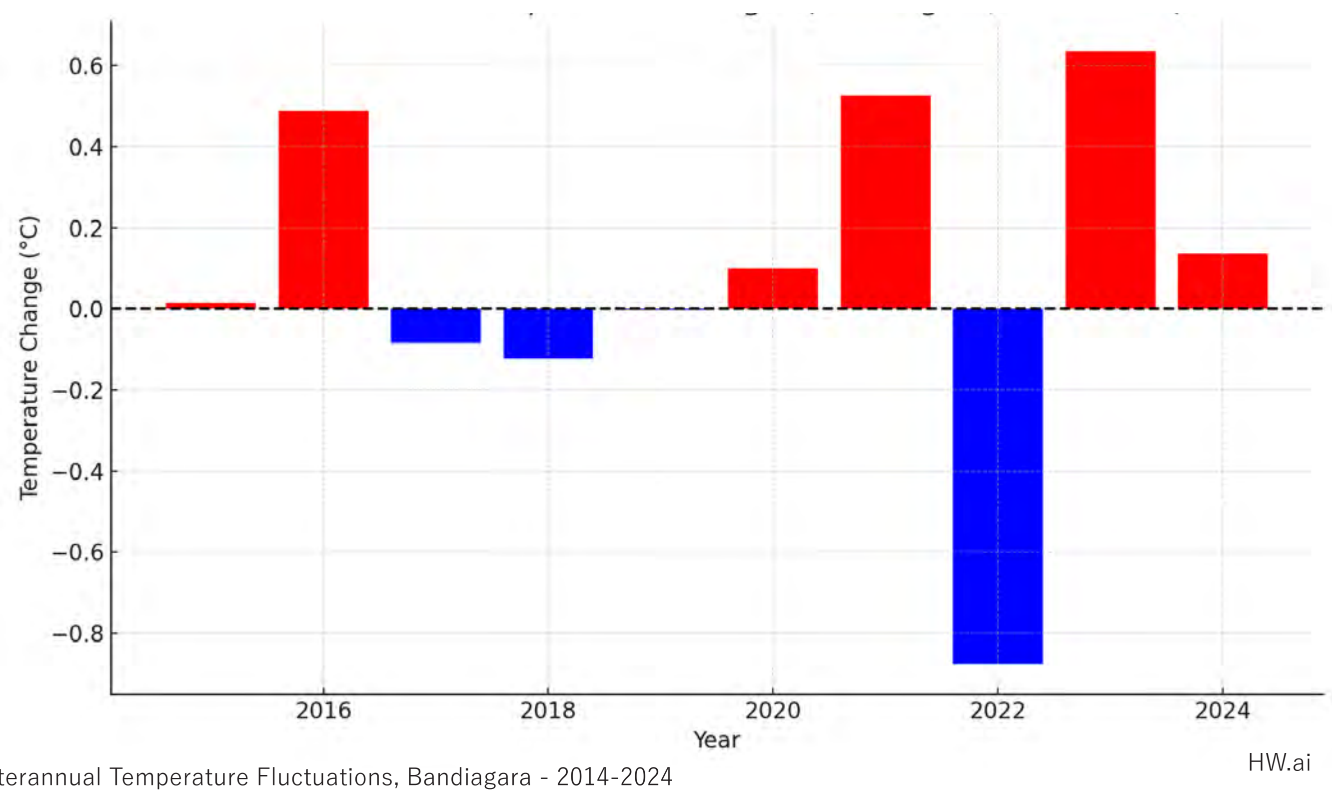
Improving vegetation levels have tangible benefits for the preservation of Bandiagara's unique cultural heritage. Dense plant cover buffers the landscape against erosion, helping stabilize the Dogon escarpment architecture and terraced agriculture. Moreover, the return of vegetative vigor supports ritual, agricultural, and communal practices linked to seasonal ecological rhythms. As such, the observed greening reinforces not only environmental sustainability but also the intergenerational transmission of intangible heritage embedded in the land.

C- Climatic Context in Bandiagara, Mali: Temperature Trends and Rainfall (1993–2024)

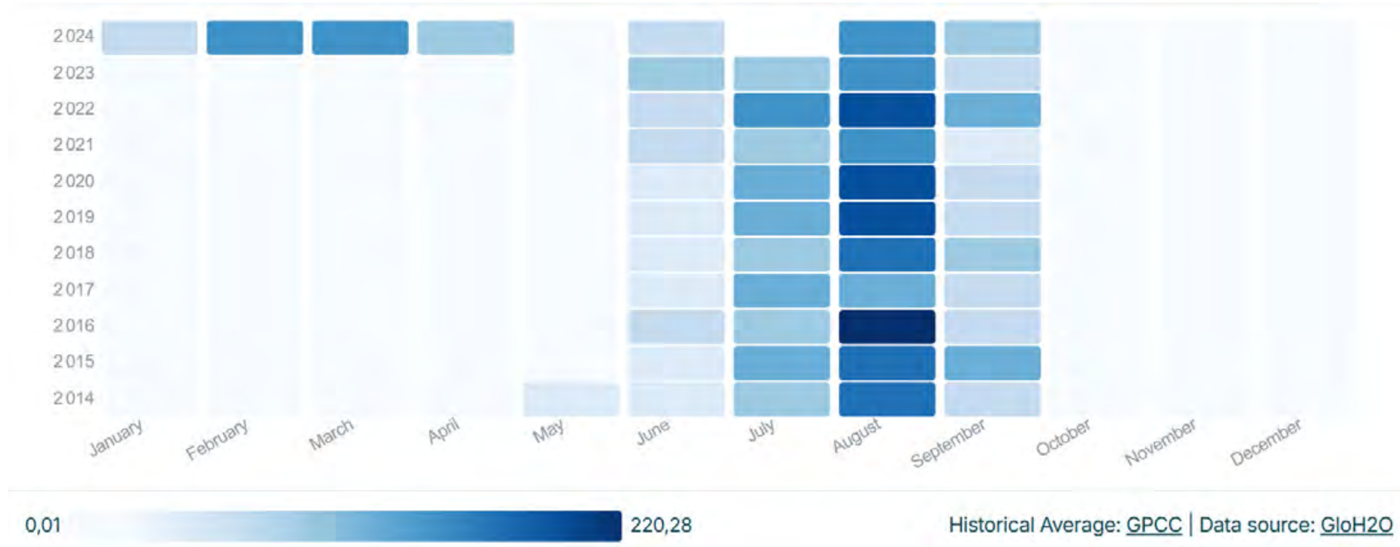
This section presents monthly temperature trends and rainfall for the selected area between 1993 and 2024. The data is sourced from the Africa Data Hub's Climate Observer platform, which compiles information from the Global Precipitation Climatology Centre (GPCC) for rainfall and Berkeley Earth for temperature.



Temperature anomalies, Bandiagara - 1993-2024



Interannual Temperature Fluctuations, Bandiagara - 2014-2024



Average Monthly Rainfall (mm), Bandiagara – 2014-2024

Long-Term Trends (1993–2024)

Rainfall:
Bandiagara, located in the southern Sahel, experiences seasonal rains from July to September. The wettest recorded month was August 2016, with 220.3 mm, suggesting a likely extreme weather event. Dry-season months like January 2017 recorded as little as 0.01 mm, reflecting pronounced seasonality. Over three decades, rainfall has become more variable, with recent years showing increased annual totals and more frequent off-season events.

Temperature:
A clear warming trend is observed, especially in the pre-rainy season (April–June), where average temperatures now regularly exceed 33° C. The strongest anomaly occurred in March 2024, with temperatures 3.23° C above the long-term average. Both daytime highs and nighttime lows are rising, reducing natural cooling periods.

Recent Decade Focus (2014–2024)

Rainfall:
2024 was the wettest year on record (771.79 mm), nearly double the decade's average. An exceptional anomaly occurred in February 2024 (144.1 mm vs. a norm of 0.17 mm), highlighting the growing intensity and unpredictability of rainfall. While 2017, 2021, and 2023 were notably dry, the general trend points to increased rainfall, though less evenly distributed, raising risks of erosion and flood damage.

Temperature:
Out of nine yearly intervals, five showed warming and only four showed slight cooling. 2024 featured the most pronounced heat anomalies, reinforcing a trend of chronic heat stress, with implications for agriculture and water supply.

Interpretation

Rainfall is increasing, but with greater variability and off-season events, complicating agriculture and infrastructure planning. Simultaneously, rising temperatures intensify evapotranspiration and reduce crop viability, even in wetter years. The dual pressures of heat and rainfall instability increase risks of flash floods, drought spells, soil degradation, and public health challenges.

Heritage and Cultural Implications

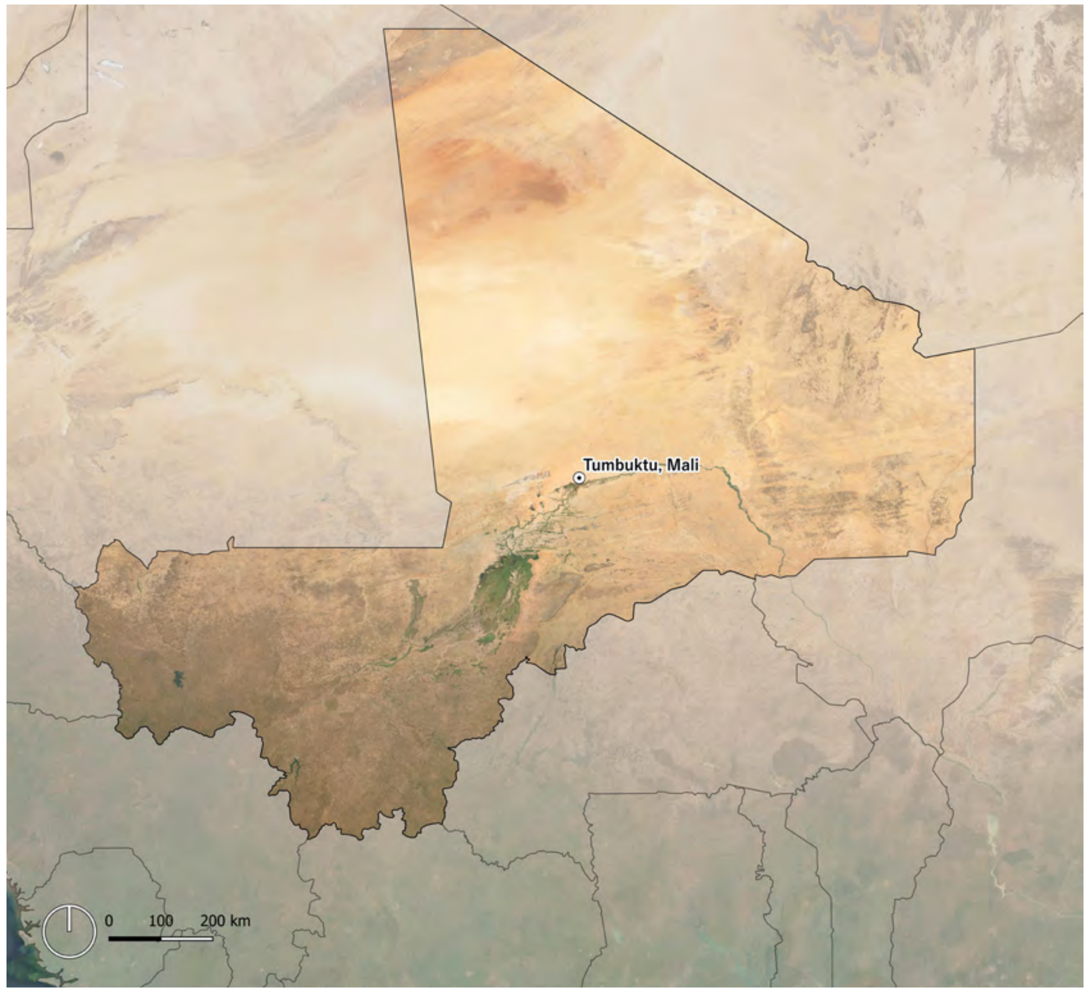
Bandiagara's designation as a World Heritage Site reflects its cultural significance. Yet, intensifying climate stress poses serious threats: Adobe buildings and cliffside structures are increasingly exposed to cracking, erosion, and collapse from heat and heavy rain. Ritual cycles tied to ecological patterns are disrupted by off-season storms and extreme temperatures. Migration linked to degraded land may weaken the custodial bonds between communities and sacred sites.If these climate trends persist unchecked, Bandiagara's cultural landscape risks being altered physically and spiritually, reducing its resilience and threatening its continuity as a living heritage system.

2. SITE-LEVEL RISK AND SPATIAL ANALYSIS

2.3 TIMBUKTU, MALI

Dam in the village of Ihamid 2, commune of Tienkour - Timbuktu, Mali (2018). ACTED.

I. General Overview



Timbuktu, Mali. HW.ai

Ancient Ksour of Ouadane, Chinguetti, Tichitt and Oualata (Mauritania). © John Spooner.

Site Name: Timbuktu

Status: UNESCO World Heritage (1988)

"World Heritage in Danger" since 2012

UNESCO ID: 119rev

Coordinates: 16°46′ N 3°00′ W

Historical Context:

Timbuktu, located in northern Mali, at the intersection of the Sahara and the Gre,was established in the 5th century. It flourished in the 15th and 16th century, as a trade hub but also an important centre of diffusion of knowledge, with 180 coranic schools and 25000 students in the 14th century, During this time, the still standing Dyingerey Ber Mosque was constructed. There are over 23,000 Islamic manuscripts at the Centre de Recherches Historiques Ahmed Baba, the earliest of which date back to the 12th century. In 2012, armed groups destroyed 14 of the 16 mausoleums (UNESCO WHS) and burned thousands of ancient manuscripts from the Ahmed Baba Institute. It is also the first time that a crime against cultural heritage was considered as a war crime in front of the International Court of Justice.

Regional & Environmental Context:

Social & Demographic Context:

Climate	Hot desert climate (BWh)
Avg. Annual Temperature	29 °C
Avg. Annual Rainfall	111 mm
Soil Type	Sandy soil with low fertility, rocky outcrops
Recent Climate Anomalies	Increased desertification and sand encroachment threatening the city′ s infrastructure and heritage sites

Despite being in an arid region, Timbuktu remains inhabited with a population of 75339 (2020 census). It is home to 3 big mosques (Sidi Yahya, Sankore, and Dyingareyerber mosque) that were built for pilgrims returning from Mecca. The city holds annual festivals, manuscript scholarships to reaffirm its historical legacy and traditions.

Architecture & Construction:

Timbuktu is a typical architectural model of Sudano-Sahelian earthen construction, exemplified in its three iconic mosques. Buildings are constructed from mud bricks (banco) and finished with adobe plaster and wooden support beams (toron), which serve both structural and aesthetic purposes. The urban fabric of Timbuktu is densely clustered, with narrow, winding streets adapted to local climatic conditions and community-based spatial organization. However, these earthen structures are particularly vulnerable to environmental degradation, especially from wind erosion, sand accumulation, and interrupted maintenance cycles, often due to security concerns and displacement

Environmental risks:

Environmental threats that Timbuktu faces include advancing sand dunes, desertification, and occasional flash flooding that undermines already fragile building foundations. Anthropological pressures, notably armed conflict, looting, and insufficient conservation resources have strained heritage preservation efforts.

The past decade has seen accelerated sand encroachment, leading to structural damage and loss of habitability in peripheral zones.

Conservation efforts:

Internationally supported human interventions have led to the rebuilding of destroyed mausoleums, the preservation and digitisation of manuscripts, and community-based awareness campaigns on cultural heritage protection. Nonetheless, the desert continues to expand, threatening to engulf areas that were once integral to Timbuktu's urban core.

II. Heritage Context

Localised Map of Timbuktu with heritage sites. HW.ai

This section provides a spatial and photographic overview of heritage structures and urban patterns within Timbuktu. The map classifies a range of heritage features, including UNESCO-listed monuments, nationally protected sites, and culturally significant buildings recognized at the community level. These are categorized by typology, function, and degree of conservation.

The accompanying imagery reveals details of building materials, urban morphology, and adaptive use, offering a window into the lived heritage of the city. Collectively, the map and images document both the enduring cultural identity of Timbuktu and the mounting pressures, from environmental change to political instability, that threaten its preservation.

Lone person walking outside the walls of the ancient city of Djenné, Mali. (2023) Harrington, R. . Getty Images.

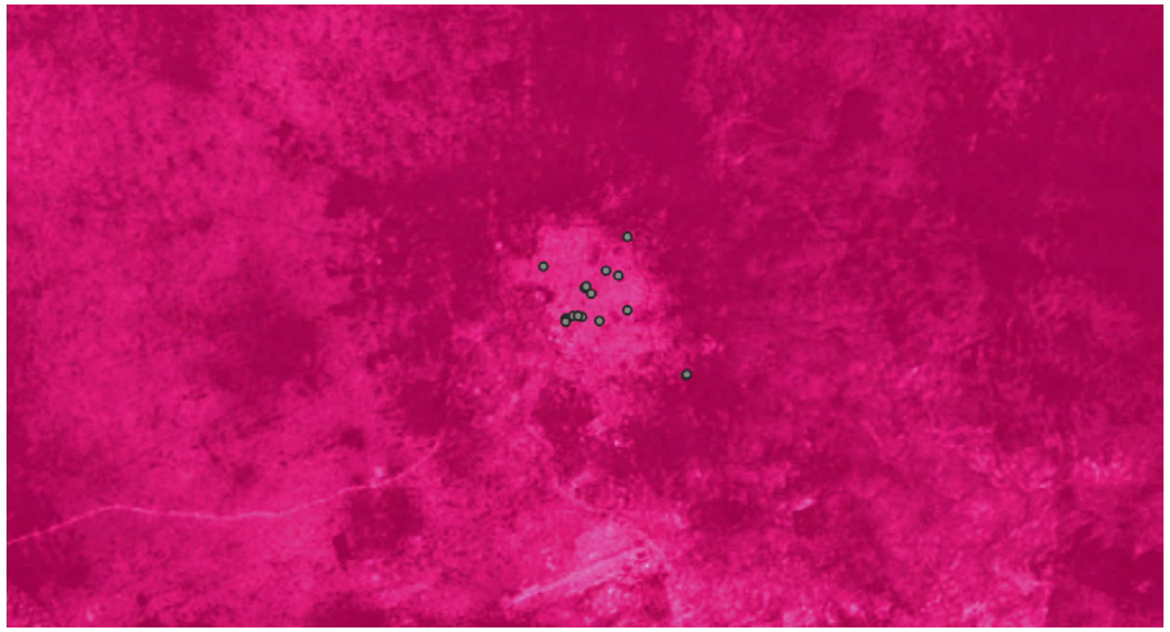
Sankore Mosque, Timbuktu (2007, September 2) Anne and David. . Wikimedia Commons.

