BLUE PAPERS

Water & Heritage for Sustainable Development

Special issue

Water Management in World Heritage Properties at a Time of Climate Change

Editor-in-Chief
Carola Hein

Edited by **Zuzanna Sliwinska** & Special Guest Editor **Tino Mager**

Leiden-Delft-Erasmus Universities

2025 (Vol. 4 No. 2)

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Journal Description

Blue Papers : Highlighting the Critical Role of Water and Heritage in Sustainable Development

Water in all its forms is key to human survival and well-being. Humans have created intricate and ingenious solutions to survive and thrive in difficult and complex territories, and adapt to changes in social and environmental conditions. Remnants of past practices, structures and objects are still with us – in the built environment, in our institutions, in our ways of living and in our languages. Sometimes we call these objects and practices heritage, but more often they are so much a part of our everyday lives that we take them for granted.

As emphasized in the *UNESCO Thematic Indicators for Culture in the 2030 Agenda,*[1] culture is an important part of the Goals and Targets of the 2030 United Nations' Agenda for Sustainable Development. Stand-alone technological interventions cannot solve the complexities of the social, cultural and economic implications of climate change in the long term. New solutions require the engagement of local stakeholders and local knowledge to address social and cultural dimensions of water and to create a new embedded water awareness in the built environment, in institutions and culture(s), so that we can preserve and protect our heritage, understand and learn from the past, and activate history and heritage for future sustainable and inclusive living.

The biannual peer-reviewed journal *Blue Papers* explores the complex relationship between water, culture and heritage to assess lessons from the past, to protect heritage sites, to make use of water heritage and to contribute to the development of inclusive and sustainable future water systems. The past can help build a new platform for awareness of water and heritage, which involves shared methodologies and terminologies, policies and tools that bridge disparate fields and disciplines. To achieve this, we also need to rethink the role of water in the UN Sustainable Development Goals (SDGs). Water is not fully captured in *Goal 6: Ensure access to water and sanitation for all*; it is also an integral and inseparable key to all SDGs that carry us forward to a more sustainable future.

All issues of the journal will be loosely based on themes that link to water, culture and heritage, including (but not limited to):

- Transcending the nature-culture divide
- Tangible and intangible aspects
- Integrated discourses and practices
- Capacity building for holistic systems

1. The UNESCO Thematic Indicators for Culture in the 2030 Agenda (UNESCO Culture|2030 Indicators), https://whc.unesco.org/en/culture2030indicators/.

- Long-term (living) history perspectives for comprehensive understanding
- Preservation, protection and reuse of water-related (living) heritage
- Human and non-human stakeholders
- New practices and rituals for water awareness and engagement
- Strategies for inclusive sustainable development, including those drawing on heritage.

Special issues

Blue Papers periodically publishes Special Issues dedicated to exploring topics of global relevance at the intersection of water and heritage management. These themes are proposed by special guest editors, who are invited to join the editorial team for a particular issue due to their specific expertise and professional connection to the subject. The chosen themes align with priorities highlighted by international institutions like UNESCO. Each Special Issue brings together professionals and researchers from around the world, presenting case studies that offer diverse perspectives on the chosen subject. All contributions are original and have not been published before.

The launch of the open access, peer-reviewed journal *Blue Papers* has been led by the Chair History of Architecture and Urban Planning, Delft University of Technology; the UNESCO Chair Water, Ports and Historic Cities; and the LDE PortCityFutures Center. It was made possible thanks to financial support from the Ministry of Infrastructure and Water Management, the Netherlands; the Chair History of Architecture and Urban Planning, TU Delft and the LDE PortCityFutures Center. Setup and development of Blue Papers has been supported by ICOMOS NL, ICOMOS Germany, ICOMOS ISC Water, the Initiative for the Future of Great Rivers (IFGR), WAMU-NET, Waternet, Witteveen+Bos, and Stichting OpenAccess Platforms (SOAP). Over the years, colleagues from The University of Pennsylvania, Living Waters Museum, UNESCO Chair Heritage and Urban Regeneration and UNESCO Chair River Culture – Fleuves et Patrimoine have joined.

Cover image: Green plain within the Ilulissat UNESCO World Heritage property (Source: Bo Albrechtsen, 2025).

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Icons as a Tool to Connect Water Practices, Functions and Values across Space and Time: A Second Attempt

Carola Hein, Lea Kayrouz, Zuzanna Sliwinska and Matteo D'Agostino

Humans have shaped water systems for millennia, creating complex networks of physical structures, institutions and cultural practices. These systems reflect locally embedded yet globally influenced values that evolve over time. From infrastructure and landscapes to rituals and laws, human engagement with water is both tangible and intangible, deeply influenced by societal pref-erences, climate conditions and historical choices. To better understand this diversity, we devel-oped a set of icons to represent various water spaces, functions, practices and values. Rather than offering a fixed taxonomy, these icons are intended as tools for discussion – making visible the multiple dimensions of water and the meanings knowledge holders assign to it.

Originally introduced in 2022 (Hein et al. 2022), the icons were used by authors in our journal to highlight key themes in their work. While we envisioned them as a way to map specific water-re-lated elements across time and geography, they also served as visual keywords, helping to reveal prominent aspects of water heritage and practice. This goal has guided our ongoing efforts to enhance the icons' interpretive and comparative value, stimulating deeper cross-contextual re-flection (Hein et al. 2025). In our second attempt to build a taxonomy of water practices, functions and values, we have introduced new icons and revised others, notably by adding representations of aesthetic and economic aspects and refining examples.

Ultimately, these categories are suggestions – not exhaustive or mutually exclusive – designed to illuminate how water has been managed, valued and lived with across different times and places, and how the past continues to influence the present and shape our future.

As we make the water icons open source (CC-BY) available for download on the *Blue Papers* website, we invite readers to build on the current set and expand it to fit their own context. The goal is to foster a dialogue around water values, invite collaborative engagement and spur new insights.

Blue Papers 2025 (Vol. 4 No. 2), pp. 1–4
10.58981/bluepapers.2025.2.wicon

Tangible

Drinking Water
Access to and provision of fresh, potable water is a universal need. Humans employ many different techniques and infrastructures to transport, store, filter, pump, redistribute and use drinking water. Examples include the use of reservoirs and pipelines for storage and distribution, both above and under the ground, as well as filtration systems that ensure water quality meets safety standards.

Agriculture and Irrigation
A wide range of strategies and technologies are used to harness water for food production, such as by irrigating crops and providing water for livestock. Agriculture and irrigation practices vary across different contexts ranging from agroforestry to terrace farming, including techniques that leverage seasonal water changes like flood agriculture.

Drainage Water and Sanitation Systems
The removal of excess and sewage water, including rainwater, runoff, black water and gray water, requires extensive infrastructure and treatment systems. Sanitation systems are essential for public health and environmental sustainability. Examples include wastewater treatment plants that recycle water, formal and informal sewer networks, and waterless solutions such as composting toilets.

Protection of Human Settlements
Humans have created architectural, urban and landscape structures to adapt to their environments and address challenges posed by water, animals and enemies. Responses to rain, snow, floods and droughts include canals, dikes and moats. Water has also been used defensively through fortification walls and floodable landscapes designed to deter or delay potential threats.

Water and Health
Access to clean water is essential for human well-being, with water quality playing a critical role in individual, public and ecosystem health. The purification of water for human consumption, for example, through boiling, filtration or adding chemicals, has influenced the development of public health, planning and environmental policy and has sparked private and public interventions.

Energy and Industry
Water management systems play a critical role in supporting energy production and industrial processes, often facing challenges related to resource efficiency, environmental impact and sustainability. Examples include the use of dams for hydroelectric power generation, water-cooling systems in machinery and factories, and water-intensive industries like mining and breweries.

Shipping
Water bodies, including seas, rivers and canals, are vital for moving people and goods, supporting daily mobility, tourism and commerce. Natural and manmade waterways are linked to the boats and ships they serve. Specialized infrastructure such as quays, cranes, warehouses, ports and dredging operations enables navigation, transport and the storage of goods.

Places of Leisure
Water bodies, natural and man-made, serve leisure practices in multiple ways. The tangible aspect of water leisure focuses on physical spaces and infrastructure designed for recreational activities at the intersection of land and water. Examples include waterfront promenades, swimming pools, water parks and beaches, which serve as functional features that facilitate human interaction with water.

Sacred and Spiritual Spaces
Humans have long created sacred spaces to honor water, using it as a medium for spiritual connection or reverence for the divine. Religious architecture often includes elements like fountains, baptismal fonts, ablution facilities and temple tanks. These features not only symbolize purity and renewal but can also play a role in local water management.

Aesthetic Water Sites
Physical spaces and structures, whether permanent or temporary, serve as tangible manifestations of cultural and artistic connections to water, often becoming sites of community significance. Examples include architectural interventions such as squares and fountains, as well as the urban design of coastlines, waterfront parks and promenades that celebrate water and encourage interaction with it.

Food from Water Bodies
Natural and artificial water bodies, such as rivers, lakes, seas and ponds, support diverse ecosystems and provide vital food sources through a wide variety of traditional and modern practices, from seashell collection to large-scale aquaculture and industrial fishing. These waters are home to a wide range of plant and animal species, sustaining local livelihoods and global food systems.

Intangible

Daily Water Practices
Daily water practices are fundamental to human well-being, woven into routines that sustain health and hygiene. These include sourcing water for cooking and drinking, communal laundry, bathing and showering practices. Such everyday habits highlight water's essential role in both practical needs and sociocultural practices across communities.

Preservation, Adaptation, Reuse
Diverse traditional and contemporary practices aim at preserving or strategically changing water bodies, related ecosystems and the social customs connected to them. Examples include the use of local knowledge in cultural heritage protection, wetland conservation, modern techniques of river restoration and community efforts to maintain traditions, rituals and structures tied to water.

Knowledge Systems and Capacity Building
Socialization and education are key to healthy and sustainable living with water. This can occur through community engagement, school curricula, capacity-building initiatives, the preservation of traditional wisdom about local water systems and sustainable practices, and all initiatives aimed at exchanging or transmitting knowledge and raising water awareness.

Laws, Policies and Planning
Water management, access and use have long been regulated through governmental policies, customary law and land use planning. These frameworks, implemented by state, corporate or traditional authorities, determine rights and responsibilities through tools like zoning regulations, land ownership policies and infrastructure planning that affect how water is distributed, accessed and controlled.

Language and Idioms
People's connection to water is expressed through diverse cultural and artistic forms, reflecting its deep symbolic and practical importance. This shapes how communities understand and relate to water. For example, language often includes words and proverbs about water, embedding traditional wisdom and values that arise from close daily interaction with water in different environments.

Economic Value of Water
The economic value of water is often realized through its exploitation for agriculture, industry and energy production, such as intensive irrigation in agribusiness, dam-based hydropower, and mining operations that rely heavily on water access. These practices can generate significant income and infrastructure but also raise questions about equity, environmental impact and long-term resilience.

Institutions, Organizations and Governance
Water management involves diverse institutions and governance structures across local, national and cross-border levels. Formal entities like ministries and water boards, informal groups such as activist movements and community alliances, and customary bodies like traditional councils all play key roles. They set and enforce rules, guide social behavior and enable public participation in water governance.

Leisure Practices
Water-related leisure practices encompass activities and traditions that highlight the interaction between land and water. Examples include water sports, cultural events like fishing festivals, seasonal celebrations, informal gatherings for picnics or swimming at local rivers and recreational practices that bring communities together at waterfronts.

Rites, Rituals and Ceremonies
Water holds deep cultural, religious and spiritual significance, reflected in many practices and traditions. These include purification rites, blessings, baptisms, water festivals, and rituals that commemorate historic water events or celebrate the opening of new water structures. Such ceremonies highlight water's vital role in faith, community identity and cultural heritage across societies.

Music, Arts and Dance
Various cultural and artistic forms reflect the deep symbolic and practical importance of water. Examples include dance, spoken and written words, music, visual arts and other creative expressions. These forms offer insights into how communities relate to and understand landscapes shaped by water, highlighting its central role in human life and culture.

Water Access and Equity
Water infrastructures serve different users in different ways, with their social, environmental and economic impacts varying widely across contexts. These variations often reflect deeper inequalities of gender, ethnicity or economic background, which are at the heart of water justice and the power dynamics shaping access to and control over water.

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Water Management in World Heritage Properties in Times of Climate Change

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Water remembers. It is humans who forget.
Elif Shafak, *There are Rivers in the Sky*

Water management is a complex process, particularly at World Heritage sites. It leverages long-standing experience while requiring new expertise for changing conditions. Water – whether as a natural heritage, a component of built heritage, or a cultural space – embodies the collective memory of past generations. This memory lives on through our ancestors and traditional communities, who historically lived with, rather than against, water – a sustainable relationship based on adaptation, deep knowledge and minimal environmental impact.

UNESCO's World Heritage List formally recognizes and protects many outstanding examples of such ancestral water stewardship. Yet today, unplanned development, population growth, shifting value systems, widening inequality and the growing risks posed by climate change are changing this relationship. How can we manage water in uncertain times, especially around heritage sites, where governance must balance preservation with the need to adapt management strategies to address the impacts of climate change?

Building community stewardship through shared learning dialogues and participatory decision-making processes is essential for just and sustainable water governance. Such stewardship strengthens local ownership of conservation measures, ensures that diverse social groups are included in management decisions and enhances the adaptive capacity of communities to respond to water-related risks stemming from climate change. Integrating these local perspectives into heritage management plans is essential for achieving both site preservation and long-term resilience.