Timbuktu (Mali). (n.d.). Bandarin, F. UNESCO World Heritage Centre.

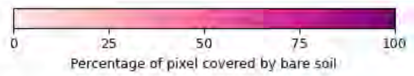
III. Risk Analyses

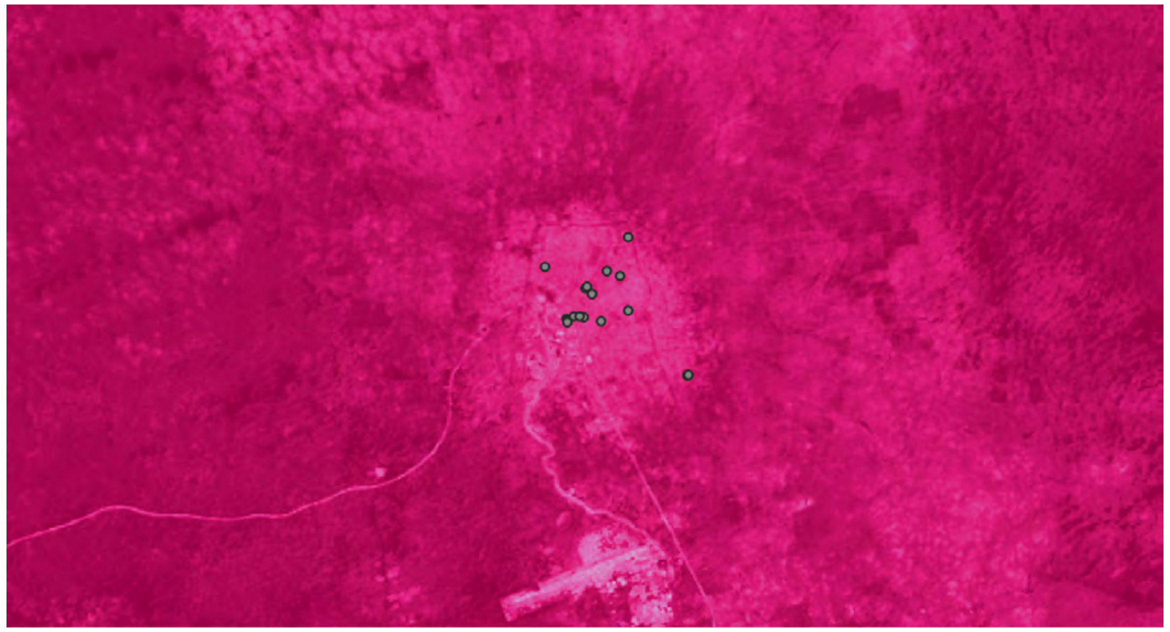
A- Bare Soil Exposure in Timbuktu, Mali (2014–2024)

This section analyses the 90th percentile of bare soil coverage to assess the extent of exposed land surfaces and their evolution over the decade, using data derived from Landsat 5, 7, and 8 imagery processed through the CSIRO fractional cover algorithm and distributed by Digital Earth Africa.

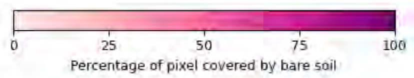


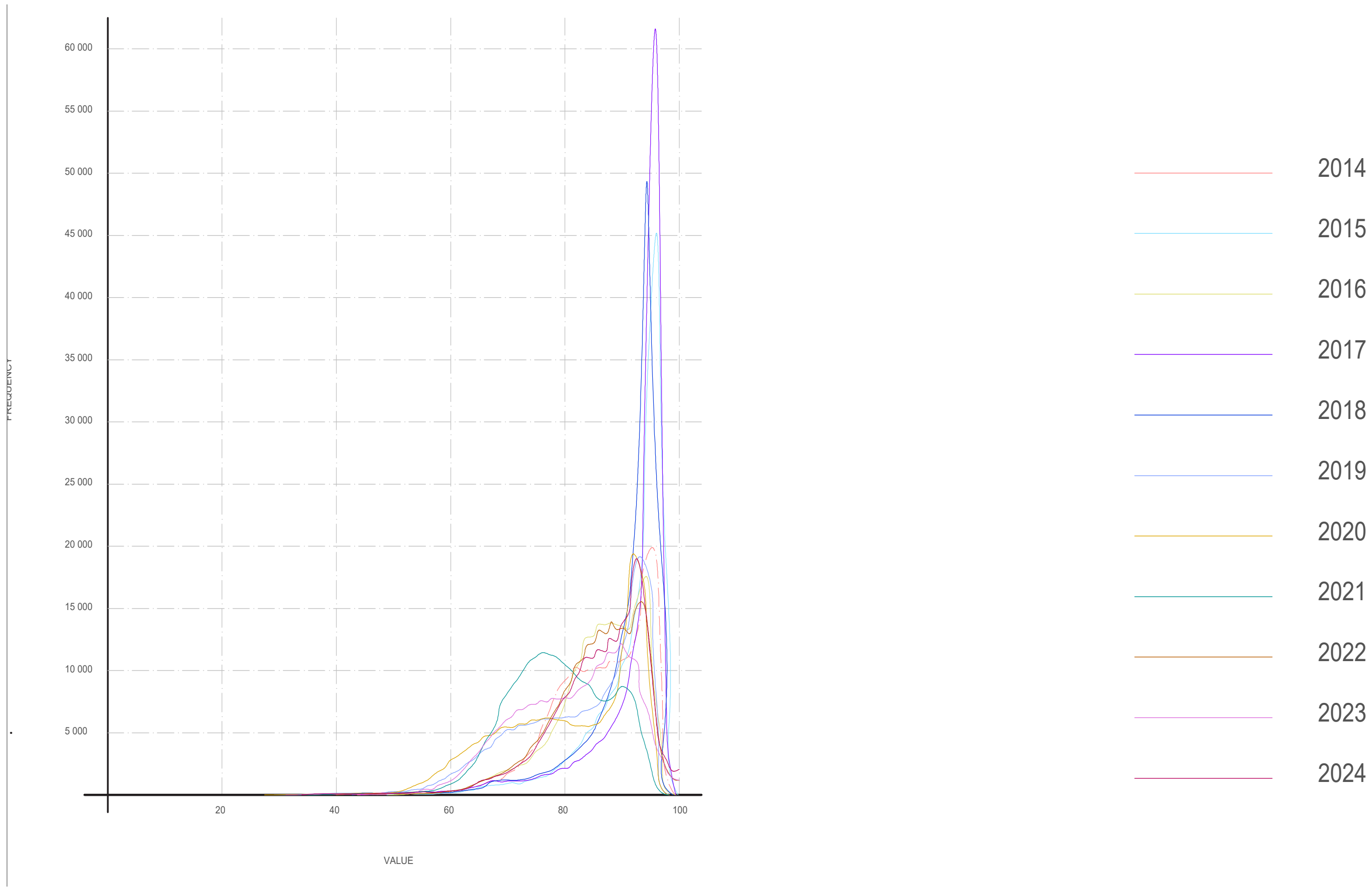
Bare Soil Coverage Distribution, Timbuktu – 2014





Bare Soil Coverage Distribution, Timbuktu – 2024





Cumulative Bare Soil Coverage Distribution, Timbuktu – 2021-2024 HW.ai

Observations of Histogram Distributions

Between 2014 and 2019, the histograms exhibit strongly unimodal and leptokurtic shapes, with values tightly clustered around the 90–95% bare soil range. This indicates a highly homogeneous landscape, dominated by consistent and extensive bare soil exposure, characteristic of a hyper-arid environment with minimal vegetative buffering.
From 2020 onward, a shift occurs: the histograms begin to broaden, flattening slightly and spreading toward both lower and higher values. This trend continues through 2021 to 2023, suggesting the emergence of surface variability, likely influenced by climatic fluctuations, episodic vegetative regrowth, or changes in land use patterns. By 2024, there is a modest return to high-value clustering near 95–97%, but without the earlier tight concentration. This suggests a partial reversion to previous exposure levels, yet within a more spatially varied landscape.

Interpretation and Trends

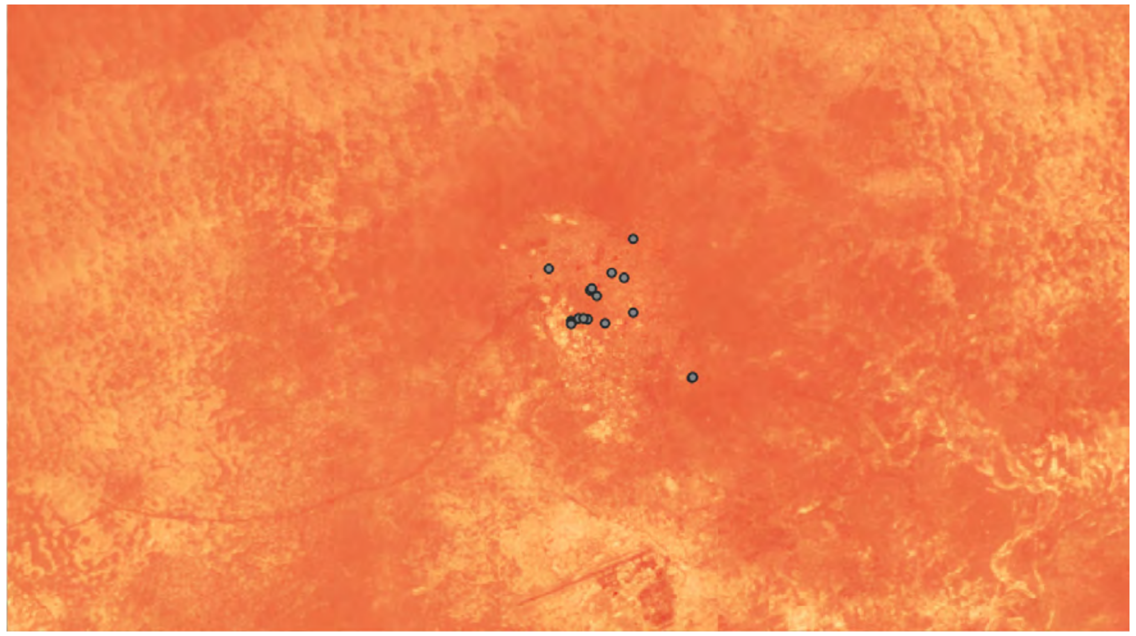
Timbuktu's surface condition reflects a transition from prolonged ecological uniformity toward increasing spatial complexity and instability. While early years show sustained and extreme degradation, recent distributions suggest a landscape that is no longer consistently barren, but instead marked by patches of degradation, resilience, or flux, indicative of a system under stress, but no longer in stasis.

Heritge Impliations

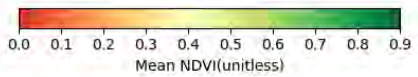
The high and persistent bare soil coverage across much of the time series leaves Timbuktu's famed earthen architecture, including its mosques, shrines, and historical dwellings, highly susceptible to wind erosion, sediment burial, and foundation weakening. The more recent increase in surface heterogeneity may exacerbate risks by disrupting sediment transport patterns, accelerating erosion in some zones while shielding others, creating unpredictable conservation pressures. Meanwhile, the ecological instability around Timbuktu threatens to fragment traditional land use systems, such as pastoral routes, seasonal settlements, and pilgrimage paths. As access to viable land diminishes, the transmission of intangible cultural heritage, especially that rooted in local ecological rhythms, becomes more fragile.

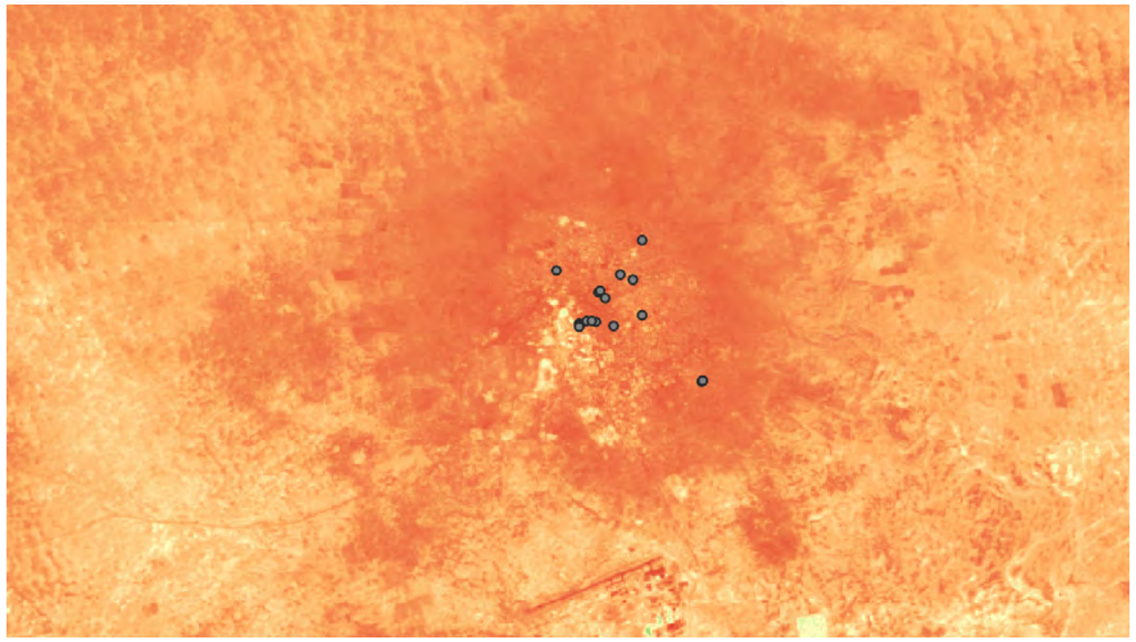
B- Vegetation Density Trends in Timbuktu, Mali (2017–2024)

This section analyzes the August mean NDVI to assess vegetation cover and its temporal variation between 2017 and 2024, using data derived from harmonized Landsat 5, 7, and 8 imagery processed into monthly climatologies and distributed by Digital Earth Africa.

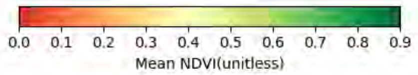


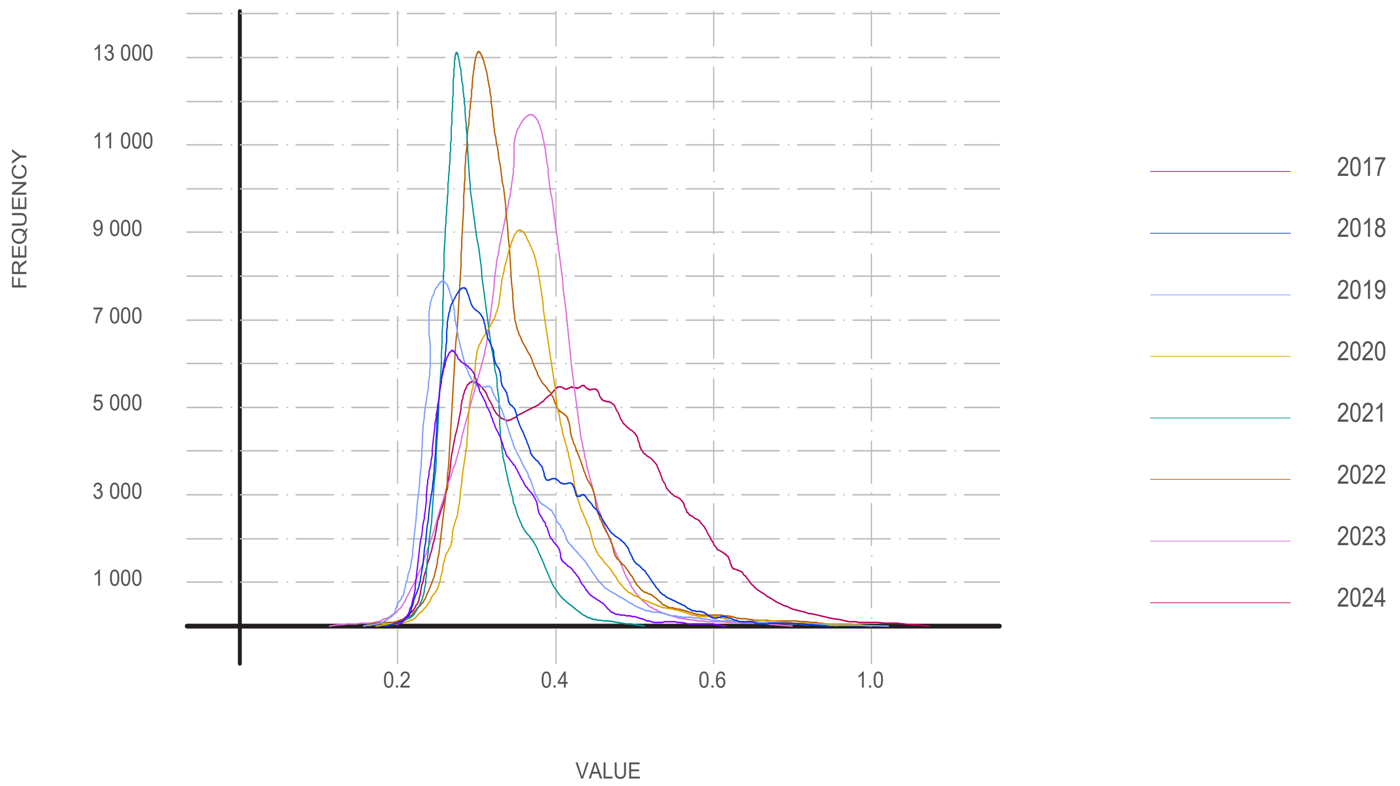
Mean NDVI Distribution, Timbuktu – August 2017





Mean NDVI Distribution, Timbuktu – August 2024





Cumulative Mean NDVI Distribution, Timbuktu – 2017-2024 HW.ai

Observations of Histogram Distributions

From 2017 to 2020, NDVI histograms in Timbuktu show sharp, right-skewed unimodal distributions, with peaks centered between 0.14 and 0.20. This consistent pattern indicates extremely low vegetation density, typical of arid environments with minimal ecological variability. In 2023, an anomalous shift appears: the distribution becomes more symmetric, with a peak closer to 0.22–0.24, hinting at temporary vegetation recovery. By 2024, the histogram adopts a bimodal shape, combining one mode in the low NDVI range and another closer to 0.27–0.30, suggesting growing spatial differentiation in vegetation condition.