However, establishing community stewardship cannot be an end in itself – it needs to be supported by an engagement process that recognizes the intersectionality of gender, age, ethnicity, race, class, caste and ability – and the different interests these may bring to heritage management. Listening to this diversity of interests is as important as hearing water "speak". It means reflecting on the words of our ancestors while acknowledging that, for a heritage site to remain relevant and actively sustained, the incentives for local guardianship must be balanced with natural flows, including the ebbs and tides of our past, present and future.

Blue Papers 2025 (Vol. 4 No. 2), pp. 5–6
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Preface

Editorial Issue 2/2025
Water, Climate and World Heritage: Navigating Threat and Opportunity

Zuzanna Sliwinska, Tino Mager and Carola Hein

The frequency and intensity of weather extremes are rising globally due to anthropogenic climate change, the degradation of ecosystems' integrity, and the breach of six out of nine planetary boundaries over the last decades (Richardson et al. 2023). Water is central to understanding these changes and a critical focus for adaptation. According to the World Meteorological Organization (2021; cited in UNESCO 2025a), water-related hazards such as droughts, storms and floods have caused over 90 per cent of the world's major disasters since 1970, and have led to more than 2 million deaths and economic losses exceeding US$3.6 trillion.

While today water is related to the most significant threats of a changing climate, it has always been a fundamental source of opportunity and a key factor in the rise of civilizations. This long-standing relationship between humans and nature has generated a wealth of sustainable water management practices. Some of the most outstanding examples of this water-culture nexus are protected as World Heritage properties under the 1972 World Heritage Convention. Examples include the Cultural Landscape of Bali Province: the Subak System in Indonesia, the Mill Network at Kinderdijk-Elshout in the Netherlands and the Persian Qanat in Iran.

Water connects natural and cultural elements of heritage with intangible practices. Water management is an inherent part of our cultural heritage; it is also an integral part of "natural" systems and landscapes. A focus on water challenges the current nature–culture dichotomy, a philosophical schism originating with Descartes that remains present within the institutional practices of UNESCO itself. A stronger focus on water-related aspects of cultural heritage can provide impetus for solutions to mitigate climate change and adapt to its consequences, providing a framework for re-evaluating the fractured human-nature relationship that the climate crisis represents.

Climate change was introduced as a scientific concept by Svante Arrhenius in the nineteenth century, yet UNESCO only recognized its potential impact on World Heritage properties in 2005 (World Heritage Committee 2005). In its *Policy Document on Climate Action for World Heritage* (2023), UNESCO affirms that "Climate change is one of the most significant and fastest growing threats to World Heritage properties." A recent assessment by UNESCO and the World Resources Institute (WRI) underscores the scale of the problem, showing that 73 per cent of World Heritage properties face high exposure to water-related hazards, including drought, water stress, and riverine or coastal flooding (UNESCO 2025a).

Blue Papers 2025 (Vol. 4 No. 2), pp. 7–18
10.58981/bluepapers.2025.2.ed

Editorial

Direct impacts of climate change – and specifically water-system change – include structural damage and material decay caused by flooding, erosion and landslides; land loss and saltwater intrusion into aquifers from sea-level rise (e.g., in Everglades National Park, where drinking water supplies for nearby communities are at risk); and the destruction of terrestrial and marine heritage by wildfires and changing marine conditions (UNESCO 2025b). Indirect, cascading and systemic consequences that compromise the value, management and social context of heritage include both economic and non-economic losses. These include community displacement, reduced adaptive capacity and the loss of ecosystem services and materials needed to sustain specific practices and knowledge, such as the construction of traditional structures. They also affect traditional governance, cultural diversity, traditional knowledge systems, and archaeological evidence (UNFCCC 2024), potentially resulting in the degradation or loss of Outstanding Universal Value (OUV).

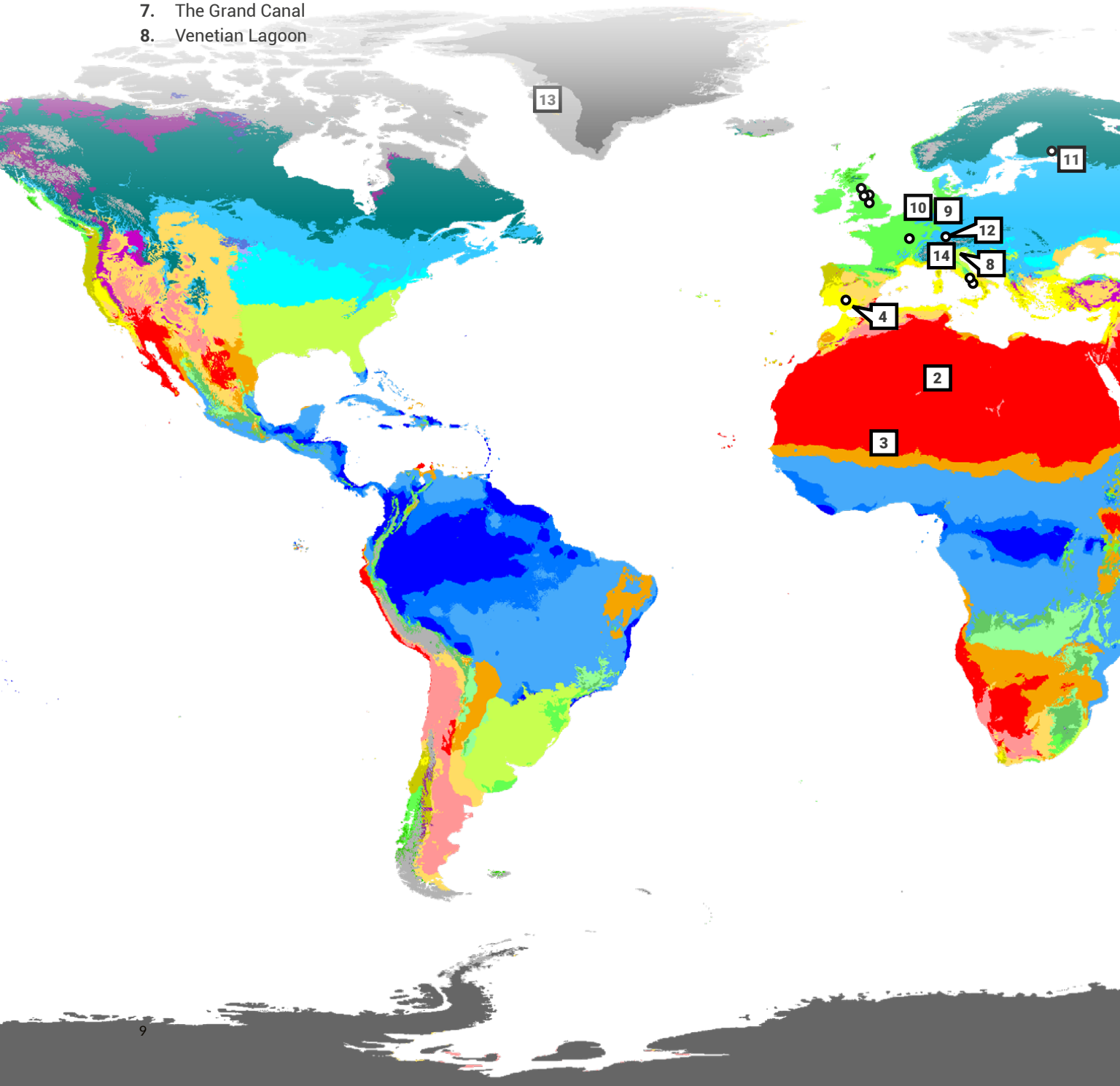
These challenges highlight the dual imperative of water management: safeguarding heritage sites shaped by water as sources of identity and inspiration for future generations, and protecting all heritage sites from water-related climate risks. Addressing these emerging threats requires sustainable approaches to water management and comprehensive strategies to support adaptation (Hein 2020; Mager 2024).

Sustainable water management is crucial for the preservation of World Heritage properties. Although water systems have historically been integral to many sites, this role has not always been fully recognized, leading in some cases to the loss of site-specific knowledge and to the introduction of unsustainable water management. Site managers, therefore, need to integrate water strategies into management plans. Recognizing heritage as a dynamic process influenced by social, economic and environmental factors is essential for sustainable development. However, UNESCO's *Policy Document on Climate Action for World Heritage* (2023), while emphasizing the importance of researching and documenting water management techniques to support climate science, does not explicitly refer to water management plans for individual properties.

As water-related climate variability intensifies, water management will become increasingly important for World Heritage properties. Further research, international collaboration and guidelines are needed to embed water strategies into site plans. A unified approach that bridges cultural and natural heritage is also necessary, given the deep interconnections between monument preservation and climate resilience.

This special issue of *Blue Papers* on "Water Management in World Heritage Properties at a Time of Climate Change" presents a global perspective on water heritage, bringing together 16 articles that explore World Heritage properties and a UNESCO Biosphere Reserve across diverse climatic zones. World Heritage properties are both highly vulnerable to climate change and vital sources of resilience. The contributions by heritage professionals and local custodians demonstrate that the preservation of these properties is not only a cultural concern but a fundamental component of sustainable climate adaptation (fig. 1).

1. Cultural Landscape of Bali Province: The Subak System as a Manifestation of the Tri Hita Karana Philosophy
2. Tassili n'Ajjer
3. Tomb of Askia
4. Sierra Nevada UNESCO Biosphere Reserve
5. Cultural Landscape of Honghe Hani Rice Terraces
6. Classical Gardens of Suzhou
7. The Grand Canal
8. Venetian Lagoon



9. Mines of Rammelsberg, Historic Town of Goslar and Upper Harz Water Management System
10. Seventeenth-Century Canal Ring Area of Amsterdam inside the Singelgracht
11. The Historic Center of St. Petersburg and Related Monuments
12. Water Management System of Augsburg
13. Ilulissat Icefjord
14. Prehistoric Pile Dwellings around the Alps
15. Selected UNESCO properties which include historic water mills across Europe (France, UK, Italy, Spain, Germany, Finland, Russia). Specific locations are marked with dots.

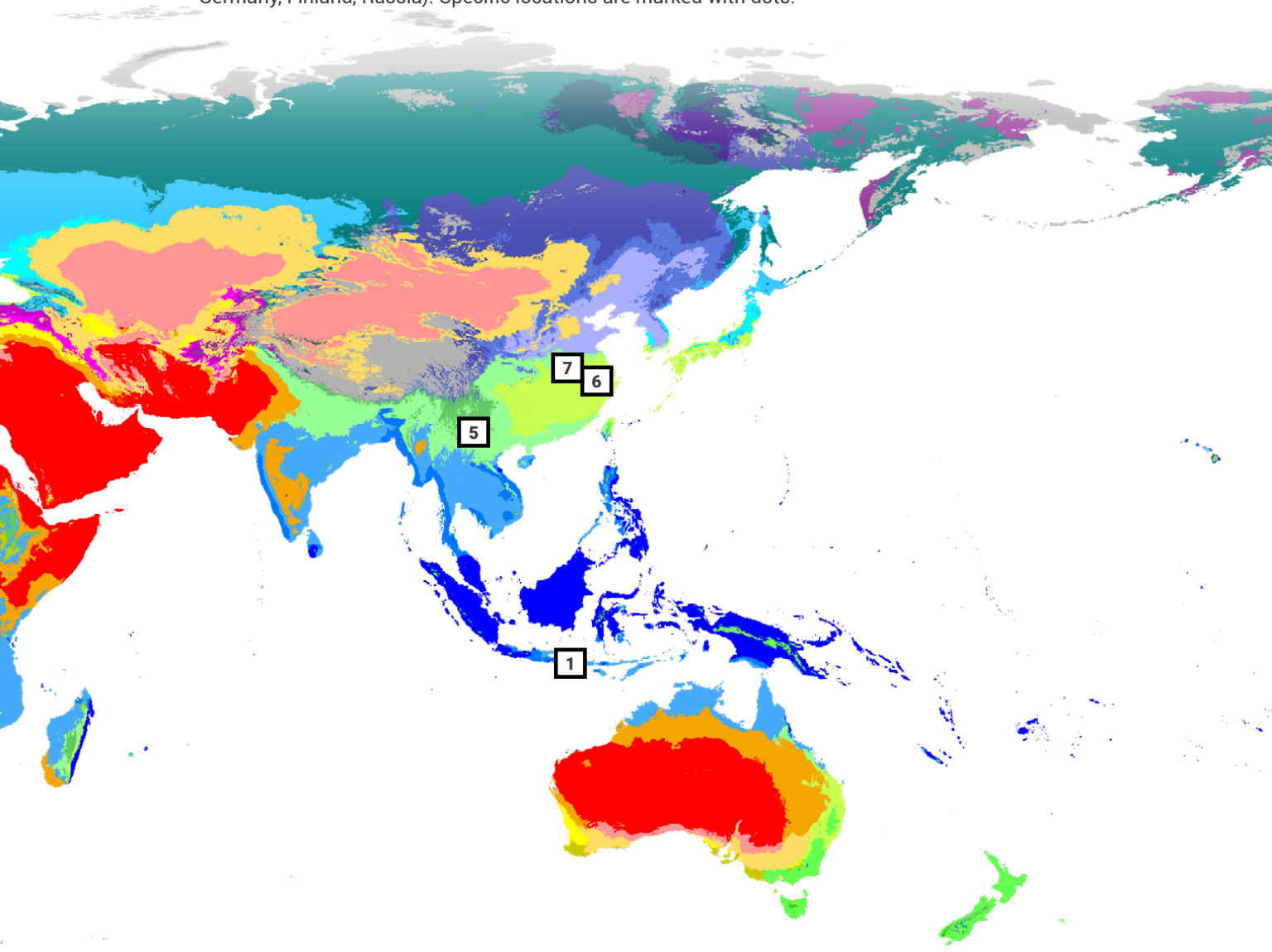


Fig. 1 All World Heritage properties and a UNESCO Biosphere Reserve that appear in this special issue are marked on the Köppen-Geiger Climate Classification Map, 1980–2016 (Authors: Beck, H.E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., & Wood, E. F. Source: Wikimedia Commons, CC BY-SA 4.0).