Interpretation and Trends

The NDVI data from Timbuktu indicates a landscape that remains largely ecologically stressed, with persistent low vegetative productivity from 2017 to 2020. This stability in low NDVI values suggests chronic aridity and the limited regenerative capacity of the ecosystem, possibly due to soil degradation, overgrazing, or a prolonged deficit in precipitation. The isolated shift in 2023 toward higher, more symmetric NDVI values likely reflects short-term climatic improvement, such as an above-average rainy season, or localized land interventions (e.g., reforestation plots or fallow rotation).

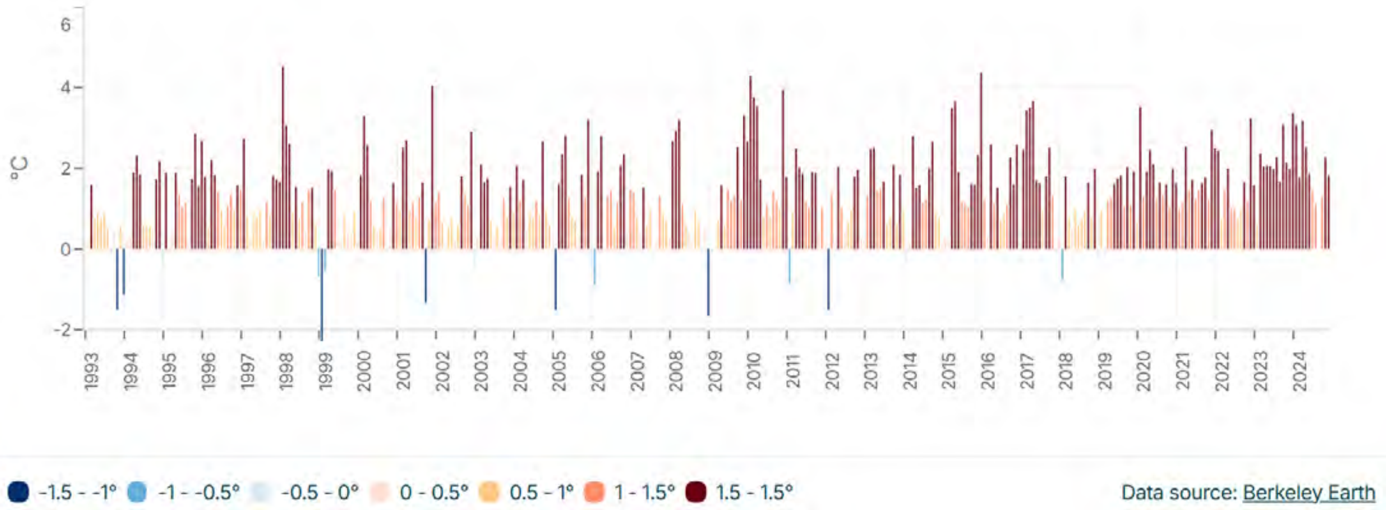
The emergence of bimodality in 2024 is especially telling: it signals the beginning of landscape bifurcation, a condition in which zones of relative ecological improvement (through either natural recovery or managed rehabilitation) begin to contrast more sharply with areas that remain ecologically depleted. This diverging trend may also reflect socioeconomic stratification in land access or use, with better-managed or irrigated plots recovering, while marginal lands continue to deteriorate.

Heritage Implications

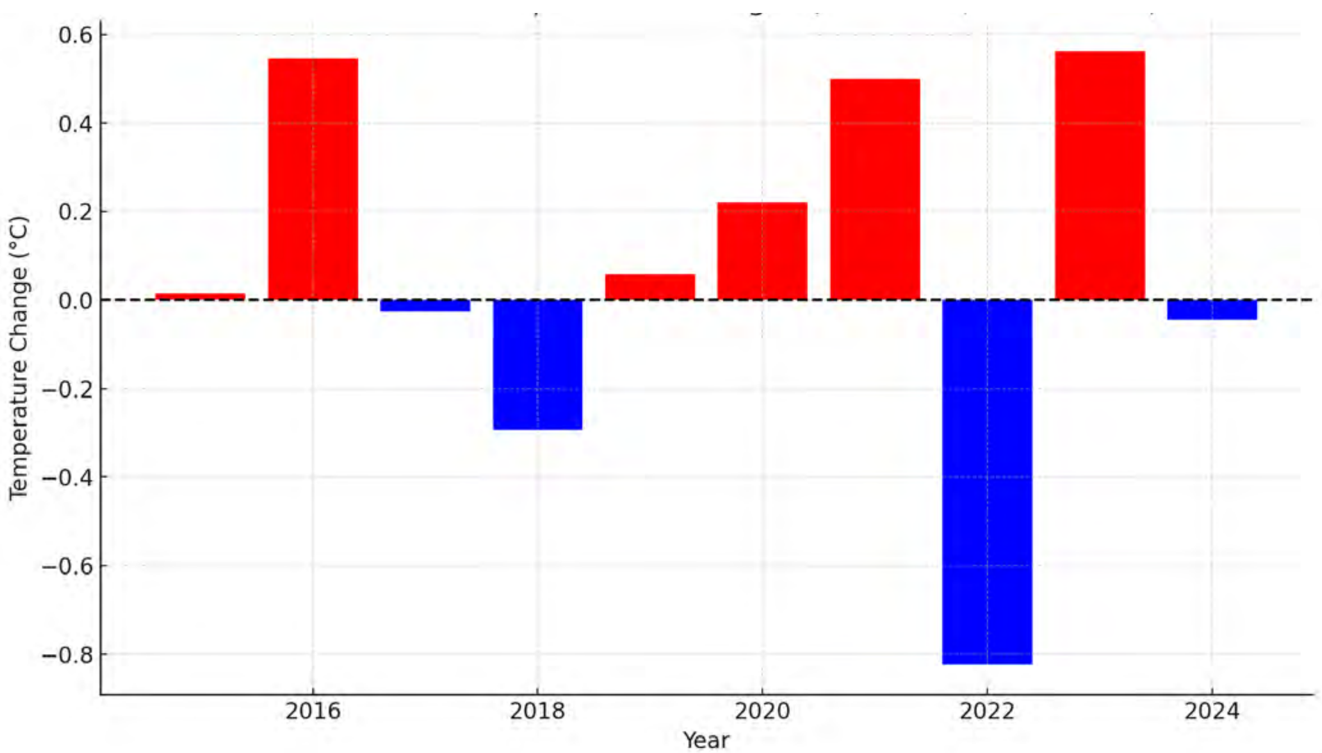
Timbuktu's earthen architectural heritage is particularly susceptible to the impacts of low and unstable vegetation cover. A lack of vegetative buffer accelerates wind erosion and sand encroachment, weakening the physical integrity of historic mosques, mausoleums, and dwellings. The observed divergence in vegetation further complicates this picture by fragmenting traditional land-use systems, such as seasonal migration routes and agricultural rhythms, potentially undermining the cultural cohesion and continuity that support the safeguarding of both tangible and intangible heritage.

C- Climatic Context in Timbuktu, Mali: Temperature Trends and Rainfall (1993–2024)

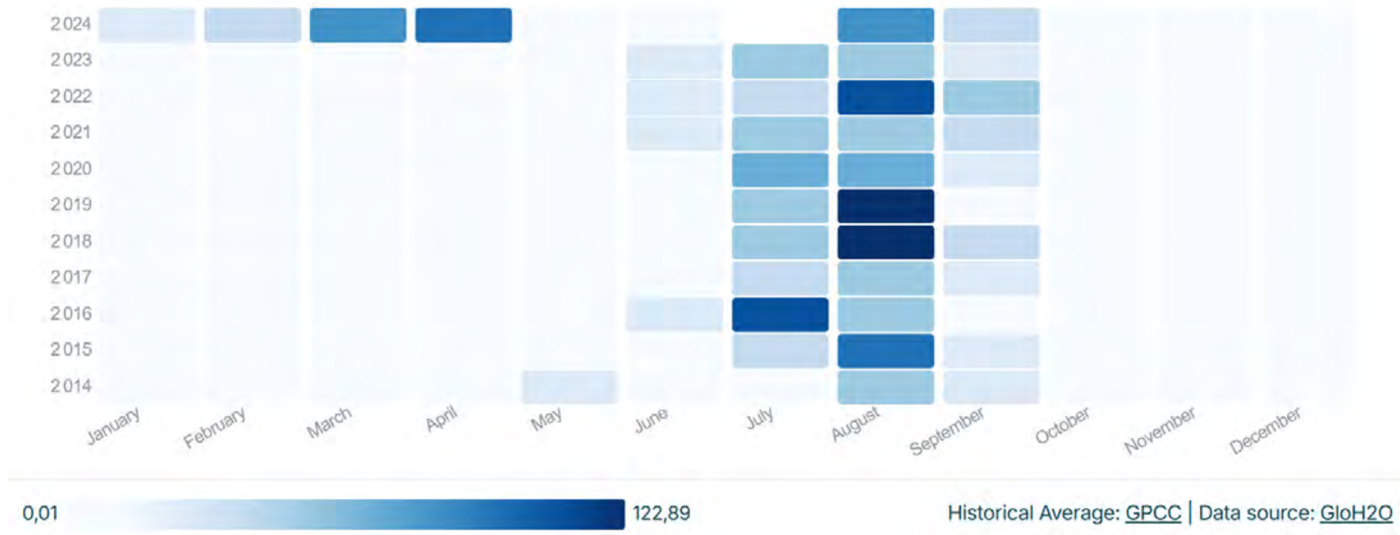
This section presents monthly temperature trends and rainfall for the selected area between 1993 and 2024. The data is sourced from the Africa Data Hub's Climate Observer platform, which compiles information from the Global Precipitation Climatology Centre (GPCC) for rainfall and Berkeley Earth for temperature.



Temperature anomalies, Timbuktu - 1993-2024



Interannual Temperature Fluctuations, Timbuktu - 2014-2024 HW.ai



Average Monthly Rainfall (mm), Timbuktu – 2014-2024

Long-Term Trends (1993–2024)

Rainfall:
Timbuktu lies in an arid zone influenced by the Sahelian monsoon, with rains concentrated in July to September, peaking in August. Annual rainfall in the 1990s and early 2000s often remained below 250 mm, reflecting desert-margin conditions. The wettest month on record was August 2018 (122.9 mm), likely associated with intense storms or flash flooding. Since 2015, a modest upward trend in rainfall has emerged, including off-season anomalies in months like February and March, which were previously dry.

Temperature:
Timbuktu has experienced steady warming over the past 30 years, especially during transitional seasons (March–May, October–November). Recent years show a reduced diurnal range due to rising nighttime temperatures, signaling greater heat retention and discomfort. Maximum temperatures now frequently exceed historical highs, increasing exposure to heat extremes.

Recent Decade Focus (2014–2024)

2024 was the wettest year, with 344.45 mm, unusually high for a desert-edge location. In contrast, 2017 recorded just 130.73 mm, underscoring persistent variability. While the peak remains in August, notable off-season events, particularly in February, challenge traditional rainfall timing. Increased rainfall often arrives as short, intense bursts, raising risks of flash flooding and infrastructure damage.

Temperature anomalies are now frequent:
From 2015 to 2024, all years exhibit positive temperature anomalies, particularly between April and June. No sustained cooling trend has been observed during this decade. The 2020s mark a period of accelerated warming, with frequent record-setting months and intensifying heat stress.

Interpretation

Timbuktu's climate is trending toward greater volatility: While rainfall totals are increasing, their distribution is irregular, with unpredictable off-season events. Rising temperatures, especially nighttime lows, diminish natural cooling and strain both ecosystems and infrastructure. The city now faces concurrent risks of drought and flash flooding within the same seasonal cycle.

Heritage Implications

Timbuktu faces growing environmental threats that endanger its heritage: Earthen structures such as mosques and manuscript libraries are highly sensitive to thermal stress and water damage. Flash floods treaten historical buildings, especially those near wadis or lacking robust drainage. If warming and rainfall irregularities persist, Timbuktu may face irreversible transformations.

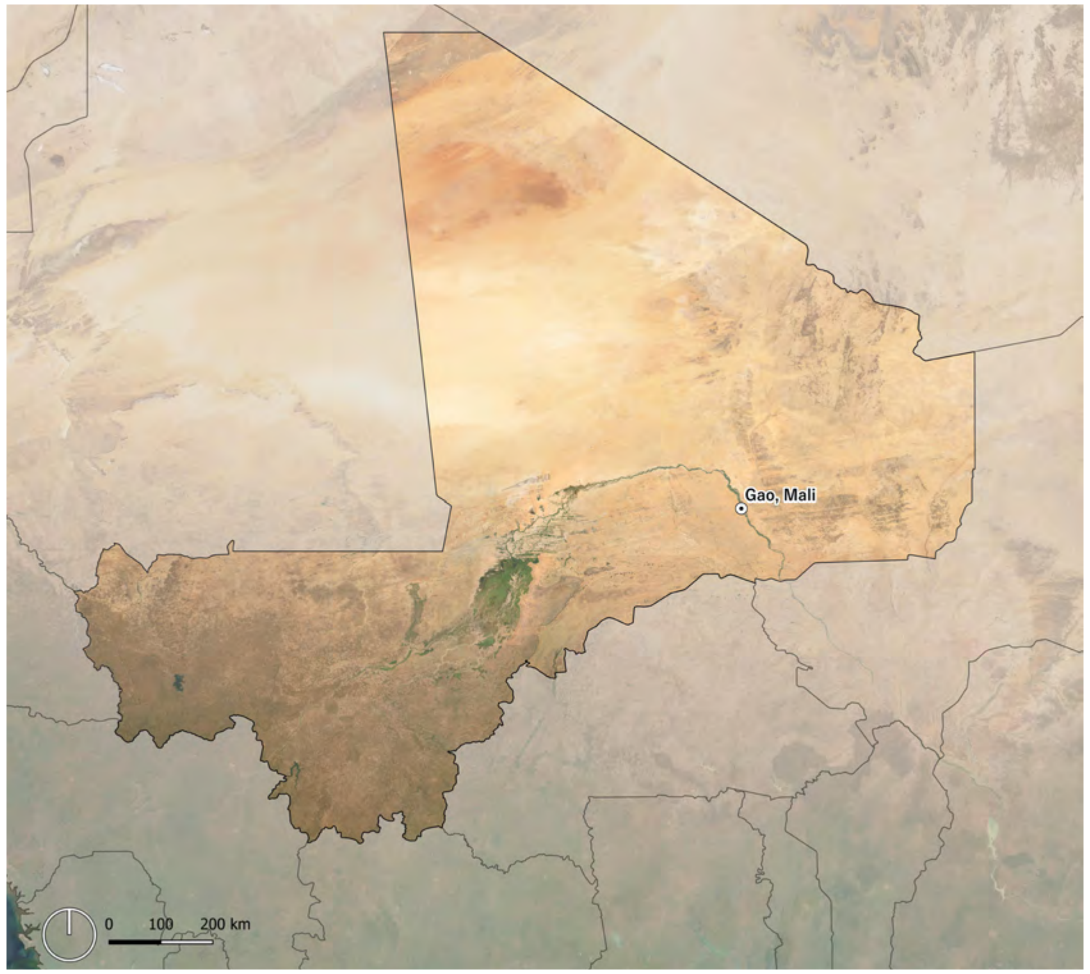
2. SITE-LEVEL RISK AND SPATIAL ANALYSIS

2.4 GAO, MALI

UN Mission in Mali. (2022, June 23). Dicko, H. 22-06-23-QRF Jordanie-01

Getty

I. General Overview



Gao, Mali. HW.ai

Gao aerial view (2013). Dormino, M. United Nations.

Site name: Gao

Status: UNESCO World Heritage (Tomb of Askia since 2004) listed as "World Heritage in Danger" since 2012

UNESCO ID: 1139

Coordinates: 16°16′ N 0°03′ W

Historical Context:

Gao is one of the oldest trading city in West Africa, inhabited since the 7th century and served as the capital of the Songhai Empire in the 15th century. Its architectural style is epitomised by the Tomb of Askia, built in 1495.

Gao has historically been vulnerable to environmental shifts due to its location near the Niger river. In 2012, the Tomb of Askia was added to the UNESCO List of World Heritage in Danger due to threats from armed conflict in the region.

Regional & Environmental Context:
Social & Demographic Context:

As of 2015, Gao had a population of approximately 111 878 inhabitants. The city maintains traditional practices such as the annual replastering of the Tomb of Askia involving community members in conservation efforts.