The impact of climate change on World Heritage properties has not been well reported or documented for a number of reasons, including reliance on self-reporting, lack of standardized monitoring methodologies and capacities, and the difficulty of attributing specific damage directly to climate change (UNESCO 2025b). Several articles gathered in this special issue of *Blue Papers* illustrate how climate change poses a direct threat to the World Heritage. **Bo Albrechtsen**'s case study on the *Ilulissat Icefjord* demonstrates how thawing permafrost both erases important archaeological evidence and threatens modern Inuit infrastructure. **Sergey Gorbatenko** reveals that for the *Historic Center of St. Petersburg and Related Monuments*, the existential threat of flooding is compounded by a lack of integrated governance and legal frameworks. Similarly, **Mamadukou Samaké**'s case study of the *Tomb of Askia* in Mali demonstrates how, in contexts of vulnerability, climate change acts as a threat multiplier, with flooding and desertification intrinsically linked to regional insecurity. **Amira Ghennaï** and **Said Madani** show how unprecedented rainfall is now destroying the prehistoric rock art of *Tassili n'Ajjer* that serves as a record of ancient climate shifts.

In the face of these threats, top-down governance models are proving inadequate, exposing a critical need for community-led and collaborative approaches. **Diana Rahman** demonstrates that centralized management is failing, and the future of the *Cultural Landscape of Bali Province* depends on genuine co-creation that empowers local communities as the primary agents of its adaptation to climate change. This governance challenge is equally clear in the analysis of the *Venetian Lagoon* by **Maria Chiara Tosi, Luca Velo, Michela Pace** and **Mette Juhl Jessen**, who explain a phase of administrative inertia and the pitfalls of singular technological solutions like the MoSE barriers. In response to such failures, **Tosi**, together with **Alessia Franzese** and **Mette Juhl Jessen**, presents the Wetland Contract for the Northern Lagoon of Venice as a practical model of participatory governance that fosters a "belonging community" to manage the lagoon as a commons. Similarly, **Ting Wang** argues that managing *Suzhou's Grand Canal* requires collaborative governance as much as technological monitoring to overcome jurisdictional fragmentation. A similar need for integrated governance is clear in **Manuela Armenat, Christian Bellak** and **Andreas Lange**'s analysis of the *Upper Harz Water Management System*, which shows that managing a "living" World Heritage property requires integrated governance to balance historic functions with modern climate and safety demands. This call for a paradigm shift is echoed in **Luis José García-Pulido**'s examination of Pampaneira, located in the *Sierra Nevada UNESCO Biosphere Reserve*, where a historical, community-managed hydraulic system proves to be an important bioclimatic regulator in adapting to aridification.

Ultimately, this issue reframes water heritage from a vulnerable asset into a source of essential knowledge for sustainability and climate resilience. **Maria Carmela Grano** shows how European watermills can be understood as dynamic infrastructures, emphasizing their potential for micro-hydropower and water regulation as catalysts for regenerative development. Similarly, **Christian Schaller** presents the *Water Management System of Augsburg* as a proven model in which a historical management plan successfully integrates heritage preservation with modern climate adaptation, offering a replicable blueprint for sustainable urban water governance. This view is expanded by **Cyril Dworsky** and **Barbara Fath**, who show how *Prehistoric Pile Dwellings* around the

Alps, tested for thousands of years, offer practical blueprints for modern climate-resistant construction amid rising sea levels. **Tianchen Dai** and **Carola Hein** examine the *Honghe Hani Rice Terraces*, noting that the future of this socio-ecological system depends on balancing the economic opportunities of modernization with the traditional community practices that sustain its ancient water system. **Yapeng Ou, Zhen Cai** and **Qingzhou Wu** find that the *Classical Gardens of Suzhou* have lost resilience due to their disconnection from the historic urban water network. The solution, they argue, is not just maintaining the gardens, but re-integrating them with the water network on which they depend. Completing this picture, **Carola Hein, Regina Klinger, Christel Voncken, Prapti Gupta** and **Vincent Baptist** argue that for Amsterdam's decaying quay walls, overcoming sectoral fragmentation through shared heritage narratives is key to transforming this historic infrastructure into a foundation for climate-adaptive and culturally continuous urban design.

Together, these contributions show that protecting water heritage is not about preserving a static past, but about sustaining dynamic systems of knowledge, practice and ecology that are essential for navigating climate uncertainty. They offer insights into pressing challenges and propose pathways to solutions for World Heritage properties and beyond. The lessons from these diverse locations converge on a single imperative: The path to resilience lies in integrating historical wisdom with collaborative, adaptive governance.

	Name	Location		Climate
1	Cultural Landscape of Bali Province: The Subak System as a Manifestation of the Tri Hita Karana Philosophy	Indonesia		(Af) Tropical Rainforest Climate)
2	Tassili n'Ajjer	Algeria		(BWh) Hot desert climate
3	Tomb of Askia	Mali		(BWh) Hot desert climate
4	Sierra Nevada UNESCO Biosphere Reserve	Spain		(Csa) Mediterranean Climate
5	The Cultural Landscape of Honghe Hani Rice Terraces	China		(Cwa) Humid subtropical climate
6	Classical Gardens of Suzhou	China		(Cfa) Humid Subtropical Climate

Water-Related Climate Change Challenges and Other Challenges	Recommendations
• Water scarcity and shifting rainfall patterns due to climate change. • Competition for water between agriculture and tourism. • Other: Rapid tourism development and land conversion; disconnect between top-down heritage management and local community needs; restrictive World Heritage regulations hindering adaptation.	• Integrate co-creation and local knowledge into heritage and water management strategies. • Support community-led adaptive practices, such as rotational irrigation and crop diversification. • Align conservation goals with local economic incentives and sustainable agriculture.
• Unprecedented intense rainfall and flash flooding. • Increased humidity and microclimatic changes degrading rock art. • Other: Vulnerability of rock surfaces and pigments; malpractices by tourists; need for updated legal frameworks and integrated conservation strategies.	• Establish comprehensive climate and condition monitoring systems for the site. • Strengthen legal frameworks to explicitly address climate risks to heritage. • Integrate community engagement and traditional knowledge into conservation planning.
• Intense rainfall and catastrophic flooding of the Niger River. • Desertification and drought reducing water availability. • Other: Regional insecurity and armed conflict; Lack of emergency plans, funding, and reduced availability of traditional building materials.	• Provide flexible funding for disaster preparedness and heritage-specific climate models. • Support local initiatives (e.g., building water collectors, community awareness). • Recognize that cultural heritage requires a higher level of protection than ordinary buildings.
• Reduced rainfall and snowfall, leading to decreased water availability. • Increased evaporation and rising temperatures. • Vanishing springs and reduced river flows. • Other: Overexploitation of water by commercial agriculture; breakdown of traditional management systems; abandonment of agricultural terraces; pressure from tourism.	• Promote sustainable water management in heritage sites to mitigate climate change effects. • Implement active policies to support local actors in safeguarding water resources and maintaining system connectivity. • Learn from and apply historical knowledge of resilient, low-impact water systems.
• Increased frequency of droughts and floods. • Damage to irrigation canals and water conservancy facilities. • Degradation of the water-retaining forests. • Other: Rural outmigration and decline of traditional farming; pressure from tourism infrastructure; disruption of social structures and traditional water management practices.	• Strengthen climate resilience by reinforcing irrigation infrastructure and integrating it with community life. • Establish an ecological compensation budget to support farmers and promote sustainable practices like rice-fish co-cropping. • Provide funding and support for youth entrepreneurship in heritage-related sectors.
• Increased flooding and waterlogging from heavy storms. • Degradation of water quality and aquatic ecology. • Disconnection from the historic urban water system reducing resilience. • Other: Fragmented “isolated management” between garden and water system authorities; high costs of artificial water purification; loss of waterways and groundwater connectivity from urban development.	• Treat the gardens and the historic urban water system as a single organism and restore their symbiotic relationship holistically. • Ensure connectivity between gardens, rivers, lakes and wetlands to strengthen ecological exchange and flood regulation.

	Name	Location		Climate
7	The Grand Canal	China		(Cfa) Humid Subtropical Climate
8	Venice and its Lagoon	Italy		(Cfa) Humid subtropical climate
9	Mines of Rammelsberg, Historic Town of Goslar and Upper Harz Water Management System	Germany		(Cfb) Oceanic climate
10	Seventeenth-Century Canal Ring Area of Amsterdam inside the Singelgracht	Netherlands		(Cfb) Oceanic climate
11	The Historic Center of St. Petersburg and Related Monuments	Russia		(Dfb) Humid continental climate

Water-Related Climate Change Challenges and Other Challenges	Recommendations
• Riverbank erosion and degradation from storms, typhoons and floods. • Changes in precipitation affecting water levels and flows. • Slow-onset impacts like weathering and foundation settlement. • Other: Fragmented "Nine Dragons" governance across multiple departments; balancing active transport use with heritage preservation; integrating new monitoring technologies into management; lack of biodiversity monitoring.	• Collaborate with private enterprise to adapt and localize monitoring technologies. • Expand the monitoring platform to include biodiversity conservation. • Integrate technical platforms with management reforms to create a comprehensive, multi-stakeholder governance model.
• Rising sea levels and intensifying storm surges causing frequent flooding (acqua alta). • Coastal erosion and degradation of salt marshes. • Ecological disruption and biodiversity loss. • Other: Fragmented and overlapping governance; administrative inertia; balancing mass tourism and depopulation; social fragility; conflicts between large-scale technical solutions (e.g., MoSE barriers) and ecological/community needs.	• Establish unified, adaptive governance at a metropolitan level to harmonize regulations and projects. • Prioritize collaborative, bottom-up approaches in management. • Recognize the dynamic, amphibious nature of the lagoon as central to its heritage.
• Increased water scarcity affecting drinking water supply. • Increased risk of flooding and need for enhanced flood protection. • Increased sediment input and ecological pressure on water bodies from extreme weather events. • Other: Balancing hydraulic engineering and safety requirements with monument protection; financial constraints; managing multiple uses (tourism, energy, ecology) while preserving OUV.	• Maintain constant, integrated management and communication between all stakeholders to find future-oriented compromises. • Clearly define the non-negotiable features of the site to preserve its OUV while allowing for necessary adaptation.
• Sea-level rise, salinization, and extreme weather threaten the city's livability and the integrity of the World Heritage property. • Other: Lack of a shared value system amongst practitioners; Lack of standardized methods and a common vocabulary around heritage; Fragmented, difficult to access historical data.	• Use heritage as a resource for sustainable, climate-adapted and circular design. • Make heritage data accessible and visual. • Use local heritage narratives for context.
• Sea-level rise and more frequent storm surge floods. • Projected expansion of flood zones that threatens coastal heritage. • Other: Rapid urbanization, high-rise construction, and land reclamation damaging the cultural landscape; Lack of a management plan, buffer zones, and weak legal protection for the World Heritage property.	• Strengthen the Climate Adaptation Plan to explicitly protect cultural heritage. • Revise the Law on Protection Zones to include World Heritage concerns. • Establish buffer zones and create a management plan that addresses climate risks.

	Name	Location		Climate
12	Water Management System of Augsburg	Germany		(Dfb) Warm-summer humid continental climate
13	Ilulissat Icefjord	Greenland		(ET) Tundra climate
14	Prehistoric Pile Dwellings around the Alps	Switzerland, Germany, France, Italy, Austria, Slovenia		Diverse
15	Selected UNESCO sites which include historic water mills across Europe (France, UK, Italy, Spain, Germany, Finland, Russia)			Diverse

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Water-Related Climate Change Challenges and Other Challenges	Recommendations
• Water scarcity, flooding from heavy precipitation and high river levels, and ecological stress on the Lech River. • Other: Balancing heritage preservation with urban development and modern infrastructure needs; managing stress from tourism; coordinating multiple stakeholders with diverse interests.	• Leverage historical water heritage for public awareness and cross-border dialogue. • Scale up local innovative solutions for global application.
• Coastal erosion from oceanic forces and permafrost thaw, leading to the loss of the Sermermiut archaeological site and cultural heritage. • Other: Balancing urban expansion and local community needs with World Heritage protection restrictions; managing increased tourism pressure; securing long-term funding for conservation.	• Integrate local Inuit knowledge with scientific research in management. • Ensure local community involvement in decision-making and equitable benefit-sharing. • Secure sustained government funding for preservation.
• Flooding and rising water levels that threaten submerged cultural heritage. • Increased runoff and soil surface sealing in modern settlements. • Other: Lack of ratification of the 2001 UNESCO Convention (Austria, Germany); Need for specialized expertise in underwater archaeology and conservation.	• Ratify and implement the 2001 UNESCO Convention on Underwater Cultural Heritage. • Establish permanent university programs for underwater/wetland archaeology. • Fund interdisciplinary research (archaeology, hydrology, climate science).
• Reduced river flows, sedimentation, floods, and droughts. Hydro-geological risks and slope instability. • Other: Tourism pressure and ecological conflicts (e.g., fish migration); Fragmented governance and undervaluation of non-UNESCO mills.	• Integrate mills into Nature-Based Solutions for water retention and flood regulation. • Develop interoperable digital platforms for hydrological, cultural, and energy data. • Empower community-based governance and support miller associations.