Architecture & Construction:

Climate	Hot desert climate (BWh)
Avg. Annual Temperature	29.9°C
Avg. Annual Rainfall	220 mm
Soil Type	Sandy & Clayey soil with low fertility, poor water and nutrient retention
Recent Climate Anomalies	Increased desertification and irregular patterns, exacerbating environmental challenges

Gao is characterised by Sudano-Sahelian architecture, using locally sourced materials such as mud bricks (banco), adobe plaster, and wooden beams (toron) for construction. The urban fabric of the city is typical of traditional Sahelian layout, with narrow streets and clustered structures.
These architectural forms remain vulnerable to deterioration, exacerbated by more extreme environmental events.

Environmental risks:

The city faces several environmental risks, notably the advance of sand dunes, ongoing desertification and flash floods. In the past decade, increased sand encroachment and episodes of heavy rainfall hae contributed to structural and land degradation.

In addition to environmental threats, human pressure such as the ongoing armed conflict (since 2012), deliberate destruction, shortages of resources also exacerbate the city's vulnerability.

Conservation efforts:

Conservation efforts have been implemented through initiatives led by ALIPH & UNESCO, between 2012 and 2018, but in a Sate if Conservation report from 2024, the inscribed site of Askia, is at risk of occupation by armed groups, and collapse due to a lack of site management and armed conflit. A budget of 7485 USD was approved to update the management and conservation plans for the 4 inscribed UNESCO sites.

II. Heritage Context

Localised Map of Gao with heritage sites.

HW.ai

This section provides a synthesized spatial and visual account of Gao's cultural heritage. The map illustrates the distribution and classification of key features, ranging from UNESCO World Heritage Sites to sites on Mali's Tentative List and other culturally significant places embedded in the city's social and historical fabric.

The images that follow offer a closer look at architectural forms, building materials, and site conditions that reflect both the endurance and vulnerability of Gao's heritage. The pairing of spatial and visual analysis highlights how layers of historical development continue to shape the urban landscape, even as natural and human-induced threats place that legacy at increasing risk.

Tomb of Askia, Gao, Mali [Photograph]. (ca. 1920). In I. Samuel, A complete history of the old city of Gao ca. 700–1898. African History Extra.

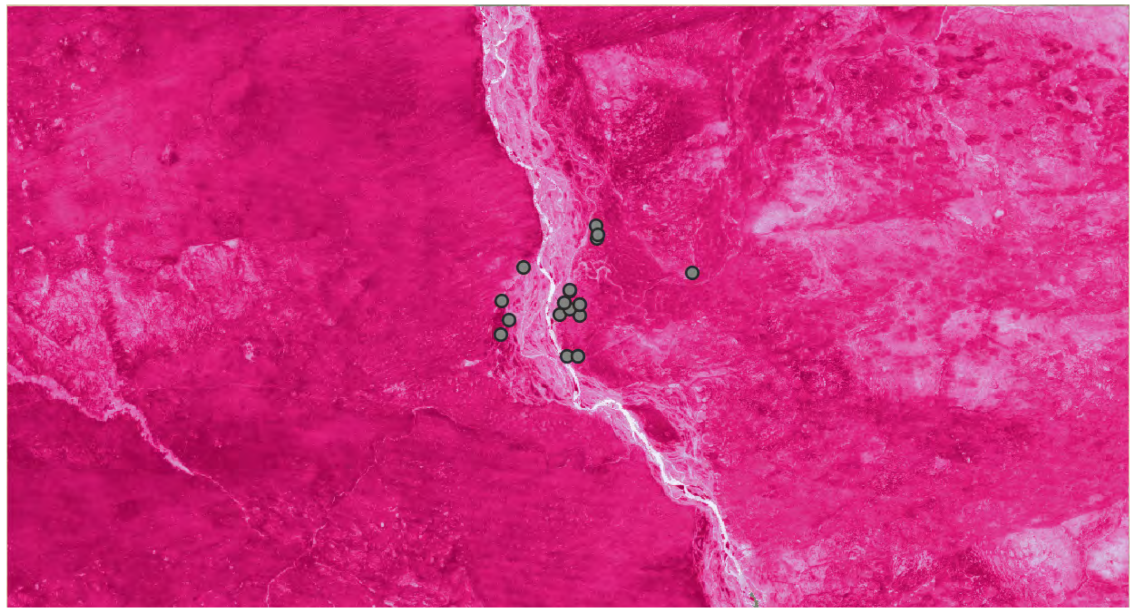
Gao Ancient ruins, Cahiers d'études africaines, 2012

Kankou Moussa Mosque (n.d.). Islamic World Heritage Centre (IWHC).ICESCO Heritage Portal.

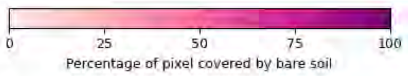
III. Risk Analyses

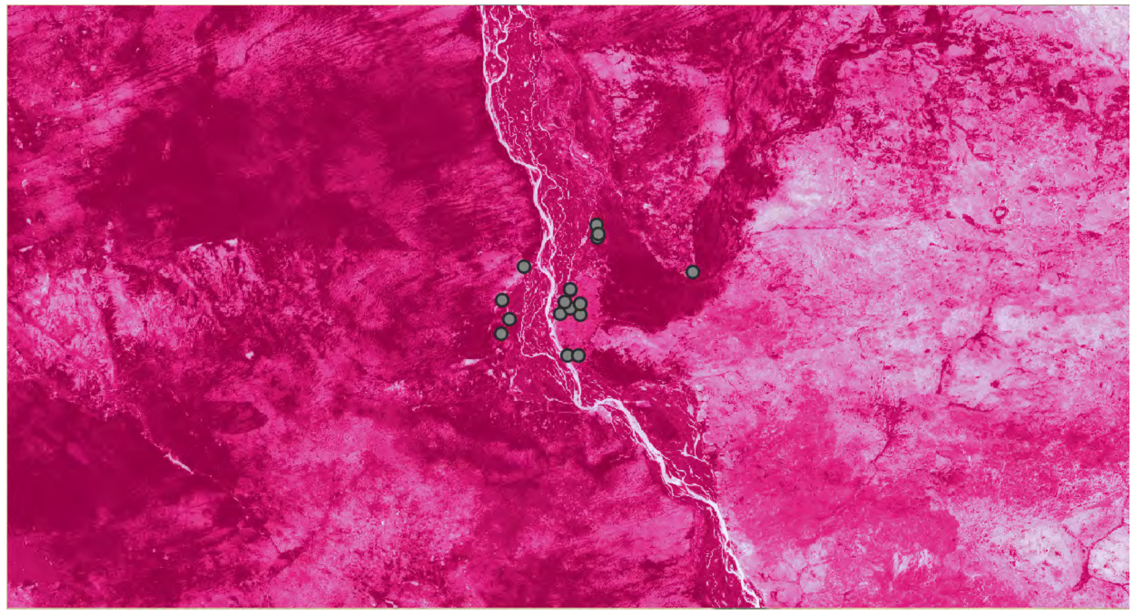
A- Bare Soil Exposure in Gao, Mali (2014–2024)

This section analyses the 90th percentile of bare soil coverage to assess the extent of exposed land surfaces and their evolution over the decade, using data derived from Landsat 5, 7, and 8 imagery processed through the CSIRO fractional cover algorithm and distributed by Digital Earth Africa.

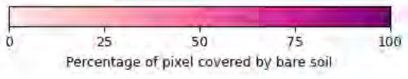


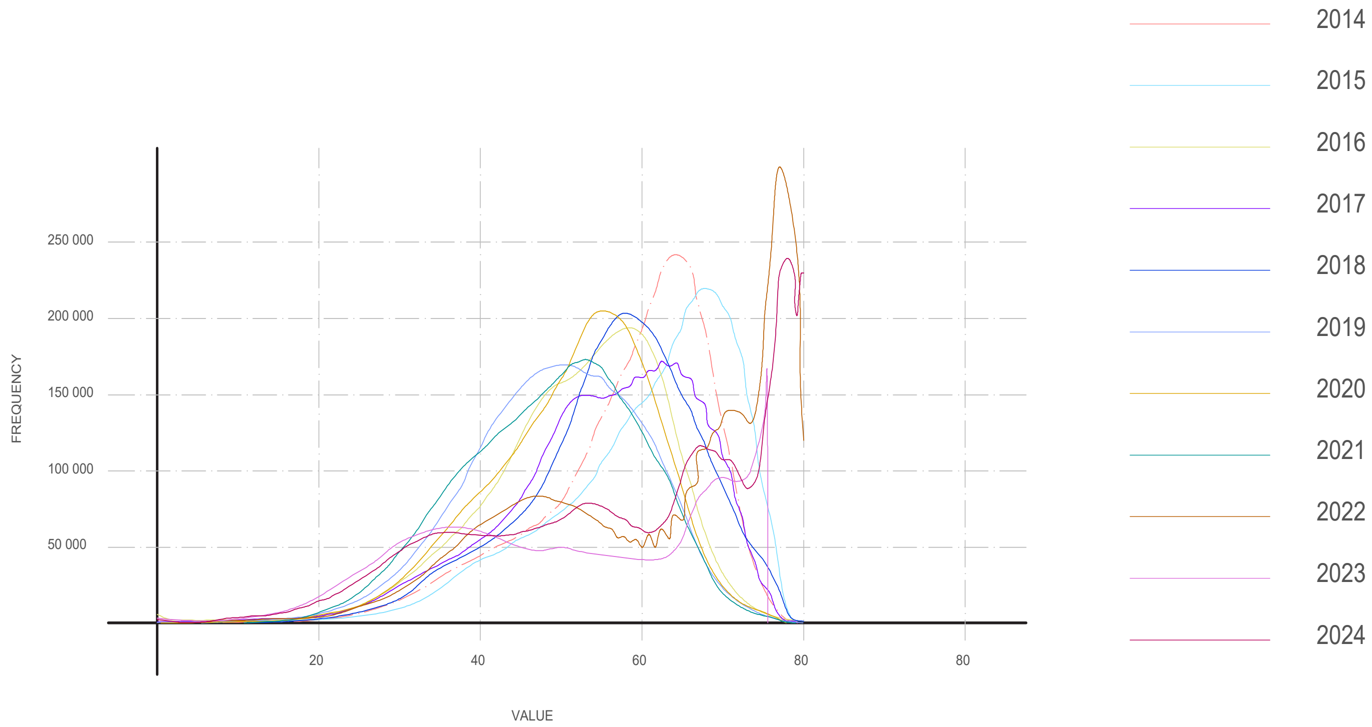
Bare Soil Coverage Distribution, Gao – 2014





Bare Soil Coverage Distribution, Gao – 2024





Cumulative Bare Soil Coverage Distribution, Gao – 2014-2024 HW.ai

Observations of Histogram Distributions

From 2014 to 2016, Gao's histograms display moderately spread distributions, with most values concentrated in the 70–85% bare soil range, suggesting a mixed landscape where exposed soil coexists with zones of vegetative cover or surface protection. Beginning in 2017, the distributions shift rightward, with increased pixel frequency in the 85–95% range, indicating growing dominance of bare surfaces. This progression intensifies in 2020 through 2022, where the histograms become multimodal, revealing a fragmented pattern: some zones remain moderately covered, while others experience heightened exposure. In 2023 and 2024, the trend culminates in pronounced high-value dominance. The 2024 histogram is especially notable for its dual peaks, one near 90–92%, and another concentrated around 98–100%, indicating that Gao's surface condition is not just deteriorating but polarizing, with clear contrasts between moderately stable and severely degraded areas.

Interpretation and Trends

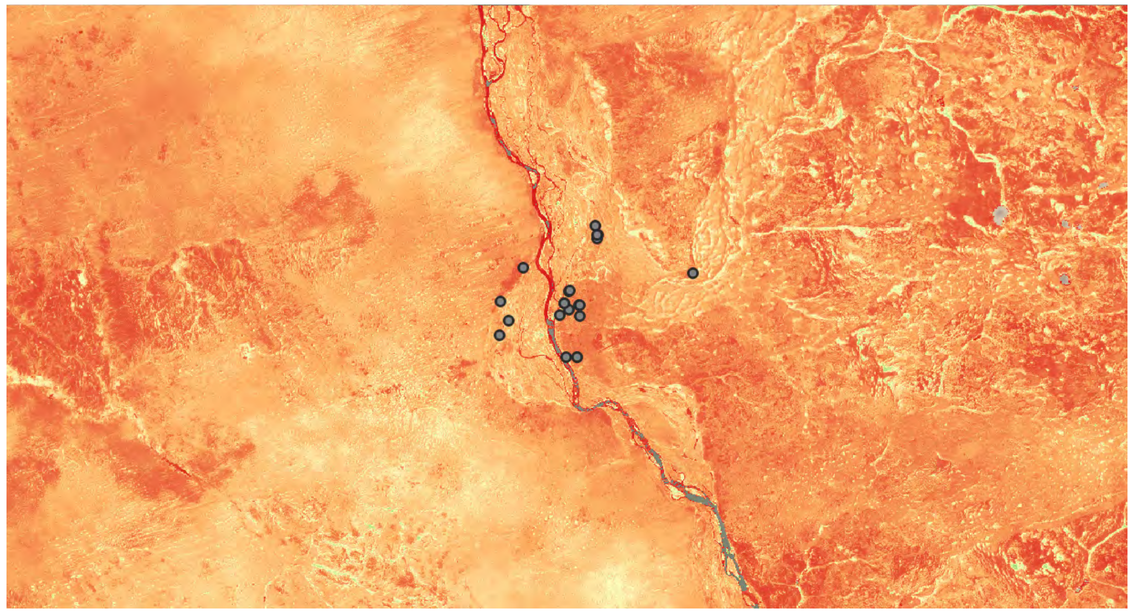
Over the decade, Gao's landscape has undergone a progressive intensification of desertification, moving from a relatively heterogeneous surface condition to a highly exposed and structurally divided environment. The emergence of multimodal distributions and high-value clustering points to a breakdown in ecological continuity, suggesting that land degradation is no longer uniform but stratified, with some areas nearing ecological collapse while others exhibit only partial resilience.

Heritge Impliations

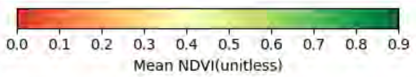
Gao's cultural landscape, historically anchored by riverine settlements, caravan routes, and pastoral corridors, faces increasing risk as surface conditions become more extreme and inconsistent. The dominance of bare soil strips the land of its natural stabilizers, exposing archaeological remains, earth-built dwellings, and burial mounds to erosion and disintegration.
The fragmentation seen in recent years may disrupt seasonal migratory patterns, water access routes, and traditional grazing cycles, all of which are integral to the intangible heritage systems of Gao's Sahelian communities. As ecological disparity grows, so too does the potential for displacement and cultural erosion, weakening the community's ability to maintain continuity between land, livelihood, and heritage stewardship.

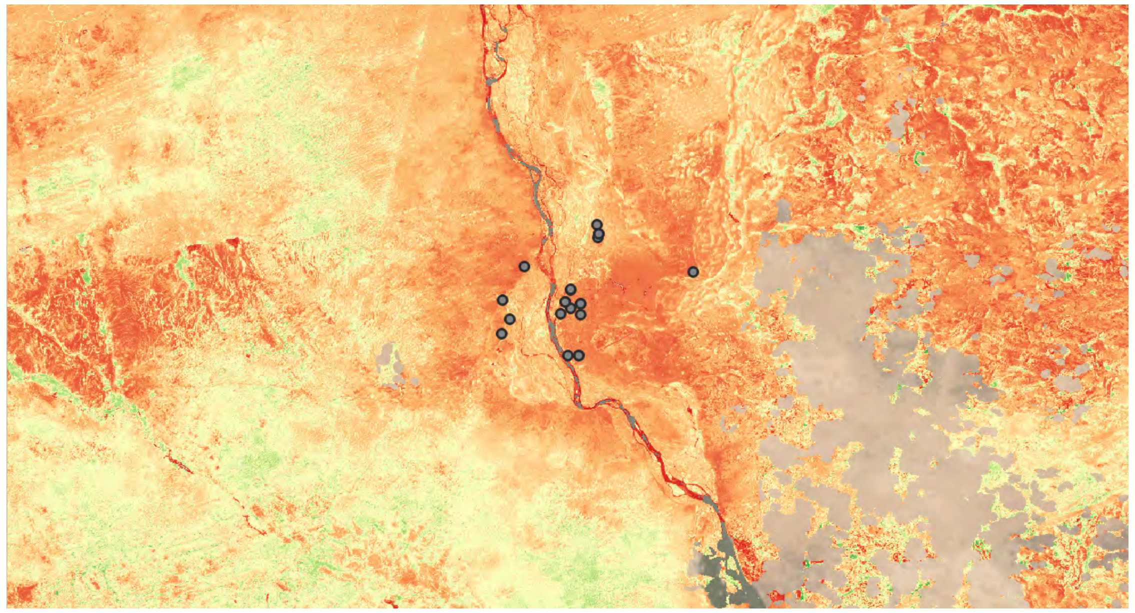
B- Vegetation Density Trends in Gao, Mali (2017–2024)

This section analyzes the August mean NDVI to assess vegetation cover and its temporal variation between 2017 and 2024, using data derived from harmonized Landsat 5, 7, and 8 imagery processed into monthly climatologies and distributed by Digital Earth Africa.