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Water Management in World Heritage Properties at a Time of Climate Change

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The Ilulissat Icefjord: Local Stewardship and Global Responsibility in a Changing Climate

Bo Albrechtsen

Abstract
The Sermermiut archaeological site at the Ilulissat Icefjord contains cultural remnants from three Inuit cultures spanning nearly 4000 years. This unique site is now under threat from climate change and oceanic forces. The permafrost layer, which has long supported the site, including the cultural-historical ruins located on it, is thawing, causing destabilization of the ground and severe erosion of the slopes. A fieldwork initiative conducted in the summer of 2024 by collaborative teams from Greenland's cultural and heritage institutions, in partnership with international technical assistance programs, studied these impacts using advanced monitoring techniques and community involvement, setting an example for adaptive management strategies that align with the UN 2030 Agenda. This article highlights how climate change is affecting both cultural heritage and contemporary life at the Ilulissat Icefjord, and emphasizes the importance of combining scientific research, responsible site management and local community engagement to safeguard this UNESCO World Heritage property. Through adaptive management, integration of local knowledge and strong collaboration across sectors, the Ilulissat Icefjord can remain both a globally significant natural site and a resilient, living Arctic community in a changing climate.

KEYWORDS

UNESCO World Heritage
Sermermiut
permafrost
erosion
cultural heritage

WATER ICONS

CLIMATE

A B C D **E**

ET: Tundra climate

Policy Recommendations

- Integrate local knowledge: Develop management strategies that combine traditional Inuit ecological expertise with modern scientific methodologies.
- Involve the local population in decision-making processes and address their concerns about the practical implications of living near a UNESCO property.
- Secure long-term funding and commitment from local and national governments to ensure the Icefjord's sustainable management and preservation.
- Promote equitable benefits: Ensure that the site's global significance translates into meaningful economic and social opportunities for the local community.

< Fig. 1 This green plain within the Ilulissat UNESCO property holds 4,000 years of Inuit history. Now, erosion is accelerating as the permafrost beneath it melts (Source: Bo Albrechtsen, 2025).

Introduction

The Ilulissat Icefjord, a UNESCO World Heritage property, spans a total area of 4,024 km² on the west coast of Greenland and is one of the most remarkable natural heritage sites in the world. Recognized by UNESCO in 2004, this vast protected area includes over 3,000 km³ of inland ice and glaciers, alongside coastal and marine zones. Its immense scale, along with climate change, poses significant challenges for effective management and conservation.

Within the World Heritage property, the Sermermiut archaeological site holds invaluable remnants of three distinct Inuit cultures spanning nearly four thousand years, including remains of Inuit housing, artifacts and tools. The site appears today as a grass-covered meadow with the scattered square outlines of ancient house ruins, beneath which lie the layered remains of earlier Inuit cultures preserved in the earth. This rich cultural heritage, situated at the shoreline, faces escalating threats due to oceanic forces and the pervasive impacts of climate change. The cultural layers of Sermermiut rest atop permafrost, which historically provided a stable foundation for the site. However, as global temperatures rise, particularly in the Arctic, where warming is amplified due to feedback mechanisms such as reduced sea ice, changes in cloud cover and increased atmospheric heat transport (Previdi et al. 2021), this frozen foundation is thawing (fig. 1), leading to catastrophic soil erosion and increased site vulnerability.

The effects of climate change extend beyond the archaeological remnants and into the nearby town of Ilulissat, located just 2 km from Sermermiut, which serves as both the physical gateway and administrative hub for this World Heritage property. As Greenland's main tourist destination and a vibrant modern Inuit community, Ilulissat plays a key role in facilitating access to and interpretation and stewardship of the Icefjord, while facing its own climate-related challenges. Here, the thawing of permafrost layers disrupts daily life, causing significant infrastructural challenges. Houses once secure on frozen ground are now losing their stability as the thawing permafrost undermines their foundations, leading to tilting structures that eventually become uninhabitable (Harmsen et al. 2018; fig. 2). Asphalt roads develop cracks, bumps and potholes, creating hazards for both pedestrians and vehicles. These visible and tangible impacts highlight the broader societal and cultural implications of a warming Arctic, underscoring the urgent need for integrated conservation and adaptation strategies that address both heritage preservation and community resilience.

Historic Continuity: Connecting Past and Present

The archaeological site of Sermermiut provides a unique window into the entirety of Greenland's Inuit history, offering access to cultural material from all main periods of settlement. Within its approximately 2.5-meter-thick midden, stratified layers reveal evidence from three distinct cultural periods. The two deepest and oldest layers belong to the prehistoric Saqqaq and Dorset cultures, named after their original discovery sites. The Saqqaq culture inhabited Greenland from around 2400 BCE to approximately 800 BCE, succeeded by the Dorset culture, which arrived from the west around 600 BCE and persisted until approximately 0 CE.

The next wave of settlement occurred in southern Greenland, where Norse and Scandinavian settlers, primarily from today's Iceland and Norway, established themselves around 1000 CE. Although the Norse are believed to have sailed

^ Fig. 2 The Ilulissat Cultural History Museum is sinking as thawing permafrost undermines its foundations (Source: Bo Albrechtsen, 2025).

past the uninhabited Sermermiut, no evidence of permanent Norse settlement has been found this far north. It was the Thule culture, the ancestors of the modern Inuit people who migrated from Alaska arriving in the thirteenth century, that established a lasting presence at Sermermiut. From approximately 1300 to 1850, the site was continuously inhabited, at least seasonally, as the semi-nomadic Inuit moved in rhythm with the region's hunting and wildlife patterns. This lifestyle was structured around the annual cycle of subsistence activities, with families relocating according to the seasonal availability of game. During autumn, people would travel inland to temporary camps to hunt caribou, while the winter months were spent in more permanent coastal dwellings, such as those at Sermermiut, where access to marine resources like seals was critical. This pattern of seasonal movement remained central to Inuit life until the mid-colonial period, when the introduction of institutions like schools, churches and trading posts began anchoring families to year-round settlements, gradually reducing their mobility.

By 1850, the last inhabitants of Sermermiut had relocated to the Danish trading post of Jakobshavn, the present-day town of Ilulissat. Such trading posts included not only merchants but also churches, schools and other institutions, and offered services and opportunities that increasingly drew people away from traditional sites like Sermermiut. Since then, and likely even before its abandonment, erosion along the coastline has revealed remnants of the site's long history. While much of this material has

been claimed by the sea, some artifacts have been collected by passersby, providing invaluable insights into the lives of Sermermiut's former residents.

While the collection at Ilulissat's Cultural History Museum predominantly comprises objects from archaeological excavations, it is supplemented by these chance finds recovered from the shoreline next to the cultural site. Their preservation makes the artifacts from the two oldest cultures, Saqqaq and Dorset, particularly remarkable. Typically, only the stone blades and tools from these cultures are found, as organic materials, such as handles and shafts, have long decayed in other regions. This is largely due to differing preservation conditions. Elsewhere, organic components have been exposed to oxygen, moisture and seasonal temperature fluctuations, often because they were buried under only a thin protective layer of soil. Without the stable, low-oxygen environments found in permafrost or deep, compact layers of earth, organic materials tend to decompose rapidly, leaving behind only the more durable stone elements. However, in the frozen layers of Sermermiut, these organic components remain intact, offering an unprecedented glimpse into the craftsmanship and daily life of these early Arctic cultures. The permafrost that preserved these artifacts has acted as a natural freezer, keeping organic materials intact for thousands of years. Despite this, the majority of the museum's archaeological collection comprises artifacts from the more recent Thule culture. This predominance reflects the larger and more substantial nature of Thule settlements, which were more extensive and complex than those of their predecessors.

The museum serves as a bridge between past and present, linking the artifacts of the Sermermiut settlement to the modern inhabitants of Ilulissat. Descendants of Sermermiut's last residents now walk the town's streets, attend its schools, and, as part of their education, view their ancestors' tools and household items with curiosity and pride. But they are not only students, many are also inspectors, leaders and directors at key institutions across the town, continuing to shape Ilulissat's future while staying rooted in its past.

In an era of accelerating globalization, where the identity of smaller communities can be easily diluted in the fast pace of digital media, the museum plays an essential role in maintaining cultural continuity. By connecting younger generations with their heritage, it strengthens a sense of belonging and pride in local history, helping to ensure that the knowledge, traditions and values of this Arctic community are not lost, but carried forward.

Climate Change: Local and Global Implications

In Greenland, the impacts of climate change are evident in rising air and sea temperatures, as well as shorter periods of sea ice cover (Selyuzhenok et al. 2020). Popularly, the effects of climate change can be linked to “moving south”[1] within the country, ushering in a slightly warmer climate where winter ice may no longer form reliably on the sea. While many of the same fish, marine mammals and land animals remain, their abundance and distribution are shifting, altering the ecological balance.

1. As climate change progresses, regions are experiencing weather patterns that historically occurred hundreds of miles closer to the equator. This means cooler areas are becoming warmer and experiencing the temperature ranges, precipitation patterns, and seasonal cycles that were once typical of locations further south.

^ Fig. 3 Sermermiut East, 2023: The cultural site of Sermermiut, a former winter settlement inhabited by Inuit for millennia (Source: Bo Albrechtsen, 2025).

Inuit cultures are renowned for their remarkable adaptability to changing circumstances. Even as Greenland draws journalists and filmmakers eager to document the visible effects of climate change, it is rare to hear residents speak negatively about the issue. This may be because climate change is not generally perceived as an existential threat within the Greenlandic population. People here have adapted to environmental shifts for millennia and have learned to respond with resilience and pragmatism to major changes. Today is no exception as many continue to adjust to the evolving conditions without overt complaint, drawing on long-standing knowledge and flexibility.

Nevertheless, some challenges are undeniable. As hunter and fisherman J. Kristensen explained to me in September 2023, capturing the essence of the changes being experienced, the absence of reliable winter ice is akin to the collapse of a bridge, cutting off access to traditional hunting grounds. Additionally, the unpredictable ice conditions have led to accidents, where previously reliable sea ice proves too thin for safe travel.

Hence, locally, the thawing of permafrost compromises the preservation of archaeological artifacts, destabilizing the frozen soil that has protected them for thousands of years. Entire ruins of winter houses (fig. 3) from the Thule culture, dating from approximately 1300 to 1850, have collapsed into the sea and are now lost forever. Additionally, modern infrastructure and buildings are increasingly threatened by retreating permafrost, leading to structural instability.

The thawing of permafrost presents challenges that extend far beyond Greenland, with profound implications globally. Alongside the artifacts preserved in the permafrost lie vast stores of organic material. As permafrost thaws and this material decomposes, it releases significant quantities of carbon dioxide and methane, potent greenhouse gases, into the atmosphere, exacerbating climate change (Elberling et al. 2010; Harmsen et al. 2018).

However, despite these significant climatic shifts, the values that underpin Ilulissat Icefjord's inclusion on the World Heritage List and its Outstanding Universal Value (OUV) remain intact. The property continues to stand as an outstanding example of important stages in the earth's history, encompassing the record of life, significant ongoing geological processes and remarkable geomorphological features (UNESCO 2004). These enduring qualities ensure that Ilulissat Icefjord remains a site of unparalleled natural and cultural heritage, resilient in its ability to inspire global recognition and conservation efforts.

While climate change poses threats to the management of the site, it compounds social and economic factors. One pressing challenge lies at the interface between the protected area and human habitation. Ilulissat is the largest settlement near the UNESCO World Heritage property and is located within its designated buffer zone. While there is also a smaller settlement nearby, Ilulissat is experiencing the greatest pressure for urban expansion due to its growing population and increasing tourism. However, the ability to expand Ilulissat's boundaries is constrained by the protected status of the site, frustrating local residents and politicians, who perceive the restriction as unnecessary. At the same time, World Heritage designation status implies limited human activity within the designated area, with only local hunters and fishermen possessing the skills and knowledge necessary to navigate the challenging conditions of the icefjord. With the increase in tourism in recent years, some of these individuals have be-

gun offering guided experiences, such as dog sledding trips, allowing a select number of visitors to venture into the icefjord. However, the majority of tourists experience the area from its periphery, viewing its grandeur from designated viewpoints or trails. The core protected area's limited accessibility further exacerbates local discontent.

In the face of the challenges involved in managing this unique site, collaboration between local authorities, scientists and international stakeholders is crucial. The collaborative effort can be further strengthened by leveraging modern technologies, such as satellite monitoring and climate modeling, alongside traditional ecological knowledge to ensure that the Ilulissat Icefjord continues to inspire and educate future generations while maintaining its extraordinary natural and cultural heritage.

Fieldwork in 2024: Monitoring and Community Engagement

As the impacts of climate change on the Ilulissat Icefjord continue to unfold, my colleagues and I remain steadfast in our commitment to protecting this unique World Heritage property. Recognizing the magnitude of the challenges ahead, we prioritize an adaptive management approach informed by the latest scientific research and local knowledge.

As erosion and the potential loss of objects to the sea become increasingly urgent concerns, multiple strategies can be employed to address these issues. One approach is to prioritize documentation, such as through archaeological excavation, to rescue and document artifacts within their cultural context. In this context, in the summer of 2024, a collaborative fieldwork initiative spearheaded by the World Heritage Office of Ilulissat, the National Museum of Greenland, and the International Technical Assistance Program under the US Department of the Interior sought to assess the impact of climate change on Greenland's cultural heritage. The project focused on understanding the long-term consequences of climate change, particularly the tangible effects of permafrost retreat. A range of scientific and community engagement strategies were employed (Bonsell et al. 2025):

1. Soil and vegetation survey: Researchers conducted a comprehensive analysis of the soil and vegetation types at the site, documenting the depth of the permafrost and establishing baseline data for future comparisons.
2. Frost tube installation: To monitor year-round changes in the frozen ground, frost tubes were installed, enabling local staff to track permafrost movement and better understand seasonal variations over a year.
3. Temperature monitoring: Temperature loggers were embedded in drilled holes along the exposed erosion face to gather continuous soil temperature data, which will be analyzed in 2025 to provide insights into subsurface warming trends.
4. Citizen science station: A unique public engagement initiative was launched to raise awareness and gather data. Visitors were invited to measure the depth of frozen ground in wet tundra, which fluctuated in response to the warming and cooling of seasons. A measuring stick and QR code system allowed for easy data submission, fostering greater interest in climate change's effects on heritage sites. This engagement with the local community is particularly important. By incorporating traditional knowledge into our management practices and fostering public participation through citizen science initiatives, we aim to create a resilient

and inclusive framework for preserving the site's universal values. Additionally, we are exploring opportunities to increase public awareness of the Icefjord's role as a barometer of global climate change, enhancing its importance not only as a local heritage site but also as a symbol of the interconnectedness of our planet.

Over the years, the Ilulissat Icefjord Office has collaborated with a wide range of scientists, contributing to a diverse portfolio of research projects. These collaborations have played a key role in advancing scientific understanding of the Ilulissat Icefjord World Heritage property and its surrounding environment, thereby supporting evidence-based decision-making in conservation planning. This summer's fieldwork focuses on the extent and impact of permafrost thaw across the area. The results will feed directly into the Icefjord Office's ongoing management work and strategic assessments. Findings will also support partner institutions such as the National Museum of Greenland in prioritizing conservation efforts at culturally significant sites, including Sermermiut.

In addition to scientific collaboration, the Icefjord Office maintains close and continuous dialogue with local fishers and hunters. These long-standing relationships ensure that the Office stays attuned to current developments within these key livelihoods, and that local knowledge and perspectives are integrated into daily management practices.

As local site managers, the staff of the Icefjord Office are committed to facilitating and applying both scientific and traditional knowledge to strengthen the long-term protection of this unique and vulnerable Arctic heritage landscape. Future efforts will focus on expanding monitoring systems to better understand the dynamics of permafrost retreat and coastal erosion. Collaborations with academic institutions and international research programs will also play a crucial role in refining our strategies, ensuring that decisions are grounded in robust data and cutting-edge methodologies. For example, ongoing partnerships with the National Museum of Greenland and the US Department of the Interior are helping us explore innovative conservation techniques, such as advanced documentation technologies and mitigating erosion through planting or building protective barriers.

Conclusion

The Ilulissat Icefjord exemplifies both the challenges and opportunities climate change poses for World Heritage properties. While the accelerating thaw of permafrost in Greenland and the increasing frequency of erosion events highlight the fragility of this unique environment, these events also underscore the urgent need for innovative, science-based solutions to better protect the Ilulissat Icefjord site.

The managers at the local Icefjord Office are not passive observers of these changes. In our collaborations with leading researchers and institutions, the my colleagues and I are developing actionable strategies that prioritize both conservation and adaptation. By integrating traditional ecological knowledge with advanced scientific methods, we strive to protect the Icefjord's extraordinary natural and cultural heritage while supporting the resilience of the local community.

This proactive approach ensures that the Ilulissat Icefjord remains a beacon of Arctic heritage, capable of inspiring future generations while contributing valuable insights to global discussions on climate change and cultural preser-

vation. The challenges are significant, but with determination, collaboration and innovation, we are confident in our ability to address them.

At the same time, effective management of the Ilulissat Icefjord requires policies that prioritize local knowledge while addressing the unique challenges of maintaining a UNESCO World Heritage property within a living community. Recognizing the value of traditional Inuit ecological knowledge is essential for developing strategies that are both sustainable and culturally appropriate. This local expertise provides invaluable insights into the dynamic environment of the Icefjord, complementing scientific research and enhancing adaptive management approaches.

Equally important is a genuine responsiveness to the experiences and perspectives of the local population, who live near the protected area. The restrictions and obligations associated with managing a UNESCO site can sometimes feel burdensome, particularly when they limit urban development or traditional practices. Policymakers must ensure that the benefits of World Heritage designation, including global recognition and increased tourism, are balanced by tangible improvements in local living conditions and opportunities.

To achieve this, strong political support is required at both the municipal and national levels. Local and national leaders must work together to secure adequate funding for conservation and management efforts. This includes financing for infrastructure improvements, scientific research and community engagement programs. Economic investment in sustainable tourism initiatives and local capacity-building will not only help preserve the site but also foster a sense of shared stewardship among residents.

By fostering a collaborative, well-funded, and inclusive approach, we can ensure the Ilulissat Icefjord continues to thrive as both a natural wonder and a living, culturally vibrant community.

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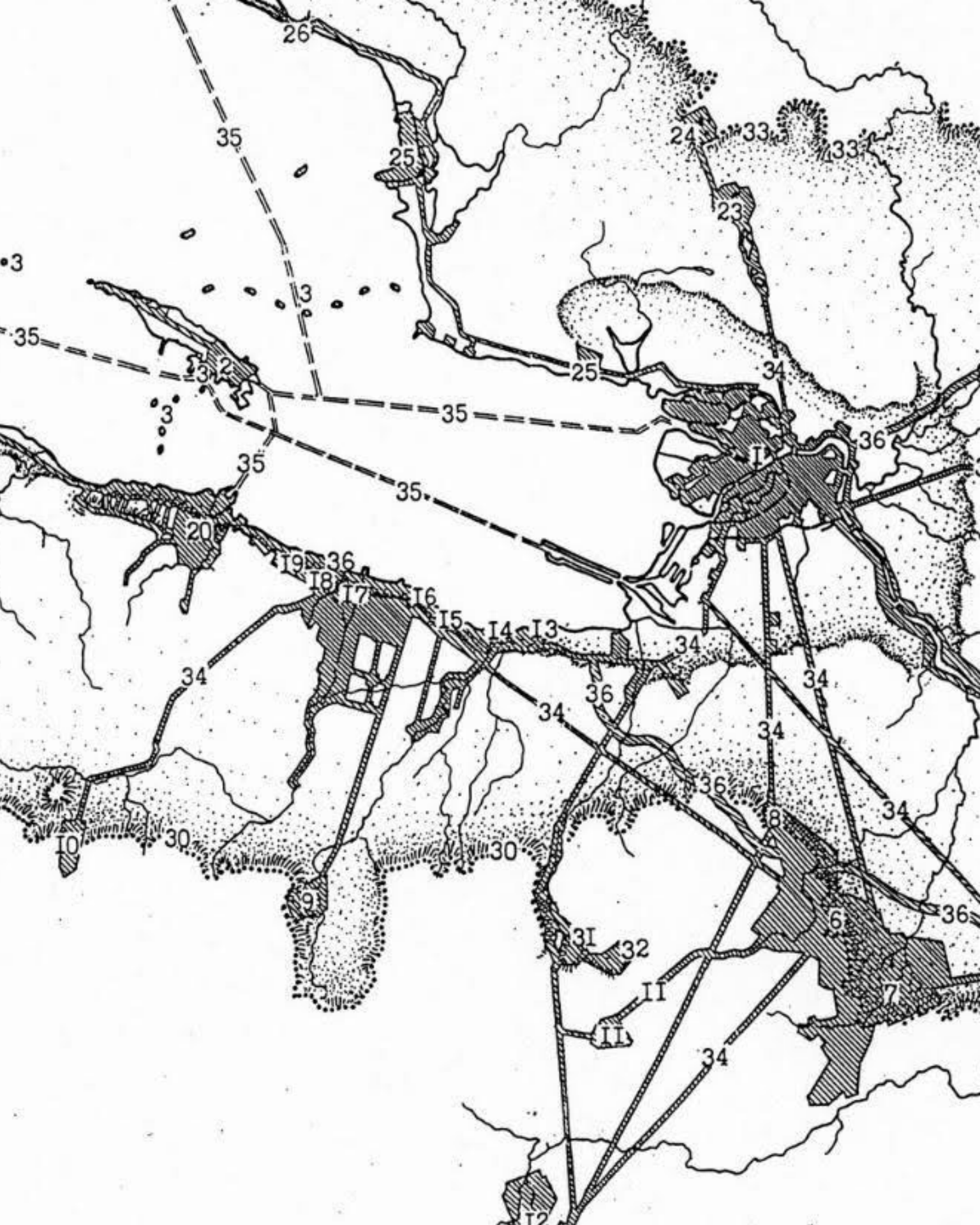
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The Water Spaces of St. Petersburg and its World Heritage: Climate Change and Other Threats

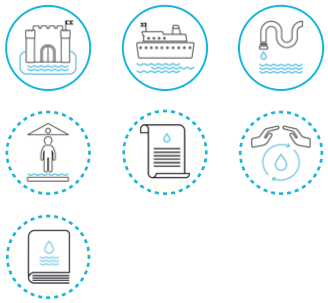
Sergey Gorbatenko

Abstract
St. Petersburg and its surrounding areas have been shaped by their relationship with water. Following the example of Amsterdam, city founder Peter the Great sought to supplement the Neva River Delta with numerous canals. He also aimed to make the new Russian capital the country's primary port and trade center by shifting it toward the open sea, which led to the establishment of the port city of Kronstadt on Kotlin Island. Today, the historic center of St. Petersburg, including the Neva water spaces and the Kronstadt forts and harbors on these islands, is listed on UNESCO's World Heritage List, comprising 116 individual cultural heritage sites. However, with the intensifying impacts of climate change, the property is at risk of flooding. Specialists' calculations have made it possible to make accurate predictions and propose measures to protect the city from such threats. The outcomes were incorporated into St. Petersburg's Regional Climate Change Adaptation Plan; however, the document pays little attention to safeguarding cultural heritage. At the same time, rapid urbanization poses just as serious a threat as climate change to St. Petersburg and its surrounding areas, and for many years has brought harm to the "Historic Centre of St. Petersburg and Related Groups of Monuments."

KEYWORDS

UNESCO World Heritage
climate change
flooding
cultural landscape
urban development

WATER ICONS



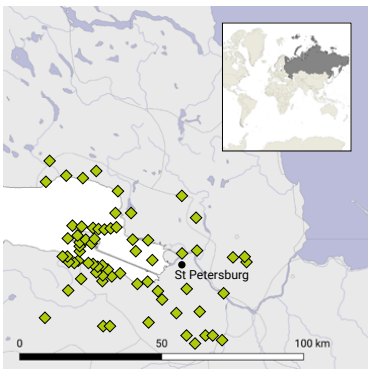
CLIMATE

A B C **D** E

Dfb: Humid continental climate

Policy Recommendations

- Strengthen St. Petersburg's Regional Climate Change Adaptation Plan by placing greater emphasis on protecting cultural heritage sites, which aligns with scientific forecasts of flooding and sea level rise.
- Revise the Law of St. Petersburg on Protection Zones to explicitly address World Heritage concerns and ensure legal protection for vulnerable cultural assets.
- Establish buffer zones and adopt a World Heritage property management plan that incorporates future climate risks.



< Fig. 1 Fragment of the map of the World Heritage property, Historic Centre of St. Petersburg and Related Groups of Monuments, shows the Gulf of Finland, the Neva Bay and the Neva River (Source: Boris Nikolashchenko, 1990).

St. Petersburg: City of Water

Water is fundamental to the Historic Centre of St. Petersburg and Related Groups of Monuments World Heritage property. The city, founded in 1703 by Peter the Great at the mouth of the Neva River, was conceived as "New Amsterdam" and "New Venice." It stretches along the powerful waterway, which feeds numerous ducts of the Neva Delta and canals created in the eighteenth century. Together with the landforms, water systems determine the character of the St. Petersburg urban agglomeration. The Neva River connects the Gulf of Finland and its narrow eastern part, the Neva Bay, separated by Kotlin Island, with the largest lake in Europe, Lake Ladoga. The central part of the Neva water area within the delta forms the main city space – a vast visual pool that encompasses the historic center, providing compositional integrity to the city and a unique unity to its image (fig. 2). This space includes key architectural ensembles such as the Peter and Paul Fortress, the buildings of the Palace Embankment (including the Winter Palace), the Admiralty, Senate Square, the Stock Exchange and University Embankment on Vasilievsky Island.

The "Historic Centre of St. Petersburg and Related Groups of Monuments" World Heritage property, encompasses a vast historic agglomeration. It includes 36 major components, which are further divided into several elements, comprising a total of 116 individual heritage sites. Many are physically connected to water, situated along shorelines or on islands (figs. 1 and 3).

The 1990 nomination emphasized the importance of St. Petersburg's water system, highlighting the way the city's landscape geography, with its vast water area, flat islands, and complex estuary, shaped an unusual urban structure. The Neva River and its network of waterways were described as an extension of the city's squares, creating an exceptional spatial scale and visual richness that significantly contributes to the site's Outstanding Universal Value (OUV) (UNESCO World Heritage Centre 1990; 2015).

At the same time, ICOMOS, as the advisory body in the nomination process, sounded an alarm:

> Leningrad[1] is now a city of nearly 5 million inhabitants and that it covers 200 square kilometers. The existence of a major industrial complex – the largest in the USSR – with its steel, petrochemical and chemical factories poses the difficult problem of the harmonization of development and safeguarding policies. The delimitation of the historic area annexed to the nomination takes major elements of the architectural heritage into account, but not the environment (ICOMOS 1990).