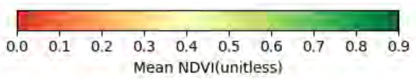


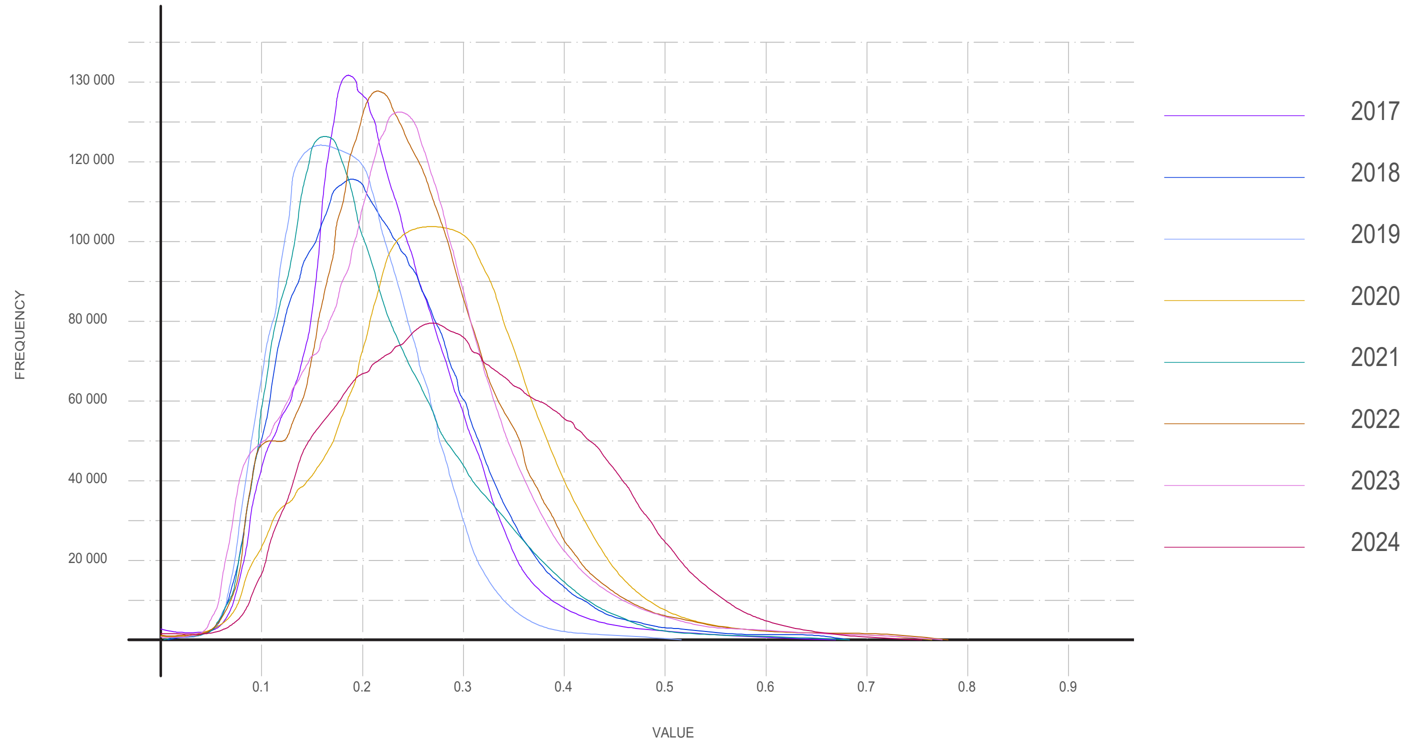
Mean NDVI Distribution, Gao – August 2017





Mean NDVI Distribution, Gao – August 2024





Cumulative Mean NDVI Distribution, Gao – 2017-2024 HW.ai

Observations of Histogram Distributions

From 2017 through 2020, Gao's NDVI histograms exhibit gradual rightward movement from low baseline values (~0.15–0.25), with narrow unimodal distributions becoming broader and less skewed. This pattern suggests a progressive increase in vegetative presence across the region. In 2021 and 2022, the distributions expand further, with more symmetric forms and tails extending into higher NDVI values (above 0.4), indicating a more varied vegetative landscape. The histogram for 2023 marks the peak of this progression, with a sharp central mode and a long right tail, reflecting the most widespread greening in the series. In contrast, the 2024 histogram flattens, with reduced central density and a continued spread into higher NDVI values, suggesting increasing spatial disparity in vegetation conditions.

Interpretation and Trends

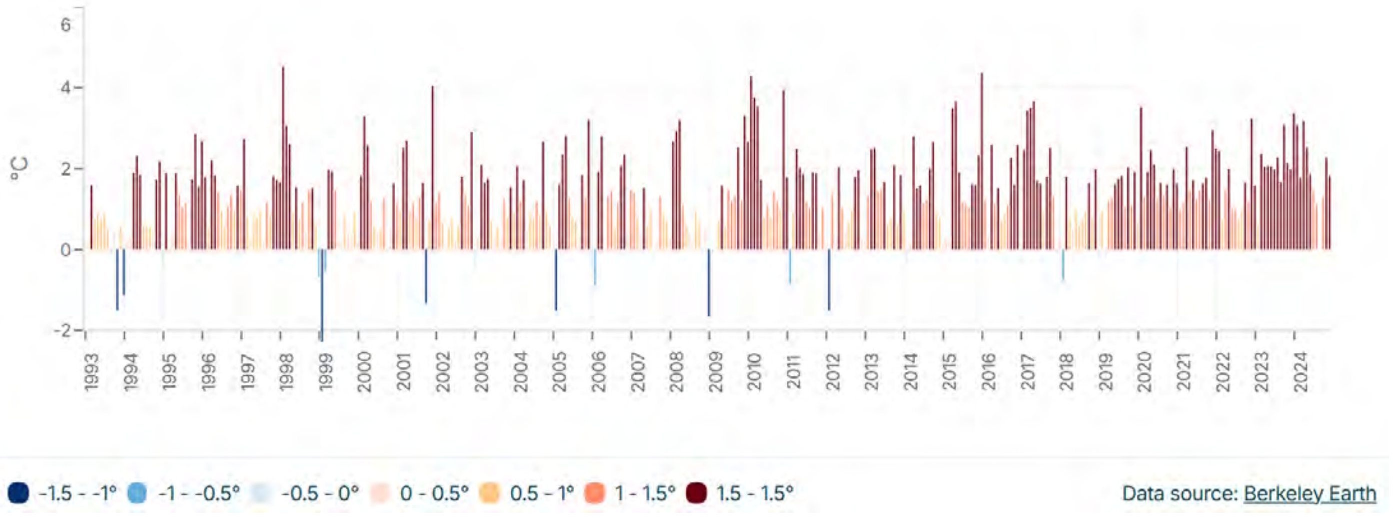
The overall trend between 2017 and 2023 indicates a steady and continuous increase in vegetative density and spatial complexity, as inferred from the gradual broadening and upward shift in NDVI distributions. This signals a multi-year period of ecological improvement. However, the shift in 2024 — from a peaked distribution to a flatter, more diffuse one — marks a departure from that trend. Rather than indicating continued uniform greening, the latest data suggest growing polarization, with some zones experiencing further vegetative gains while others stagnate or decline. This fragmentation may mark the onset of a more unstable or uneven phase in the region's vegetative trajectory.

Heritage Implications

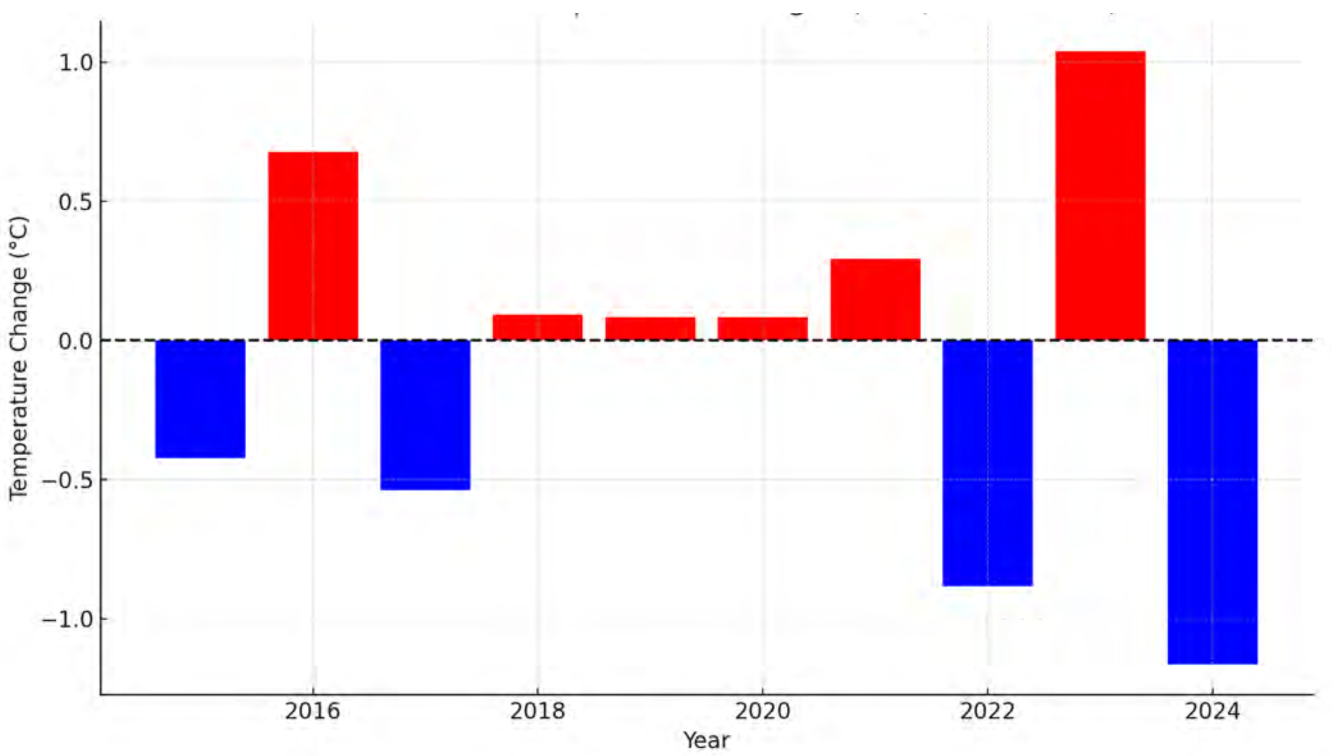
The increasing unevenness in vegetative distribution carries implications for Gao's cultural and historical landscape. In areas where vegetation has improved, there may be enhanced natural protection against wind erosion and sediment drift, beneficial for preserving earthen structures and traditional landforms. Conversely, areas that lag in vegetative recovery remain exposed to geomorphological degradation. This spatial divergence may challenge the integrity of interconnected cultural systems, such as pastoral routes, seasonal agricultural cycles, and settlement patterns, by fragmenting the ecological coherence they rely on.

C- Climatic Context in Gao, Mali: Temperature Trends and Rainfall (1993–2024)

This section presents monthly temperature trends and rainfall for the selected area between 1993 and 2024. The data is sourced from the Africa Data Hub's Climate Observer platform, which compiles information from the Global Precipitation Climatology Centre (GPCC) for rainfall and Berkeley Earth for temperature.

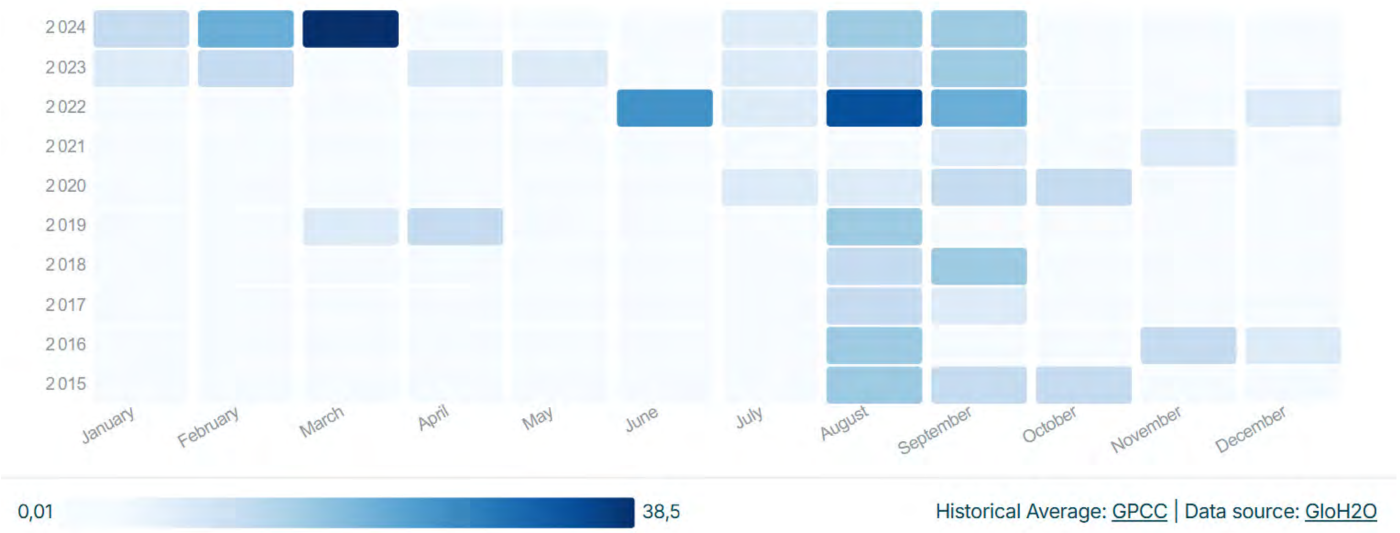


Temperature anomalies, Gao - 1993-2024



Interannual Temperature Fluctuations, Gao - 2014-2024

HW.ai



Average Monthly Rainfall (mm), Gao – 2014-2024

Long-Term Trends (1993–2024)

Rainfall:
Gao follows a typical Sahelian rainfall pattern, ith precipitation concentrated between July and September. During the 1990s and early 2000s, annual totals generally stayed below 300 mm. A clear shift in rainfall intensity began around 2018, culminating in 2024, which recorded 416.7 mm, well above the historical mean. The wettest month was August 2019, with 121.2 mm, indicating intensified mid-monsoon rainfall.

Temperature:
Temperatures have risen steadily, particularly since the early 2000s, with increases in both daytime highs and nighttime lows, reducing the diurnal temperature range and increasing thermal stress. A major anomaly occurred in April 2020, with temperatures 2.95° C above the long-term average. Recent years, notably 2021, show clustered monthly anomalies, reinforcing the broader regional warming trend.

Recent Decade Focus (2014–2024)

Rainfall:
Gao has experienced significant interannual rainfall variability: 2024 was the wettest year (416.7 mm), nearly double the 10-year average (~240 mm). 2020 was the driest, with just 111.99 mm. While August remains the core rainy month, anomalous rainfall has been recorded in early months such as February 2024, disrupting seasonal expectations. Such volatility in timing and intensity challenges water storage, flood preparedness, and agricultural calendars.

Temperature:
Of the nine year-to-year transitions since 2015, five show warming, with no sustained cooling trend. Even "cooler" years remain above the long-term average. 2021 recorded the highest cluster of heat anomalies, aligning with regional heatwaves. Persistent warming increases evaporation rates, reduces soil moisture, and disrupts traditional agricultural cycles

Interpretation

Gao is increasingly exposed to climatic extremes: Rainfall is intensifying, but with irregular timing and higher intra-annual variability, raising risks of flooding and land degradation. Temperatures remain elevated, reinforcing chronic heat stress and compounding drought risk. Together, these shifts are redefining Gao's climate vulnerability profile.

Heritage and Cultural Implications

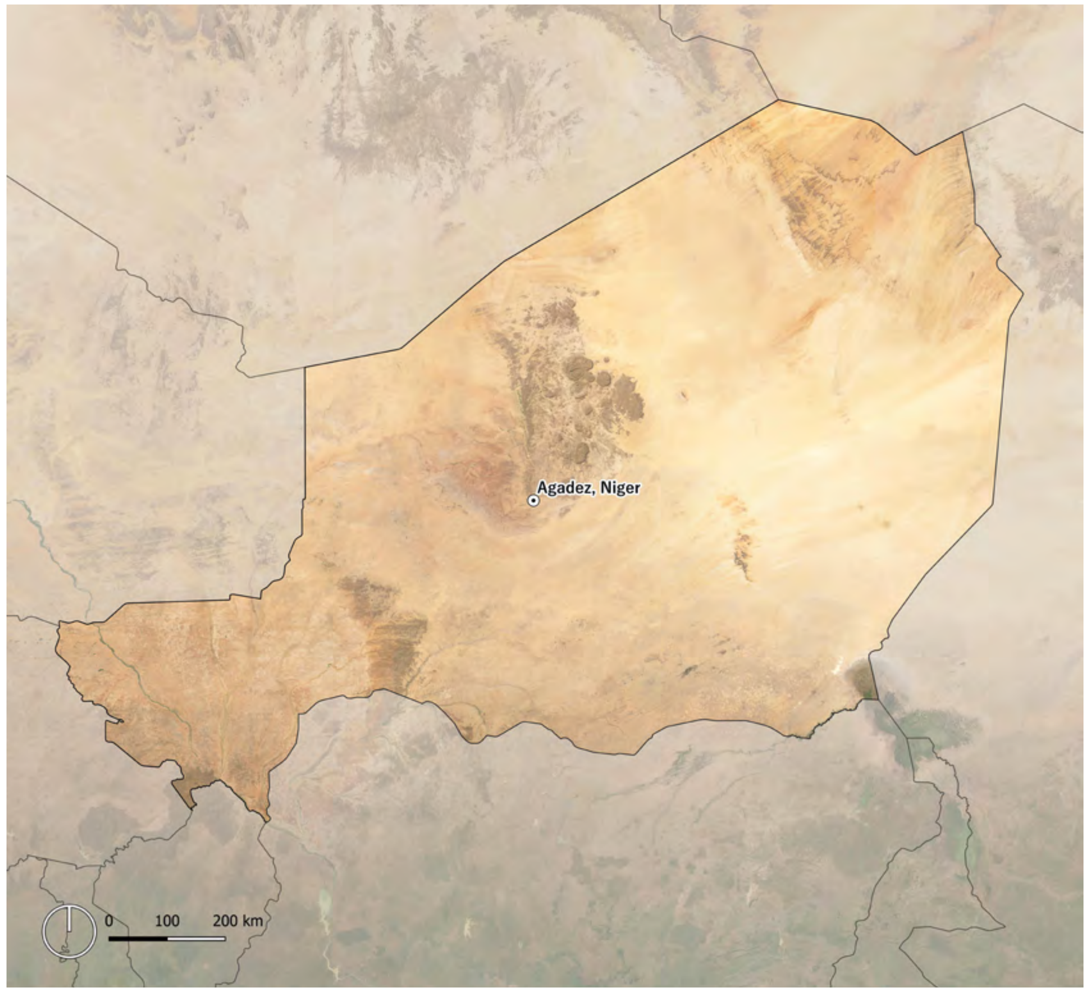
Gao's historic sites face rising risks from both extreme rainfall and chronic heat. Heavy rains threaten erosion and structural damage, especially to unprotected sites and low-lying areas, while sustained heat contributes to cracking and material fatigue in earthen buildings. Without targeted adaptation, Gao's cultural landscape risks both physical degradation and cultural detachment in the face of accelerating climate change.

2. SITE-LEVEL RISK AND SPATIAL ANALYSIS
2.5 AGADEZ, NIGER

Historic center of Agadez, UNESCO World Heritage Site, Niger, Africa Harding, R. (n.d.).

Getty

I. General Overview



Agadez, Niger. HW.ai

Aerial view of the Route Nationale 25 (RN25) cutting through the city of Agadez, in Niger. van Zeijst, V. (2019, September 12). Wikimedia Commons.

Site Name: Agadez

Status: UNESCO World Heritage (2013)

UNESCO ID: 1268

Coordinates: 16°16′ N 0°03′ W

Historical Context:

The city of Agadez, established at its peak between the 15th and 16th centuries, was historically a vital trans-Saharan trading hub and the political center of the Sultanate of Aïr. It has long served as a focal point of Tuareg culture and identity, having played a central role in the Tuareg rebellions of 1990–1995 and from 2007 to the present.

The region continues to experience instability due to ongoing conflicts and the emergence of insurgent threats, contributing to persistent insecurity in northern Niger.

Regional & Environmental Context:

Climate	Hot desert climate (BWh)
Avg. Annual Temperature	28°C
Avg. Annual Rainfall	111 mm
Altitude	520 m
Soil Type	Fine sand
Recent Climate Anomalies	Increased frequency of extreme weather events, including heavy rainfall leading to flooding, land degradation, and ultimately to desertification?

Social & Demographic Context:

As of 2025, Agadez has an estimated population of 124,324 residents (World Population Review, 2025). The city remains a center of active Tuareg cultural expression, with traditional silver, leather, and wood crafts still practiced, and events such as the Bianou festival continuing to reinforce communal identity and heritage.

Architecture & Construction:

Architecturally, Agadez is defined by its earthen construction, notably the Grand Mosque, built from clay brick in the Sudano-Sahelian style. The dense urban fabric, marked by narrow streets and decorative crenellations, contributes to its historical character. However, the reliance on mud-based materials makes the built environment highly susceptible to erosion and collapse, especially in the face of increasingly intense rainfall and flooding.

Environmental risks:

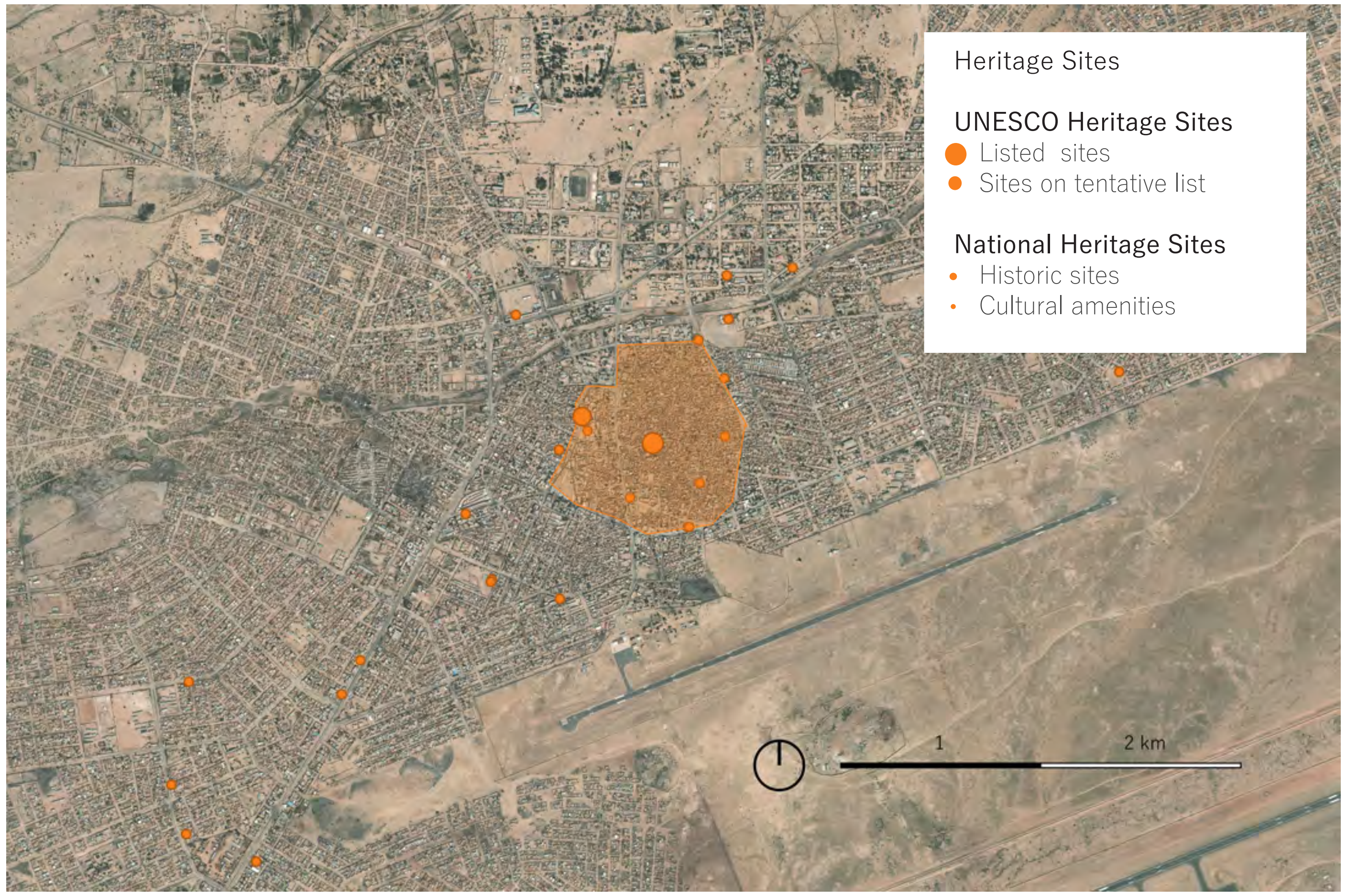
Agadez faces increasing heritage risks driven by both environmental and anthropogenic pressures. The city is particularly vulnerable to desertification, land degradation, and more frequent extreme weather events, notably flooding, which has intensified in the past decade (UNESCO, n.d.). Classified as a medium-priority site for flood and storm exposure,

Agadez also experiences threats from unregulated urban expansion and ongoing regional instability, which hinder conservation initiatives.

Conservation efforts:

Recent efforts to mitigate these impacts include the rehabilitation of 105 earthen structures under the EPPA project (2017–2019) and digital documentation and restoration support by Iconem and ALIPH in 2020. Despite these interventions, the urban landscape has visibly expanded, raising concerns about the long-term resilience of its architectural heritage.

II. Heritage Context



Localised Map of Agadez with heritage sites. HW.ai

This section offers a spatial and visual reading of the heritage fabric of Agadez's historic center. The map presents a categorized inventory of architectural and cultural assets, including UNESCO World Heritage Sites, nationally recognized landmarks, and locally important structures tied to trade, religion, and daily life. Elements are organized by architectural style, cultural role, and urban context.

Photographs on the next page showcase distinctive features of Sahelian and Saharan architecture, earthen construction, verticality, and spatial rhythms, while also documenting changes in condition and use. This combination of map and imagery invites reflection on how Agadez's heritage continues to evolve, balancing continuity with the pressures of climate, tourism, and urban development.

Traditional house, UNESCO World Heritage Site, Agadez, Niger, Africa. Runkel, M. (n.d.).

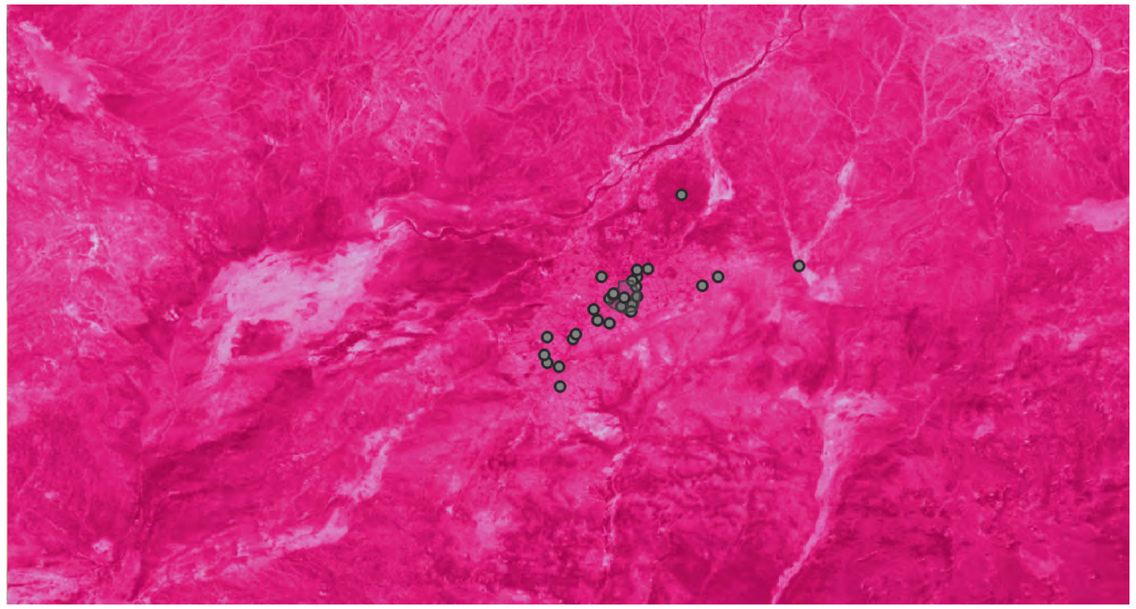
Republic of Niger – Agadez. ECPAD. (1969). ImagesDéfense.

Agadez Historical Centre. Misse, A. (2013). UNESCO World Heritage Centre.

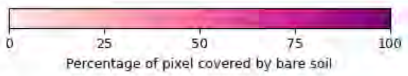
III. Risk Analyses

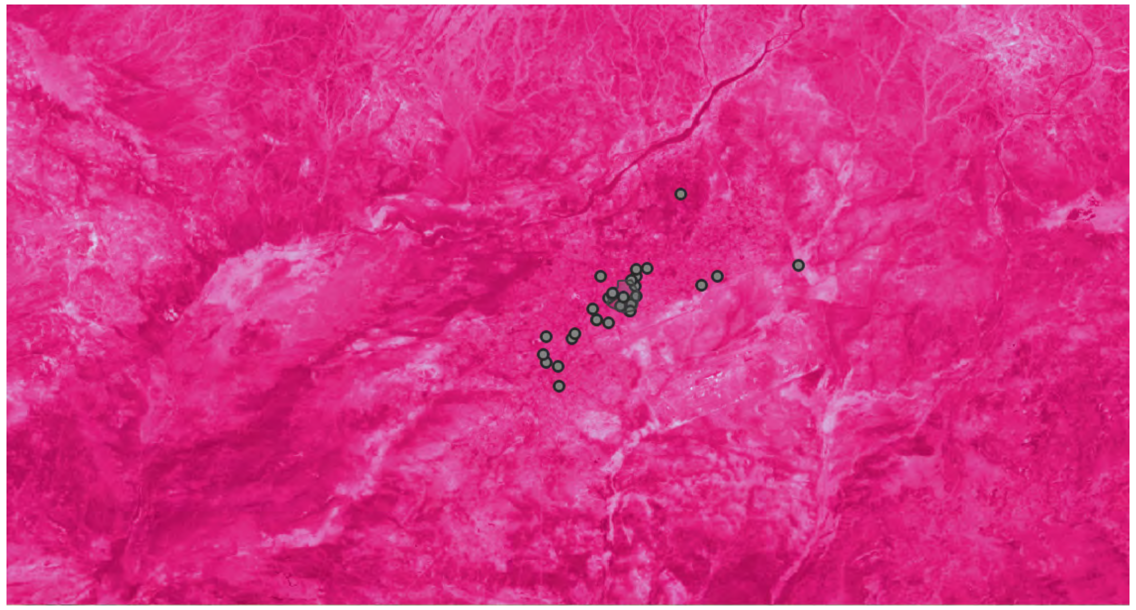
A- Bare Soil Exposure in Agadez, Niger (2014–2024)

This section analyses the 90th percentile of bare soil coverage to assess the extent of exposed land surfaces and their evolution over the decade, using data derived from Landsat 5, 7, and 8 imagery processed through the CSIRO fractional cover algorithm and distributed by Digital Earth Africa.

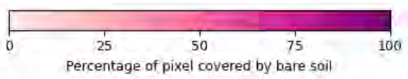


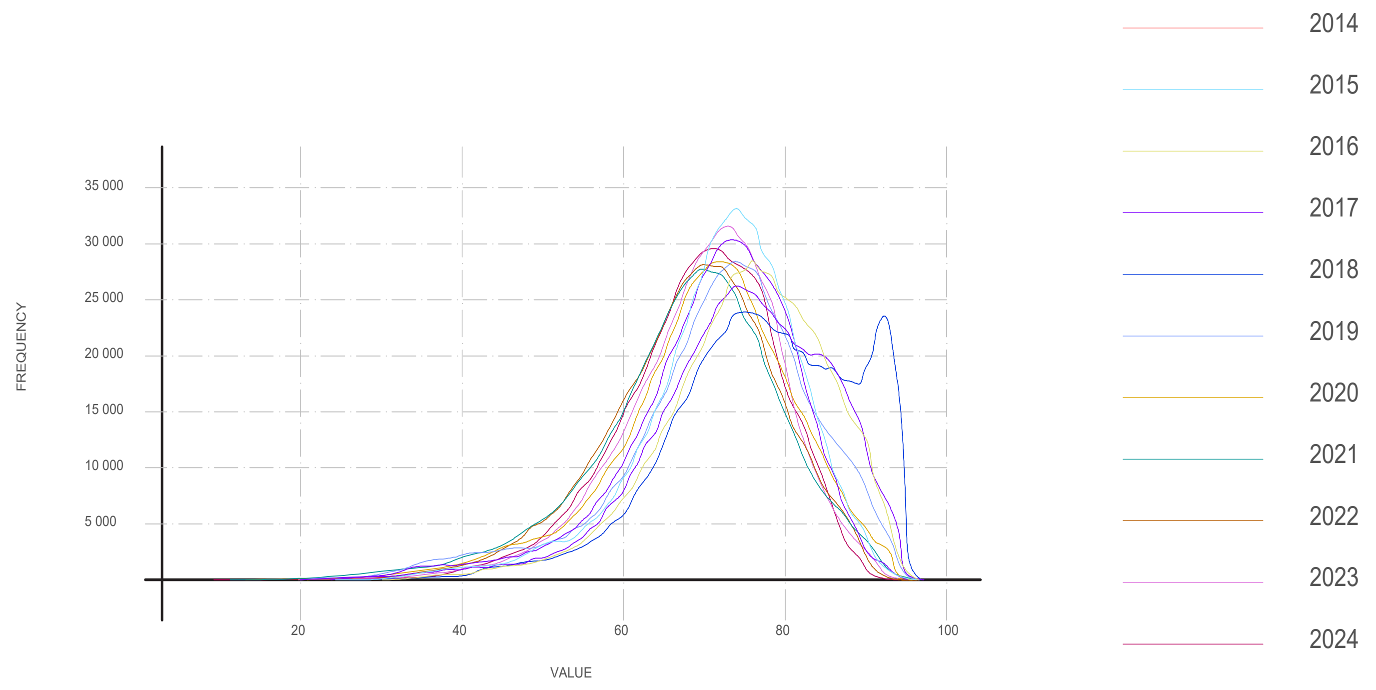
Bare Soil Coverage Distribution, Agadez – 2014





Bare Soil Coverage Distribution, Agadez – 2024





Cumulative Bare Soil Coverage Distribution, Agadez – 2014-2024 HW.ai

Observations of Histogram Distributions

Between 2014 and 2016, the histograms exhibit tight, unimodal peaks centered around 70–75%, indicating a relatively stable but exposed surface condition, characteristic of dryland systems with sparse vegetation but not yet fully degraded. From 2017 through 2019, distributions begin to broaden and flatten, showing more pixel values in both higher and lower ranges. This loss of central concentration reflects increased spatial variability, possibly due to early stages of vegetation breakdown, surface erosion, or heterogeneous land use pressures.By 2020 to 2022, the histograms begin to show subtle bimodality, with distinguishable modes near ~65–70% and ~90–95%, suggesting the coexistence of patches of degraded land alongside zones retaining some vegetative or crust cover. This spatial duality becomes more pronounced in 2023–2024, where the peaks become clearer, indicating an emerging polarization in land condition.