Since then, the property has faced increasing pressure from two major threats: flooding associated with climate change and rapid urban development. Rising sea levels and storm surges pose a threat to the low-lying areas of the site, while construction projects and inadequate regulation compromise the cultural landscape's visual and spatial integrity. Current heritage management and climate adaptation frameworks do not adequately address these threats. Despite nearly 35 years having passed since the city and surrounding areas attained World Heritage status, no management plan has yet been developed. The components and individual heritage sites are located within different adminis-

1. Leningrad was the name of St. Petersburg from 1924 to 1991, during the Soviet period. The city reverted to its original name following a public referendum in 1991.

^ Fig. 2 Main City Space of St. Petersburg (Source: Sergey Gorbatenko, 2008).

trative units of the Russian Federation, specifically the city of St. Petersburg and the Leningrad Region (Leningrad Oblast), which creates additional challenges in organizing the management of the property.

St. Petersburg Under Threat of Climate Change

Throughout the twenty-first century, annual increases of the sea level in the eastern part of the Gulf of Finland have reached approximately 4 mm each year. One area particularly vulnerable to this phenomenon is the historic center of St. Petersburg (fig. 4).

St. Petersburg's surge floods, caused by strong westerly winds generating the so-called long wave, have also become more frequent. The danger of the surge was largely eliminated with the commissioning of a protective structure, the St. Petersburg Flood Prevention Facility Complex (KZS, also unofficially known as the "St. Petersburg Dam"). However, this 25-km-long structure, built between 1979 and 2011,[2] caused great damage to the landscape of Neva Bay. It crossed the chain of historical estates on the southern shore, Kotlin Island, the line of the Northern Batteries, fairways, and underwater barriers – all these sites included in the 1990 nomination, were seperated, disrupting their historical continuity. Although the dam intervention significantly altered the landscape, the overall OUV of the World Heritage property was not formally recognized as affected. This is because, in the official retrospective Statement of OUV adopted in Bonn in 2015 (UNESCO World Heritage Centre 2015), the landscape qualities of the

2. Flood Prevention Facility Complex, https://dambaspb.ru/en/#intro.

3. Federal Law of 02.07.2021 "On Limiting Greenhouse Gas Emissions", http://publication.pravo.gov.ru/Document/View/0001202107020031.

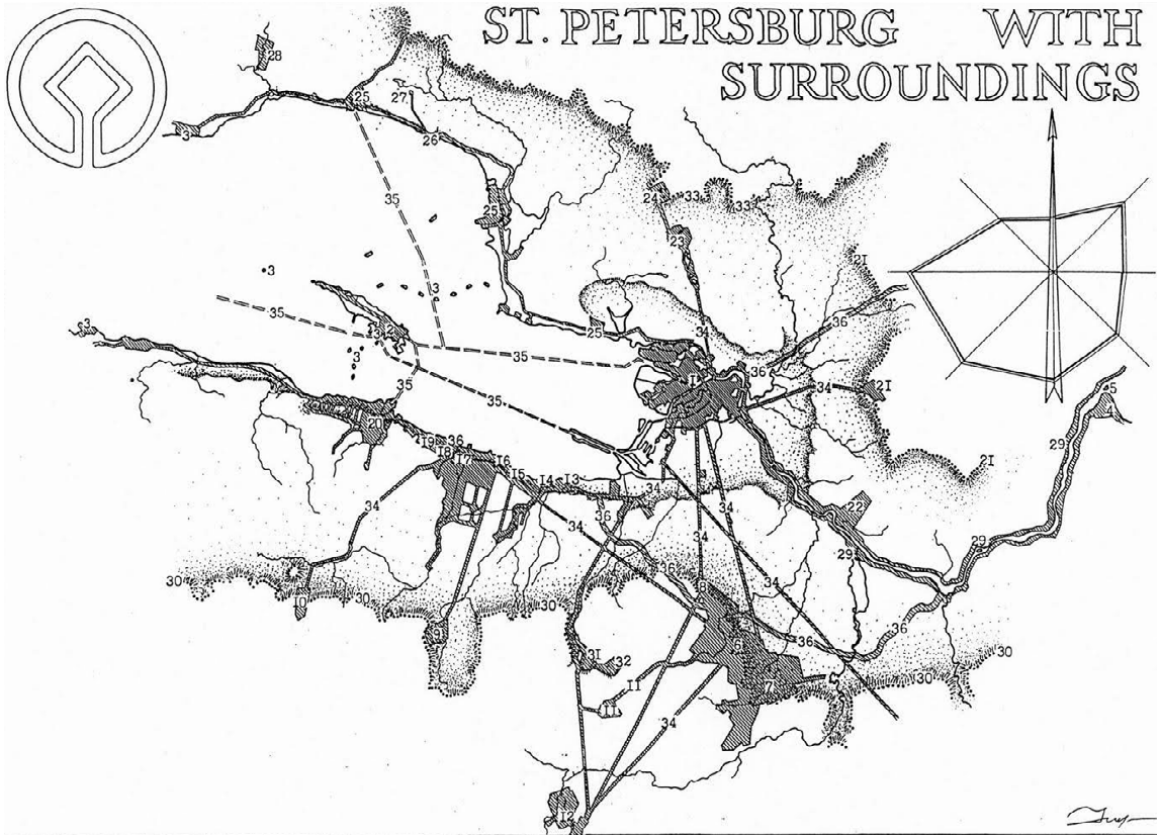
4. https://interactive-atlas.ipcc.ch/.

"related groups of monuments" – particularly their relationship to surrounding water and open space – were entirely overlooked.

St. Petersburg and the Regional Climate Change Adaptation Plan

Undoubtedly, St. Petersburg and the Leningrad region negatively contribute to climate change, primarily due to the intensive burning of fossil fuels. At the same time, the Russian authorities, including the St. Petersburg administration, have taken several measures to correct this situation. In particular, in 2021, the Federal Law "On Limiting Greenhouse Gas Emissions" was adopted.[3] Following this, by the decision of St. Petersburg Governor Alexander Beglov, dated December 21, 2023, the Regional Climate Change Adaptation Plan for St. Petersburg was approved (Government of St. Petersburg 2023).

The Regional Climate Change Adaptation Plan, which was developed by St. Petersburg specialists, indicates that by 2050, the climatic zone of St. Petersburg (according to the Köppen-Geiger climate classification) may change from "humid continental with warm summers" (Dfb) to "moderately warm with uniform humidification" (Cfb) of the "marine" sub-type. Recent climatic observations indicate that the frequency of sea surge floods in the region has increased significantly, with the seasonal peak shifting from autumn to winter. According to projections from the Interactive Atlas[4] of the Intergovernmental Panel on Climate Change (IPCC), the average sea level in

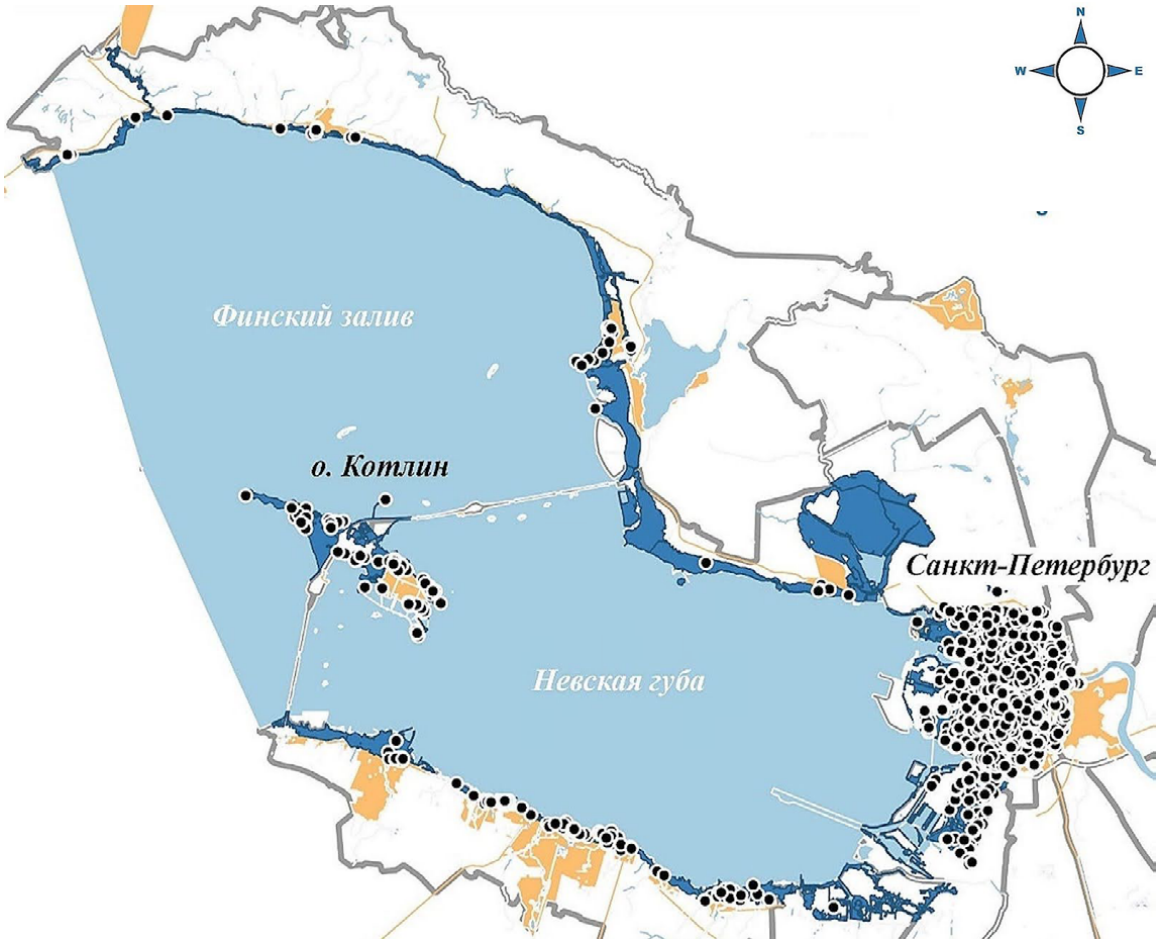


^ Fig. 3 A nomination scheme from the 1990 application, which corresponds conceptually to the present-day layout. The map of the World Heritage property, Historic Centre of St. Petersburg and Related Groups of Monuments, shows the Gulf of Finland, the Neva Bay and the Neva River (Source: Boris Nikolashchenko, 1990).

the eastern Gulf of Finland may rise by 10–40 centimeters between 2041 and 2060, relative to the 1995–2014 baseline, under scenarios SSP2-4.5 and SSP5-8.5. A sea level rise of 40 centimeters could result in flooding approximately 650 hectares of coastal areas in St. Petersburg. Under such conditions, the city's flood zone at peak water levels could expand by a factor of 1.5, posing a severe threat to both the urban fabric and heritage components in low-lying zones (Government of St. Petersburg 2023).

At the same time, the threat to cultural heritage and St. Petersburg's World Heritage property is mentioned only once in the Regional Climate Change Adaptation Plan. In the final chapter, "Description of Predicted Changes in the Distribution of Climate Risks of the Territory," it reads:

> An increase in the average sea level by 30-40 cm will increase the area of the flood zone of St. Petersburg by 1.5 times and the number of historical and cultural heritage sites within its boundaries by four times. This climate risk is expected to become "dangerous" by the middle of the twenty-first century. With a further increase in average sea level of up to 1 m, the impact will become catastrophic (Government of St. Petersburg 2023).



^ Fig. 4 Historical and cultural heritage sites (black dots) in the territory of St. Petersburg that fall in the flood zone (in dark blue), while the average sea level is rising by 80 to 100 cm (Source: Pavlovsky, A. A., and V. I. Shamshurin. 2021b. "The Impact of the Rising Baltic Sea Level on Russia's Historical and Cultural Heritage." Hydrometeorology and Ecology 65: 681–693; used with the author's permission).

^ Fig. 5 Peter the Great's palace in Peterhof, "Monplaisir," on the shore of Neva Bay (Source: Sergey Gorbatenko, 2005).

These forecasts are also reflected in the updated assessment of climate risks posted on the website of the Committee for Nature Management, Environmental Protection, and Environmental Safety (Akhmatovich et al. 2023). According to estimates included in the assessment, with a sea level rise of 80-90 cm by the end of this century, 3,283 such historical and cultural monuments may be flooded (Akhmatovich et al. 2023).

The relevant sections of the Regional Climate Change Adaptation Plan and the 2023 updated assessment were prepared based on research by Doctor of Geographical Sciences Artem Pavlovsky and colleagues. Based on the data from studies of the trends in the rise in the Baltic Sea level (in Neva Bay over the past decades – about 4 mm per year), the assessment identifies boundaries of the possible flooding zone of the Neva Delta, the Neva Bay and the eastern part of the Gulf of Finland (within the administrative boundaries of St. Petersburg). It indicates the factors influencing this process: for Neva Bay, this is a rise in the average sea level, the flow of Neva water, an increase in the frequency of floods, an increase in the duration of the closure of the KZS and a decrease in the water surface due to the intensive reclamation of territories for new residential construction. The juxtaposed boundaries of World Heritage property and individual cultural heritage sites of various protection levels illustrate the extent of the threat facing St. Petersburg's heritage. These risks also extend to coastal and island heritage sites in the Leningrad Region (Oblast).

To counter this threat, the Administration of St. Petersburg proposed that local protective dams be installed in combination with a system of drainage canals (Akhmatovich et al. 2023). Interestingly, at the beginning of the eighteenth century, Peter I proposed similar techniques, borrowed from Holland, for his seaside residences – Catherinehof and Peterhof (fig. 5).