Interpretation and Trends

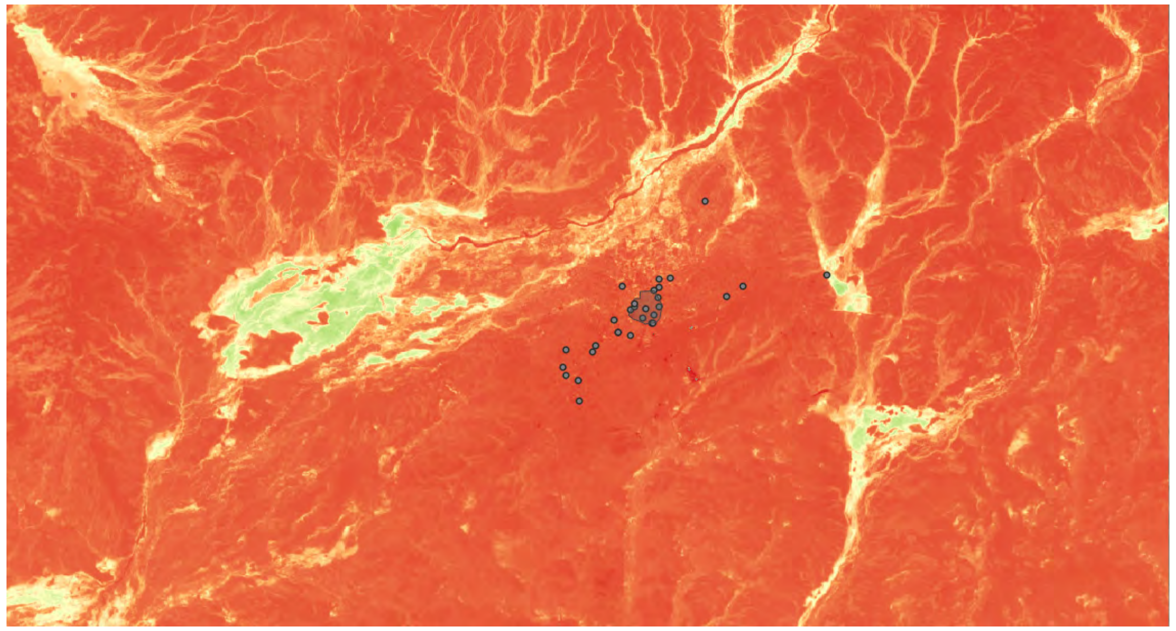
Agadez's surface evolution over the decade reflects a nonlinear but intensifying desertification process. The early concentration of moderate bare soil values gives way to a more complex distribution structure, signaling that desertification in this region is not uniform but rather unfolding in a fragmented and stratified manner. The persistent appearance of bimodality in recent years may indicate either a critical ecological tipping point or a stabilization into a semi-arid mosaic of degradation and marginal resilience. Either scenario confirms a substantial loss of surface heterogeneity, with serious implications for long-term land productivity and ecosystem services.

Heritge Impliations

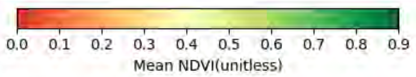
The increasing dominance of bare surfaces and landscape polarization poses direct risks to Agadez's architectural and cultural assets. The city's famed mudbrick minaret, trading caravanserais, and residential compounds are built using erosion-sensitive materials that depend on surrounding land stability. As bare soil coverage increases, aeolian activity and sediment displacement intensify, threatening both structural integrity and historical legibility. Simultaneously, the degradation of pastoral corridors, oases, and transhumance tracks disrupts nomadic practices, interregional trade routes, and oral heritage traditions grounded in mobility and ecological synchrony. The compounded effect is a weakening of Agadez's status not just as a historic site, but as a living cultural crossroads of the Sahel-Sahara interface.

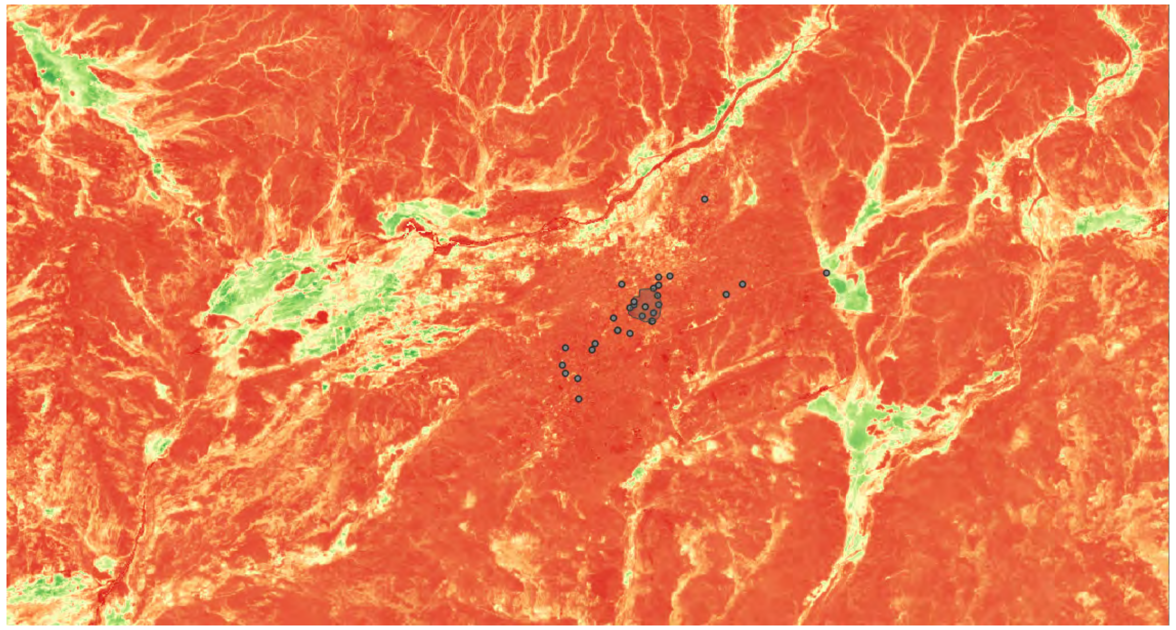
B- Vegetation Density Trends in Agadez, Niger (2017–2024)

This section analyzes the August mean NDVI to assess vegetation cover and its temporal variation between 2017 and 2024, using data derived from harmonized Landsat 5, 7, and 8 imagery processed into monthly climatologies and distributed by Digital Earth Africa.

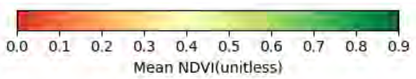


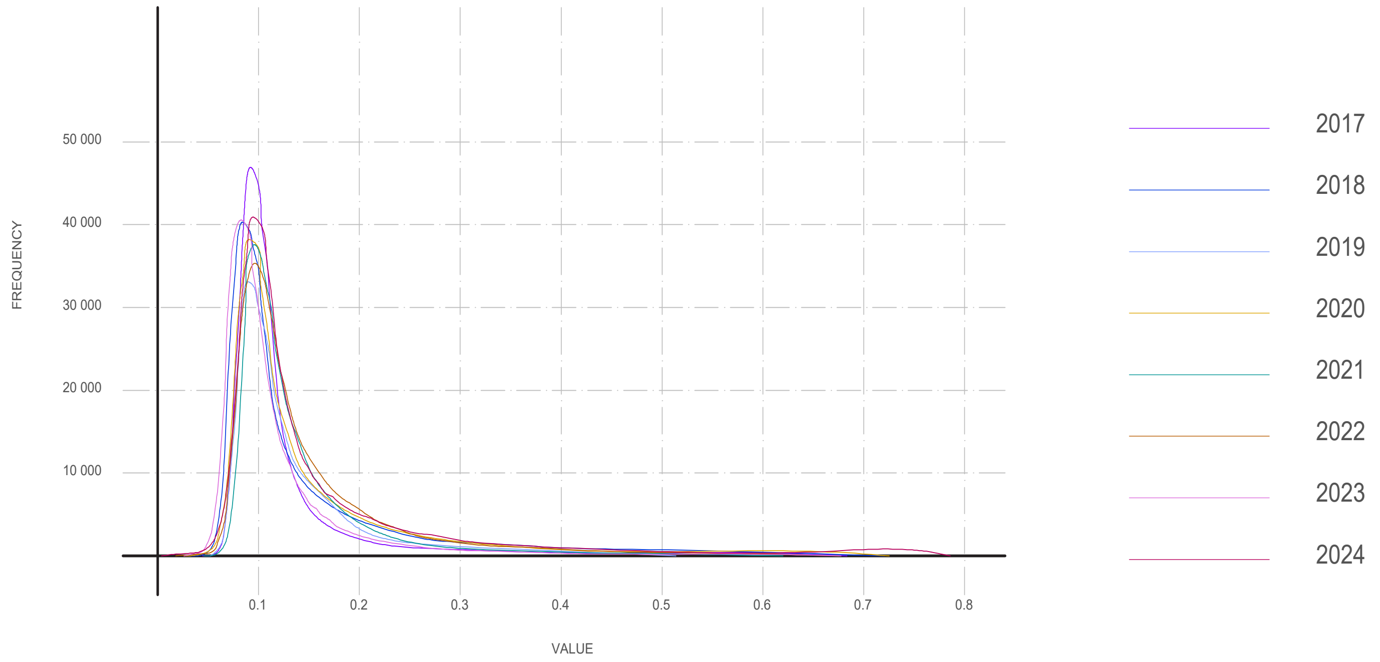
Mean NDVI Distribution, Agadez – August 2017





Mean NDVI Distribution, Agadez – August 2024





Cumulative Mean NDVI Distribution, Agadez – 2017-2024 HW.ai

Observations of Histogram Distributions

Between 2017 and 2020, Agadez's NDVI histograms display sharp, unimodal distributions concentrated around very low values (0.08–0.12), reflecting a persistently arid and vegetation-poor landscape with minimal ecological variability. These distributions are narrow and right-skewed, indicating uniformly low photosynthetic activity across the region. A subtle broadening begins in 2021 and 2022, with tails extending modestly into higher NDVI values, suggesting limited emergence of vegetated patches or micro-regional variability. In 2023, the distribution becomes more symmetric and flatter, with a shift toward mid-range NDVI values and greater spread, a notable deviation from earlier years. However, by 2024, the distribution contracts again toward the original low NDVI range, losing the broader tail observed in 2023.

Interpretation and Trends

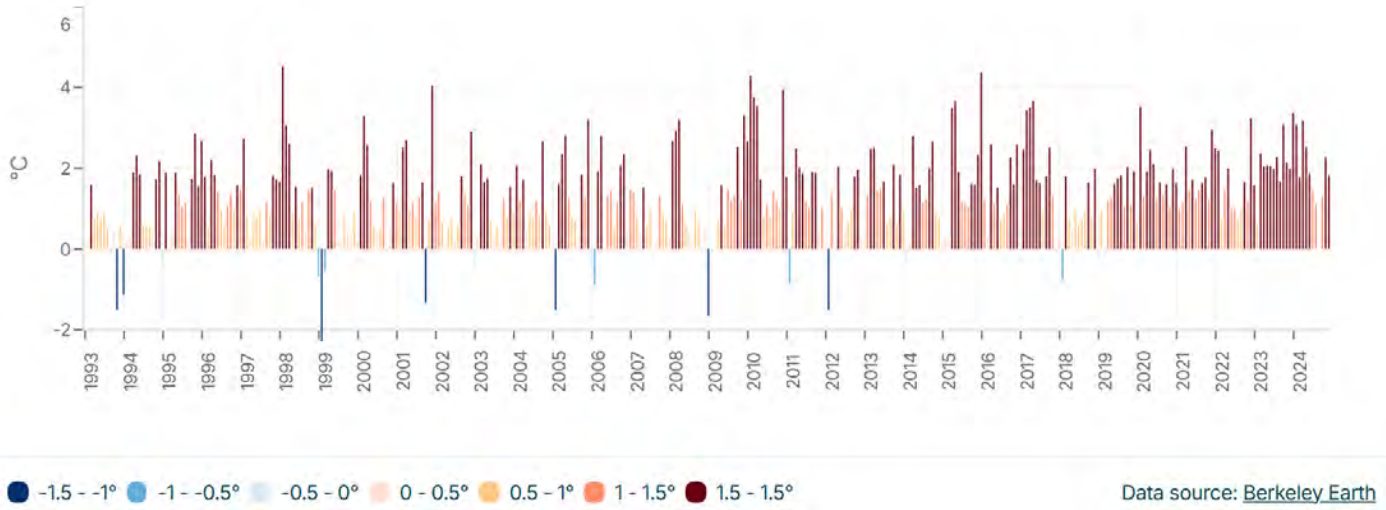
The NDVI data from Agadez indicate a stable but severely degraded vegetative baseline from 2017 to 2020. A short-lived shift toward more diverse and slightly greener conditions occurred between 2021 and 2023, peaking in 2023 with the broadest and most balanced distribution in the time series. However, the reversal in 2024 — with a contraction back toward low NDVI values, suggests this greening phase was not sustained. The overall trend is one of oscillation around a low ecological baseline, with brief, limited gains giving way to recurring stress. This pattern implies high environmental fragility and limited resilience to maintain vegetative improvements.

Heritage Implications

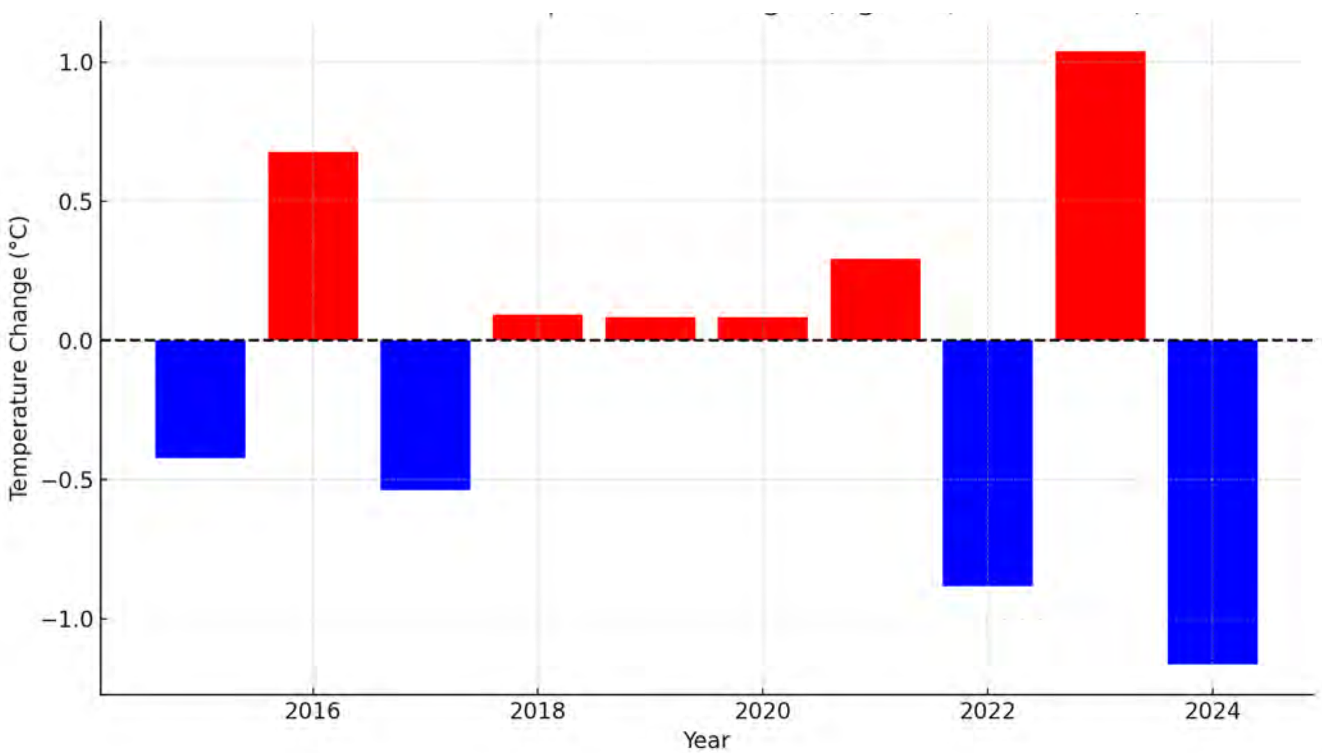
Persistent low NDVI and recurring vegetative decline threaten both the material and intangible heritage of Agadez. Historic earthen settlements, already exposed to harsh climatic forces, face increased vulnerability due to the absence of vegetation buffers that might stabilize soil and reduce wind-driven erosion. Furthermore, the ephemeral nature of vegetative gains undermines the ecological consistency required for sustaining pastoral livelihoods and nomadic cultural practices. As greening pulses fail to establish long-term ecological balance, the risk to traditional mobility routes, grazing systems, and the cultural cohesion of trans-Saharan identity systems continues to grow.

C- Climatic Context in Agadez, Niger: Temperature Trends and Rainfall (1993–2024)

This section presents monthly temperature trends and rainfall for the selected area between 1993 and 2024. The data is sourced from the Africa Data Hub's Climate Observer platform, which compiles information from the Global Precipitation Climatology Centre (GPCC) for rainfall and Berkeley Earth for temperature.

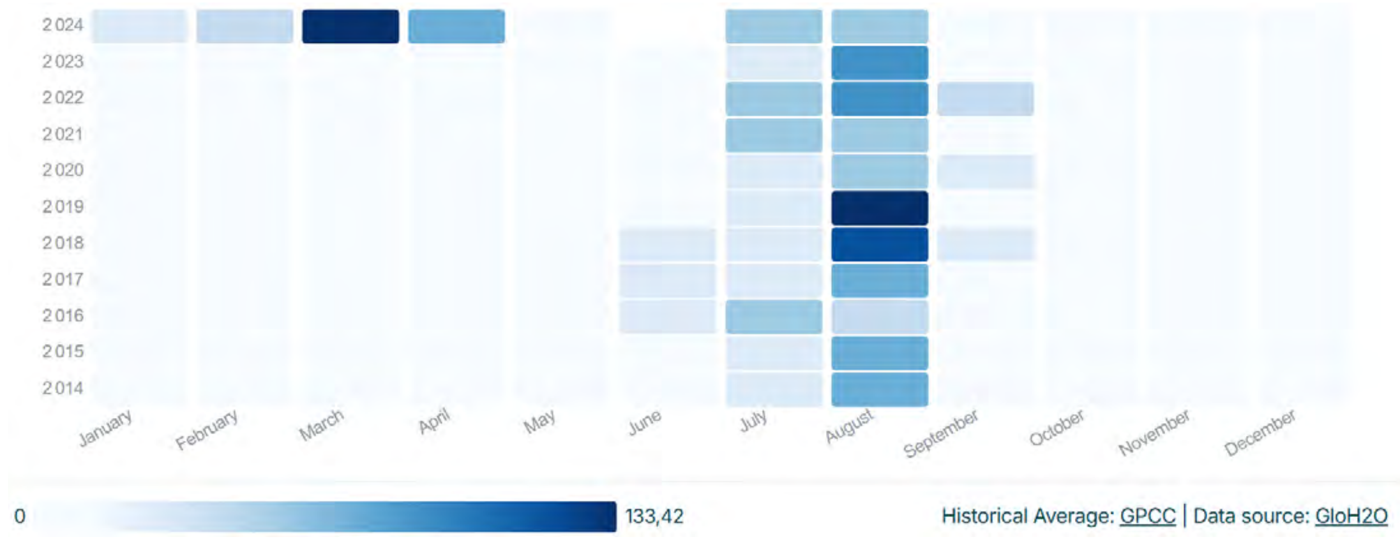


Temperature anomalies, Agadez - 1993-2024



Interannual Temperature Fluctuations, Agadez - 2014-2024

HW.ai



Average Monthly Rainfall (mm), Agadez – 2014-2024

Long-Term Trends (1993–2024)

Rainfall:
Located in the Sahel–Sahara transition zone, Agadez historically receives very low and erratic rainfall, mainly in July–September. The 1990s–early 2000s often recorded under 100 mm/year. A notable shift began in 2018, culminating in 2024, which saw record rainfall, including an unusual spike in March (133.42 mm), far outside the monsoon season. Rainfall has increased, but with greater irregularity, suggesting growing seasonal instability.

Temperature:
Agadez has experienced a steady warming trend, especially from April to June, with April 2020 showing a +3.79° C anomaly. Nighttime temperatures are also rising, reducing diurnal cooling and intensifying heat stress for both people and agriculture.

Recent Decade Focus (2014–2024)

Rainfall:
2024 was the wettest year, with March alone exceeding typical annual totals.
2015 was the driest, with severe monthly deficits.
Rainfall increases during 2018–2024 are driven by isolated extreme events, heightening risks of flooding and erosion, rather than improving water reliability.

Temperature:
Six of nine year-to-year transitions showed warming. 2024 had one of the highest concentrations of thermal anomalies. May and June routinely exceed 40° C, while even cooler months like December show warming trends.Interpretation

Interpretation:
Agadez is becoming hotter, wetter, and more erratic: Rainfall gains are concentrated in fewer, more intense events, increasing runoff and reducing absorption. Heat and humidity combined limit cooling and increase health and agricultural stress. These changes threaten both livelihoods and infrastructure resilience in a region already operating at climate margins.

Heritage and Cultural Implications

Agadez's UNESCO-listed heritage faces mounting climate risks:
Intense rain events lead to erosion, roof collapse, and material weakening in adobe structures. Thermal expansion cycles accelerate deterioration, especially in aging buildings. For nomadic and artisan communities, climate pressure on grazing routes and water sources threatens the continuity of oral traditions, craft knowledge, and seasonal rituals. Without targeted adaptation, Agadez risks the slow erosion of both its built heritage and living cultural systems under accelerating climate pressures.

3. Comparative Analysis

This comparative analysis presents a synthesis of environmental and structural risk factors affecting five key heritage sites across the Sahel and Sahara regions.

By integrating quantitative remote sensing data—such as Bare Soil Index (BSI) and Normalized Difference Vegetation Index (NDVI)—with architectural typologies and documented degradation patterns, the table below highlights varying degrees of vulnerability.

From Chinguetti's near-total loss of vegetative cover to Gao's fragmented ecological zones, each site exhibits a unique interplay between material fragility, ecological change, and exposure to climate-induced stressors.

This overview serves as a foundation for targeted conservation prioritization based on the intensity and nature of risks faced.

3.1 Cross Case Synthesis

Site	Bare Soil (2024, 90th pct.)	NDVI Trend (2017–2024)	Desertification Intensity	Architectural Materials	Key Risk Types
1-Chinguetti	96–98%	Constant low (<0.1)	Very High	Adobe (banco), stone, palm wood	Sand burial, erosion, structural fatigue
2-Bandiagara	98–100%	Increasing (0.4–0.7)	High but improving	Banco, stone, embedded cliff dwellings	Cliff erosion, slope runoff, loss of maintenance
3-Timbuktu	90–95%	Bimodal (0.19 & 0.27)	Moderate-High	Banco, toron (wood beams), adobe plaster	Wind erosion, sand drift, flood damage
4-Gao	95–100%	Polarized (0.15–0.6+)	Very High (fragmented)	Earthen ruins, riverine archaeology	Soil destabilization, fragmentation
5-Agadez	75–78%	Flat/stagnant (~0.25)	High	Adobe, pisé, decorative stucco	Wind abrasion, structure collapse, burial

Materials, Techniques, and Risk Linkages

1-Chinguetti

•Nature: 11th-century desert city with Islamic manuscript libraries and adobe mosques [UNESCO 750].

•Construction: Earth (banco), palm wood, stone masonry in clustered courtyard houses.

•Risks:
- Lack of vegetative buffer (→ sand mobility, erosion).
- Wind erosion damages banco facades and exposed walls.
- Burial of alleyways limits access and visibility.

Most Exposed Monument: Great Mosque of Chinguetti — proximity to shifting dunes from the northeast, threatened by burial and loss of access paths.

2- Bandiagara (Land of the Dogon)

• Nature: Escarpment-based cultural landscape of 289 villages [UNESCO 516].

•Construction: Banco/mudbrick granaries, dwellings, embedded sanctuaries.

•Risks:
- Erosion destabilizing cliff settlements.
- Rainfall + bare soils → runoff & wall collapse.
-Conflicts halt cyclical community maintenance.

Most Exposed Monument: Tellem cliff granaries — highly vulnerable to slope erosion and loss of cliff anchorage.

3- Timbuktu

•Nature: Center of Islamic learning; site of 3 iconic mosques & 23,000 manuscripts [UNESCO 119].

•Construction: Banco with toron beams; earth plaster exteriors.

•Risks:
-High BSI + low NDVI → no sand containment.
-Flooding and sand abrasion weaken mosque bases.
-Shifting NDVI suggests spatial fragmentation of resilience.

Most Exposed Monument: Sidi Yahya Mosque — located near peripheral zones where sand accumulation is intensifying and foundations show signs of cracking.

4- Gao

•Nature: Former Songhai capital; mixed archaeological and inhabited layers.

•Construction: Ruins in mudbrick, stratified earthen platforms.

•Risks:
-Fragmentation → archaeological layer exposure.
-Irregular NDVI recovery → unstable site microclimates.
-Pastoral/cultural pathways disrupted.

Most Exposed Monument: Askia Tomb — increasingly surrounded by bare, degraded zones, undermining stabilizing vegetative buffer.

5- Agadez

•Nature: Sahelian trading center with prominent earthen mosque [Great Mosque of Agadez].

•Construction: Adobe, pisé, decorated stucco finishes.

•Risks:
-Sand abrasion erodes plaster and inscriptions.
-High exposure and low NDVI → rapid material fatigue.
-Sacred routes and nomadic paths are threatened by burial.

Most Exposed Monument: Great Mosque of Agadez — sustained sand-laden wind exposure (Harmattan) causes visible damage to decorative elements and tower base.

The convergence of environmental degradation, material vulnerability, and diminishing maintenance capacity underscores the urgency for site-specific interventions. While all sites face some degree of desertification-related threats, the severity and complexity of risks vary significantly.

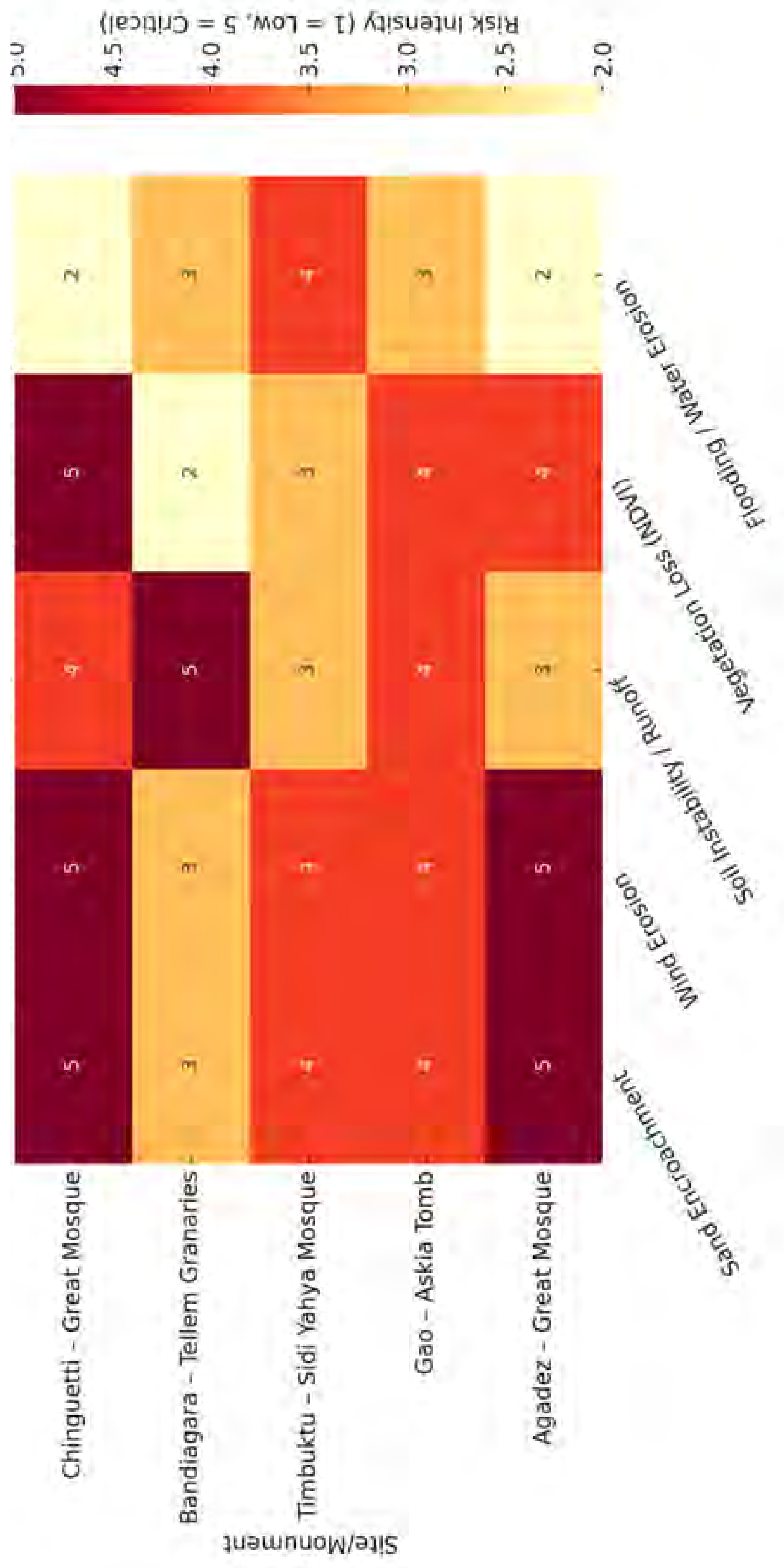
The selection of the most at-risk monuments is based on a combination of cross-referenced criteria from the risk analysis conducted, enhanced by spatial logic, architectural analysis, and environmental context. Here's a detailed breakdown of the approach:

Cross-referencing spatial data (BSI, NDVI) with heritage monument locations
Source: NDVI and BSI data, focusing on areas with very high bare soil coverage (Bare Soil Index ≥ 95%) and low or stagnant vegetation levels (NDVI < 0.3).

Analysis of architectural nature and intrinsic vulnerability of each monument
- Highly sensitive to wind or water erosion (e.g., banco, pisé, unprotected stucco),
- Dependent on cyclical, community-based maintenance (e.g., exposed toron beams like in Timbuktu),
- Built in topographically fragile zones (e.g., cliff faces, sandy basins, dry floodplains).

Monument	Key Spatial Factor	Heritage Justification
1-Chinguetti The Great Mosque	Surrounded by shifting dunes	Facades partially buried, access compromised
2-Bandiagara Tellem Granaries	Cliff-side, exposed to slope runoff	Troglodytic construction, erosion-prone
3-Timbuktu Sidi Yahya Mosque	Peripheral zone with sand accumulation	Undermining of foundations visible
4-Gao Askia Tomb	Located in fragmented and degraded soil	Large-scale adobe structure at risk
5-Agadez The Great Mosque	Open to sustained Harmattan wind exposure	Decorative stucco visibly deteriorating

The heatmap illustrates how each monument is affected across key stress categories—ranging from sand encroachment and vegetation loss to structural instability.
This cumulative risk picture informs a tiered prioritization framework, helping to distinguish between sites on the verge of irreversible damage and those where resilience mechanisms can still be supported. The following classification outlines recommended intervention priorities based on these integrated findings.



Desertification-Related Risks by Site and Type

3.2 Scenario Forecast (2025 - 2035)

Scenario A: Business-As-Usual (BAU) – No Mitigation
Assumption: Trends continue as observed (worsening BSI, stagnant or declining NDVI, increasing anomalies), with disasters recurring at similar frequency.

Site	Likely 2035 State	Risks Escalated	Monument at Risk
1- Chinguetti	Severe exposure	2+ droughts + 1 flood (based on GDACS)	Great Mosque: 75% buried by dune advance
2- Bandiagara	Collapsing base	1 major flood + erosion acceleration	Tellem Cliff Dwellings: Structural instability
3- Timbuktu	Unstable soils	1–2 flash floods, intensified heat stress	Sidi Yahya: Foundation erosion & abandonment
4- Gao	Fragmented	NDVI polarization + flood risk	Askia Tomb: Loss of surrounding buffer
5- Agadez	Desertified core	2 droughts, 1 major wildfire	Great Mosque: Decorative erosion + cracks

Scenario B: Accelerated Degradation (Worse-Than-Trend)
Assumption: 1.5× frequency/intensity of extreme events; heatwaves become annual. Reflects unchecked emissions and land degradation.

Site	Forecasted Collapse Point	Probable Cultural Loss
1- Chinguetti	2029	Full loss of northern manuscript libraries
2- Bandiagara	2033	Abandonment of >50% of cliff villages
3- Timbuktu	2032	Partial collapse of Sankore Mosque due to flash erosion
4- Gao	2031	Disappearance of minor archaeological mounds
5- Agadez	2030	Loss of stucco ornamentation on minaret

Scenario C: Partial Adaptation
Assumption: Moderate interventions (vegetative buffers, drainage, community restoration) slow decline.

Site	Stabilization Point	Resulting Condition
1- Chinguetti	2032	Dune buffer halts encroachment but alleys remain buried
2-Bandiagara	2034	Cliff dwellings stabilized, but terraced fields degrade
3- Timbuktu	2030	Central mosques preserved, outer districts vulnerable
4- Gao	2031	Archaeological zones mapped/protected
5- Agadez	2033	Maintenance resumes but heat stress persists

1. Most at Risk : Chinguetti and Gao

These areas have almost no vegetation left (near-total vegetation loss).

The land is mostly bare soil, making it very vulnerable to erosion.

They're exposed to a «dual threat» of both sand dune encroachment and flooding.

Bottom line: If no action is taken, Chinguetti and Gao are likely to suffer severe degradation or collapse of their landscapes and possibly cultural sites.

2. Most Sensitive to Intervention: Timbuktu

The vegetation index (NDVI) in Timbuktu fluctuates, meaning vegetation levels go up and down.

This suggests the area is still responsive to environmental changes or restoration efforts.

Bottom line: With proper care and intervention (like replanting, erosion control), Timbuktu could recover well.

3. Most Rapidly Fragmenting: Agadez

The area is losing small patches of vegetation that used to act as buffers (natural protection).

This loss causes more exposure of the ground and structures to environmental damage (like wind or water erosion).

Bottom line: Agadez is breaking down fast, and the loss of even small vegetated areas is accelerating damage.

4. Compound Risk: Bandiagara

The site faces multiple overlapping risks:

Conflict interrupts conservation and maintenance efforts.

At the same time, environmental shocks (like drought or flooding) are weakening structures and ecosystems.

Bottom line: Bandiagara is in danger from both human and natural factors, making it especially vulnerable unless both are addressed.

Suggested Monitoring Indicators (2025–2035)

Metric	Threshold	Interpretation
NDVI < 0.10 (3-year avg)	Severe	Structural and ecological exposure
2+ droughts in 5 yrs	Critical	Soil cohesion breakdown
≥1 flood within 2 yrs	Emergency	Adobe disintegration, runoff risks
BSI > 95%	High	Urgent revegetation needed

This table outlines key environmental metrics to monitor over the next decade, with thresholds indicating when conditions become critical, and what the implications of those thresholds are for structural and ecological stability.

NDVI < 0.10 (3-year avg)

NDVI = Normalized Difference Vegetation Index, a satellite-derived measure of vegetation health and coverage.

A 3-year average below 0.10 indicates very sparse or dead vegetation.

Implication: The area is likely exposed to erosion, loss of protective vegetation cover, and vulnerability of both ecological and built structures (e.g. historic sites).

2+ droughts in 5 yrs

Frequent droughts stress the land.

Implication: Drought depletes moisture needed to bind soil particles, leading to soil cohesion breakdown, which increases erosion and instability, especially around unprotected structures or natural slopes.

≥1 flood within 2 yrs

Flooding is becoming more frequent.

Implication: Floodwater damages adobe structures, increases sediment and runoff risks, and may compromise the foundations of vulnerable sites or ecosystems.

BSI > 95%

BSI = Bare Soil Index, another satellite-derived index used to detect areas without vegetation.

Above 95% indicates almost total exposure of soil surfaces.

Implication: Urgent revegetation is needed to stabilize the environment, reduce erosion, and prevent land degradation.

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