Threats to the Cultural Landscape of St. Petersburg's World Heritage Property

The draft design of coastal protection structures in Neva Bay is given in the updated assessment (Akhmatovich et al. 2023). However, it should not be forgotten that highly protective

dams can alter the traditional character of the landscape and heritage sites, including the views and panoramas that open onto the waters of Neva Bay and the Gulf of Finland. The KZS dam disrupted the natural horizon with a dark stripe and the unnatural silhouette of a bridge in the middle of the water area – an intervention that should serve as a warning not only against similar engineering structures but, more urgently, against high-rise developments and skyscrapers that could further compromise the integrity of the historic waterscape.

The cultural landscape of St. Petersburg has long suffered from intensive urbanization. As a result of lobbying by construction companies and widespread corruption, businesses are building up gap-free territories and waters near historical areas. Assessments on the impact on World Heritage value (despite the adoption of the relevant state standard), with appropriate communication of findings shared with international protection bodies, are carried out only sporadically.

The existing law on protection zones in relation to the international status of St. Petersburg does not work satisfactorily: suffice it to say that the World Heritage property is not mentioned at all. Buffer zones are completely absent, which is mandatory for such sites and ensures the preservation of distant views and panoramas (UNESCO World Heritage Centre and ICOMOS 2019). The Neva Bay – a potential buffer zone for coastal and island heritage elements – lacks protection status. It could be protected by World Heritage – listed historic fairways and underwater groyne barriers – but that's only in theory.

Until recently, alluvium of new territories for residential construction was widely practiced in St. Petersburg, primarily in Neva Bay, along the western coast of Vasilievsky Island (in 2018, in Beijing, at the first official working meeting of the Asia-Pacific Subcommittee of CIVVIH [Comité International des Villes et Villages Historiques, International Committee on Historic Towns and Villages], I presented a report on this topic). Only in 2021 was soil reclamation excluded from the city's general plan: the arguments of experts who proved that the reduction of the water surface could lead to a catastrophic overflow of the bay during a secondary flood were finally taken into account. However, this does not guarantee reliable protection for the Neva Bay water area. For example, the water body of Neva Bay, including along the western coast of Vasilievsky Island, has federal status, and authorities in Moscow may decide that reclamation may continue for development.

Like all components of the UNESCO property, Neva Bay lacks a buffer zone. In 2018, on behalf of the National Committee of ICOMOS (Russia), the author of these lines prepared and sent a report to the ICOMOS headquarters in Paris, listing cases of damage and warning of threats to the World Heritage property. The list included many cases related to water areas that are part of its components. Although these cases were selected based on the criteria of damage to the landscape, which was not directly related to the threat of climate change, the most egregious are worth noting. One is Gazprom's Lakhta-1 skyscraper, which has invaded the Neva and the Neva Bay panoramas. Today, despite the losses of recent years, Gazprom intends to build two more skyscrapers next to the first one – Lakhta 2 and 3. Another scandalous initiative of Gazprom is the construction of a business center on the bank of the Neva, at the mouth of the Okhta River, destroying the cultural landscape and the most valuable potential archaeological sites of the ancient settlements and Swedish fortresses located on this cape.

Conclusion

The risk of flooding coastal cities with historic centers inscribed on the World Heritage List is greater today than ever before. In St. Petersburg's Regional Climate Change Adaptation Plan, significantly more attention should be devoted to the protection of cultural heritage sites, in line with scientific forecasts. Corresponding amendments should be made to the Law of St. Petersburg on Protection Zones. Buffer zones for the World Heritage property must be developed and officially approved, and a comprehensive management plan should finally be established – one that accounts for projected sea level rise.

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The Impact of Climate Change on Cultural Heritage: The Case of the Tomb of Askia

Mamadou Samaké

Abstract
The UN SDG Agenda does not mitigate the impacts of flooding and desertification or address the regional insecurity affecting the Tomb of Askia and the surrounding area, Gao, which is experiencing devastating droughts and rainfall, increasing insecurity. Only through a deeper understanding of the interrelation of these issues and by significant reporting improvements, can we realize the UN 2030 Agenda.

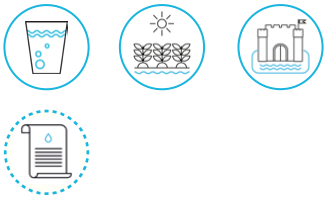
Policy Recommendations

- The mayor of Gao should be supported in his commitment to clean the water collectors and to build others, alleviating the lack of water.
- The mayor should be supported in awareness-raising amongst about the effects of climate change and flood impacts, particularly with those living and working on the Niger River banks, and with the national authorities.
- Improved disaster planning should be supported at the Tomb of Askia, and funding made available.
- Actors working with local communities to highlight and safeguard the site, when people have many other pressing concerns, should be encouraged.
- Funding agencies should encourage flexibility to adapt to changing situations.
- Governments should recognize that cultural heritage deserves a higher and more sophisticated level of protection than that afforded to everyday buildings.
- Collaborative assessments should be undertaken with the World Heritage Committee to understand the level of acceptable climate change vulnerability for removal from the List of World Heritage in Danger.
- Cultural heritage-specific climate change modelling, monitoring and adaptations must be developed.

KEYWORDS

UNESCO World Heritage
Tomb of Askia
cultural heritage protection
desertification
flooding

WATER ICONS



CLIMATE

BWh: Hot desert climate

< Fig. 1 Tomb of Askia, Gao (Source: David Sessoms, 2006. CC BY-SA 2.0, via Wikimedia Commons).

Introduction

The Republic of Mali has a rich, diverse cultural heritage, protected and promoted under national and international laws (including all six of UNESCO's cultural conventions). This article focusses on the earthen heritage of Gao, particularly the World Heritage site, Tomb of Askia.

Mali faces many challenges. It is considered a "high-risk" destination (Global Guardian 2025): travel is not advised. The cessation of tourism, economic insecurity, the exodus of young people to southern regions and border countries, and the difficult cohabitation of ethnolinguistic populations, contribute to a complex security situation, exacerbated by climate change. Climate change has been a concern for the UNESCO World Heritage Committee since 2005 (Perry and Falzon 2014), but mitigations are not well integrated into World Heritage management (UNESCO et al. 2010) and research into what constitutes acceptable levels of climate change vulnerability is limited (G7 Academies 2017). Nor is cultural heritage well integrated into the UN Sustainable Development Goals (SDGs), except via 11.4 (Protect the World's Cultural and Natural Heritage): Mali's 2022 Voluntary National Review indicated this was not a priority.

The article first describes the Tomb of Askia, before discussing the impacts of climate change on the community and cultural heritage, evaluating the mitigation measures to date, before concluding with policy recommendations.

About the Tomb of Askia

The Tomb of Askia materializes the grandeur and power of the fifteenth century Songhai Empire, centered in Gao. Built with local materials (clay, wood and terracotta) in 1495 on the orders of ruler Askia Mohamad, this monument has been maintained by local communities: today it is the most important and best conserved vestige of the Songhai Empire (figs. 1 and 2). In addition to the 17m high pyramid tomb, it consists of two flat-roofed mosques (one for men and one for women), the cemetery and an open-air prayer space, which are still in use today. The public space, also called White Stone Square, is dedicated to the Tabaski festival prayer, major sporting and cultural events, and local students use it for physical education and sports. Local people maintain a close connection with the Tomb of Askia, recognized by international organizations (World Heritage Committee 2023, 2024; ALIPH 2018).

Classified as national cultural heritage in 2003, it was inscribed on the World Heritage List in 2004 under World Heritage Convention (1972) criteria II, III and IV (UNESCO n.d), referencing the "unique architectural style" of local building traditions and the continuation of the "regular, traditional maintenance practices," such as plastering (*crépissage*) by the local community.

In 2012, extremists occupied Northern Mali (Eloundou Assomo 2022): the Tomb of Askia was inscribed on the List of World Heritage in Danger and placed under (tentative) Enhanced Protection under the 1954 Hague Convention's Second Protocol (1999), despite insufficient emergency planning (Committee 2023). Yattara, a former Sahel Museum Director, conducted a study of the movable heritage and the establishment of emergency plans for the site (Yattara 2017). However, as no technical service cited in the document (including the Cultural Mission) was involved, it was not implemented. No emergency plan currently exists. In 2022, Blue Shield International supported the site's GIS mapping as part of the Enhanced Protection registration, finally completed in 2023.

The World Heritage Committee (2023, 2024) record insecurity and risk of site collapse as two of the three reasons the site was placed on the List of World Heritage in Danger. However, links to climate change are not mentioned.

Climate Change Impacts in the Gao Region: People and Heritage

Climate Change in Gao

The Gao region is located in Mali's Saharo-Sahelian zone. For decades, it has faced negative and multifaceted effects of climate change, resulting in a rural exodus that contributes to insecurity in the cities.

The temperature has increased to around 45°C during the day and 15° or less at night. Mali is now experiencing an ongoing drought: Precipitation is less than 500mm per year. The Gao Regional Director of Nature Conservation, Mr. Touré (pers. comm. 12 February 2025) estimated that the rainfall isohyets have moved 200 to 300km, evidencing the desert's advance. The Niger is also silting up; sand is accumulating in a minor riverbed. Violent winds are loaded with sand dust. Sudden torrential rainfall now regularly results in upsurges in the Niger River levels and catastrophic flooding. Alerts are raised when water rises 4.60m above normal. In 2024, the level reached 3.99m, 4.53m in 2023 and 4.50m in 2022.

Between July and September 2024, Mali experienced the most significant rainfall since 1967, impacting over 180,000 people. Gao was one of the most affected regions (IOM 2024). The Gao Regional Social Development Department (pers. comm. 2025) surveyed the consequences: Most affected buildings were in Gao's old town.

The Regional Directorate of Agriculture (pers. comm. 2025) recorded the Niger River reaching its highest ever alert level on 26 January 2025 (4.95m): 19,716 ha of cultivable land in the Gao region were flooded between December 2024 and January 2025, impacting approximately 20,000 households and cutting off the roads linking villages to Gao city.

Consequences for cultural heritage

Climate change has caused drastic decreases in local building materials, contributing to the degradation and loss of Gao's earthen architecture. Intensifying rainfall has also increased the Tomb of Askia's structural vulnerability. Following torrential rains in August 2006, 2011, and

Impact	Numbers affected
Collapsed houses	2632
Affected (flooded) houses	2013
Collapsed toilets	28
Number of people affected Women Girls Men Boys	45,623 12,799 11,274 12,252 9,298
Households affected	6451
Number of deaths	6

^ Table 1. 2024 rainy season impacts on the Gao region (Source: Regional Social Development Department, 2025).

2017, parts of the men's prayer room roof collapsed. In 2024, two further collapses occurred following heavy rains (fig. 3). 16m^2 (4.60m x 3.70m) collapsed overnight on August 2–3; and 18m^2 (5m x 3.60m) overnight on August 22–23 (Cissé et al. 2024). Fortunately, there were no casualties: damage was discovered around 5 a.m. by the mosque's faithful attending the first daily prayer.

Advancing desertification causes fine sand to cover many tombs in the cemetery, leaving only tombstones visible, as well as the White Stone Square, hindering preparation for events and festivals.

Resilience and Protective Measures

Drought affects the people of Gao's livelihood daily, while the torrential rains and floods places their homes at great risk. Local communities' solidarity, the provision of emergency tents, shelters and the financial support of international NGOs, has alleviated (but not halted) the victims' suffering. UNHCR, the UN Refugee Agency, appealed urgently, but unsuccessfully, for US$10.6 million to address the impacts of climate-induced flooding across West and Central Africa, aiming to directly support the population, and enhance flood preparedness activities (UNHCR 2024). Now, the Regional Directorate of Civil Protection, the youth of Gao and the Town Hall municipality have been supporting the people and undertaking protective measures themselves. Activities include inspections of flood-affected buildings and moving families to safer places. Given the scale of displacement and decrease in available building materials, many homes will not be rebuilt in the traditional style and many people may not return.

The cultural sector is paying significant attention to the Tomb of Askia. The Malian authorities complete a regular State of Conservation Report which the UNESCO World Heritage Committee reviews, a monitoring requirement for sites on the World Heritage in Danger List. In 2016, the Committee and the Malian authorities agreed measures to repair and stabilize the site and to develop a timetable for conservation work (World Heritage Committee 2016). In 2018, UNESCO World Heritage Centre funded the replacement of eucalyptus wood with traditional hasu wood, hasu plant regeneration and the spreading of fine sand to counter water erosion. These are now part of the site's ongoing maintenance.

Also in 2018, donor ALIPH granted US$500,000 to the National Directorate of Cultural Heritage, the Cultural Mission of Gao, CRAterre, (and Pyramis auditors), in collaboration with local communities. The project, which eventually launched on 2 March 2024, aimed to "improve the state of conservation and authenticity of the site while continuing traditional mainte-

^ Fig. 2 Collapsed men's mosque roof (Source: Mamadou Samaké, 2024).

nance practices, such as the traditional wooden carpentry and plastering techniques which are characterized by rounded shapes resulting from the regular renewal of the plaster layer eroded by the rains each winter" (ALIPH 2018). It would:

- Repair the buildings and fence,
- Train masons and guides,
- Develop the ablutions area,
- Update the electrical installation,
- Construct latrines,
- Replace metal doors with wooden ones,
- Regenerate hasu plants at the site and supply hasu poles,
- Spread fine sand in the prayer area to counter water erosion,
- Produce booklets and a conservation manual,
- Provide computer equipment and materials to the Gao Cultural Mission.

Local labor was paid; however, two interns from the Cultural Mission worked voluntarily. The complete restoration of the men's mosque roof had not been planned for. Work was largely completed by July 2024. However, following the August collapse, the local community requested restoration, which the donor agreed to. Local masons and workers, supervised by CRATerre, carried out the repairs. Old masons' expertise and the local workforce's commitment contributed effectively to the property's conservation and promoted traditional knowledge of earthen architecture.

In 2022, the African World Heritage Fund donated US$15,000 to document historic burials (World Heritage Committee 2023). Protection at the necropolis was also strengthened by installing a stone cordon to mitigate the effect of water erosion.

The World Heritage Committee reports that "insecurity is still the major threat to the property" (World Heritage Committee 2024). However, they are now realizing that whilst insecurity impacts site conservation, it is not the only issue. In 2024, they asked if "a more in-depth and up-to-date analysis could be provided in order to better understand precisely how insecurity actually affects the management and conservation of the property" (World Heritage Committee 2024). What is not yet appreciated is the close relation between climate change, insecurity and conservation: Without addressing climate change, the other issues will remain.

It is critical that, despite the challenges facing them, the local people remain actively involved (Perry and Falzon 2014, 45). Site authorities work closely with local people to maintain and develop their attachment to the site. For example, community engagement, including the now annual African World Heritage Day celebrations on 5 May (fig. 3), raises awareness. Young people are given a tour and there are celebrations at the site (BSI 2023). The World Heritage Committee (2024) called it "commendable".

^ Fig. 3 Repair work on the roof of the men's mosque after the 2024 collapse (Source: Mamadou Samaké, 2024).

^ Fig. 4 Tomb of Askia World Heritage Site. The red and blue shield protective emblem of enhanced protection under the 1999 Second Protocol to the 1954 Hague Convention is visible in the foreground, the World Heritage sign in the background, adjacent to a UN peacekeeper vehicle, showing the tense security situation (Source: ©M. Bagayoko, with author's permission).

As of 2024, the site remains on the List of World Heritage in Danger. However, workshops were held in Senegal in 2022 and Morocco in 2024 to strategize conservation improvements for the removal of West African sites from the List (World Heritage Committee 2024). This included addressing the risks of collapse and insecurity.

Conclusion

SDG13 targets focus on strengthening resilience, knowledge and capacity for disasters and integrating climate change measures into policies and planning. However, targets report against emissions management, indicating Mali is successfully meeting SDG13 (SDR 2024). Yet in Gao, climate change rhymes with insecurity, though the links between them and heritage protection are poorly understood in policy. Many recommended heritage adaptations (UNESCO et al. 2010, Perry and Falzon 2014) are inadequate in this situation. Heritage-specific climate change modelling must be developed, with monitoring that supports targets.

Local, national, and international authorities must encourage adaptation to the effects of climate change, including building cleaning collectors to facilitate the flow of rainwater to the river. The population must comply with the safety instructions proposed by the authorities and

technical services such as civil protection, the hydraulics and metrology departments. NGOs and partners should be supported to continue to alleviate the suffering of those impacted. Young people should support technical services in raising awareness, particularly amongst those living in the riverbeds, to better protect them in the future.

This protects not only our World Heritage, but the people attached to it. Developing Climate Change resilience (SDG13) will protect heritage (SDG11.4) and tackle Mali's increasing population displacement and insecurity, improving the other targets which are negatively impacted by climate change.

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Mamadou Samaké obtained a degree in history and archaeology from the University of Bamako, Mali, in 2000. He worked on the Ancient Cities of Djenné World Heritage Site from 2004 to 2017, when he became head of the Cultural Mission of Gao and manager of the Tomb of Askia and associated sites. Mr. Samaké is vice-president of the ICOM-Mali National Committee and president of the Malian Committee of the Blue Shield. He has participated in training courses in Burkina Faso and France on archaeology and regional museum management, and ICCROM First Aid to Cultural Heritage in Times of Crisis, in Bamako, Mali, in 2018.

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

Amira Ghennaï & Said Madani

Abstract

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

Policy Recommendations

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

KEYWORDS

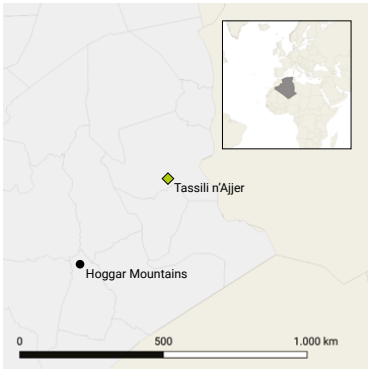
UNESCO World Heritage
Tassili n'Ajjer and Hoggar
climate change
water management
QGIS

WATER ICONS

CLIMATE

A **B** C D E

BWh: Hot desert climate



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

Introduction

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

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

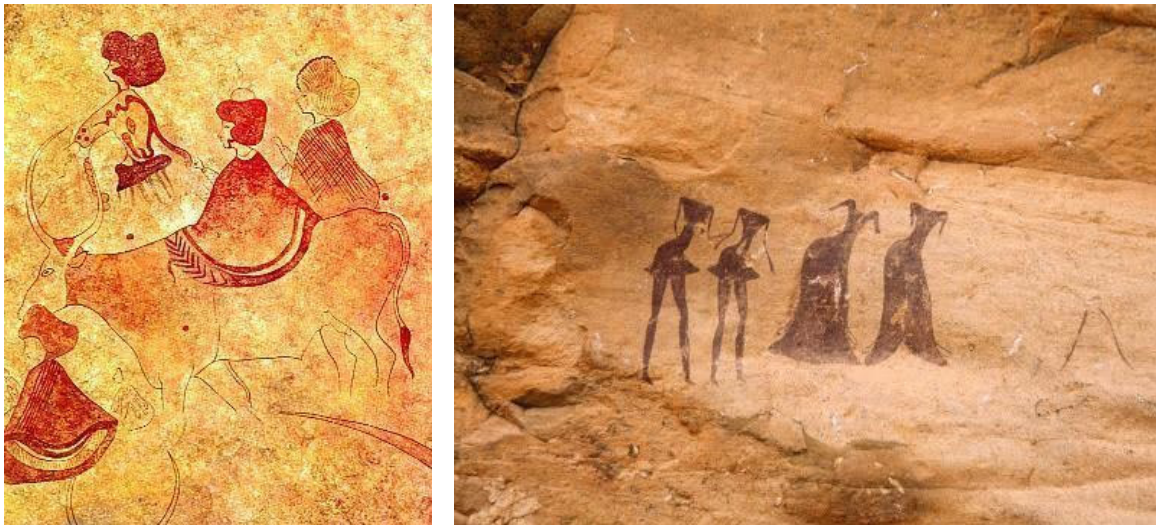
QGIS-based mapping of the Tassili n'Ajjer–Hoggar region reveals midsummer precipitation (75–150 mm, CHRS data) and associated flood risks, levels that dramatically exceed local arid norms. These findings underscore the potential for hydrological disruptions, from flash floods to microclimatic shifts,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

Rupestrian Art in the Tassili n'Ajjer–Hoggar Region

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

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

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



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

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

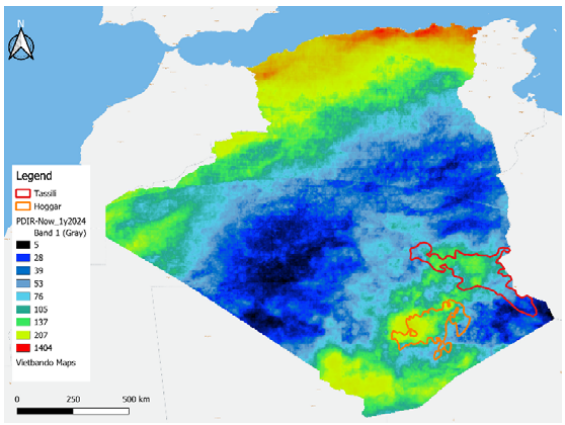
The Tuareg, have always demonstrated a remarkable ability to survive in their ultra-arid region (Hachid 1997). This cultural resilience is officially recognized; in accordance with Decision 8.COM 8.2, UNESCO (2013) has inscribed the "Practices and knowledge related to the imzad of the Tuareg communities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

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

Climate Change and the World Heritage Property

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

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



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

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

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

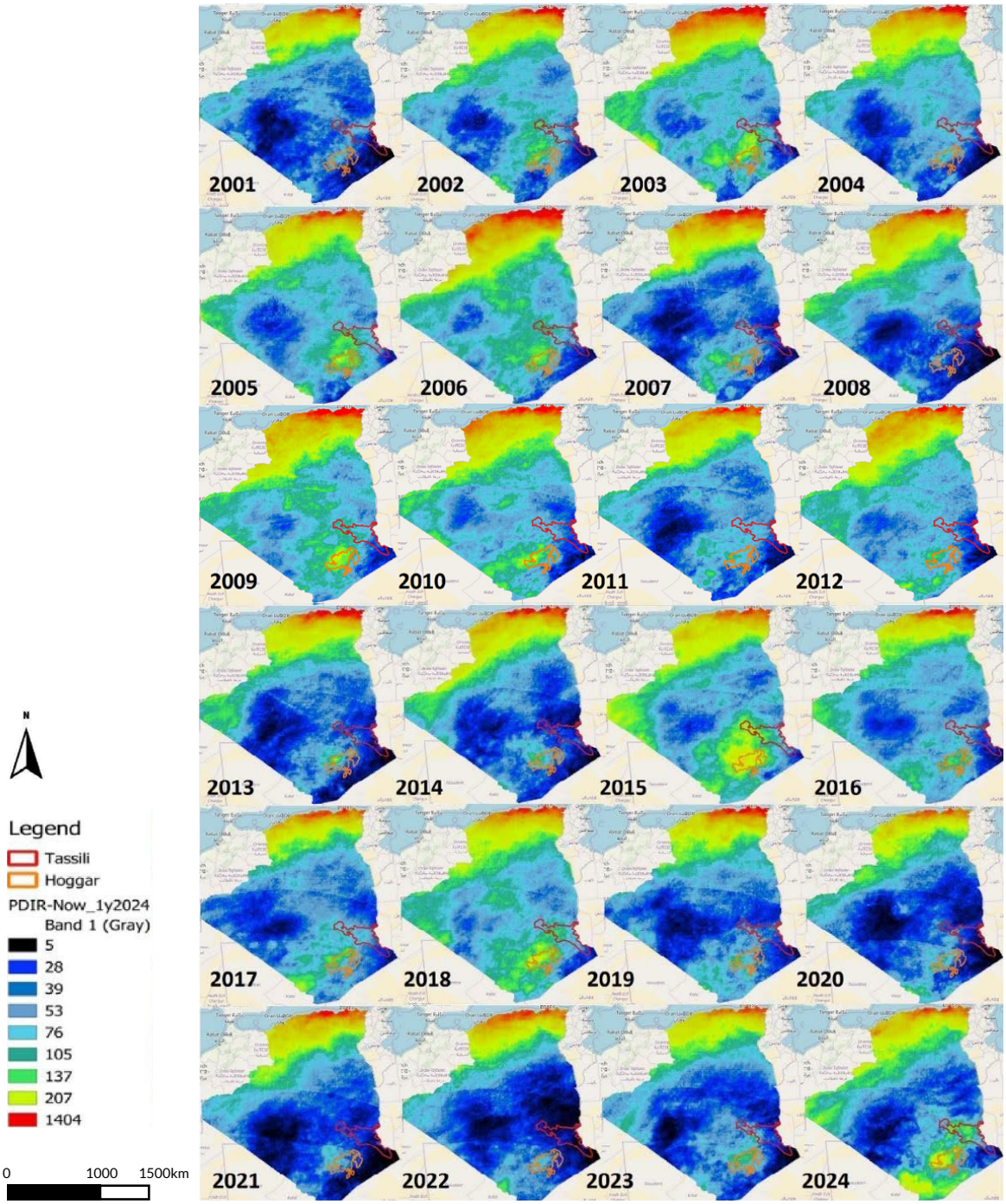
Rainfall and Flooding in the Algerian Desert

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

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

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

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



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

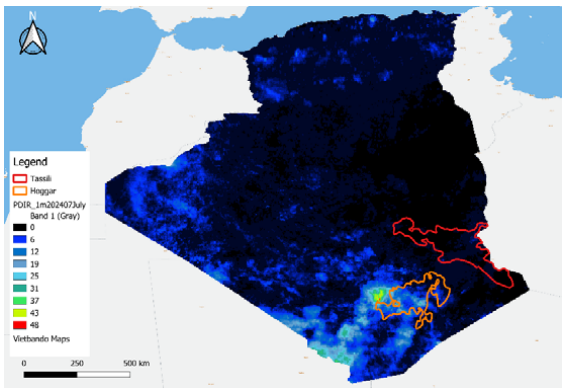
analysis of potential flooding, we have aimed to highlight the urgent need for strategies to ensure the long-term preservation of this invaluable heritage. This analysis includes the delimited study area of the Tassili n'Ajjer World Heritage property and extends to the Hoggar region (fig. 6–8). The maps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

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

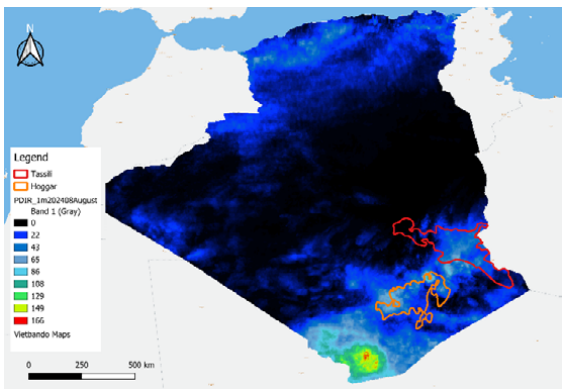
Figure 5 illustrates the rainfall history in Algeria between 2001 and 2024. It shows a continuous climatic gradation from north to south, with the northern regions receiving the highest rainfall totals. This humid zone contrasts sharply with the vast desert expanses of the south, which are generally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

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

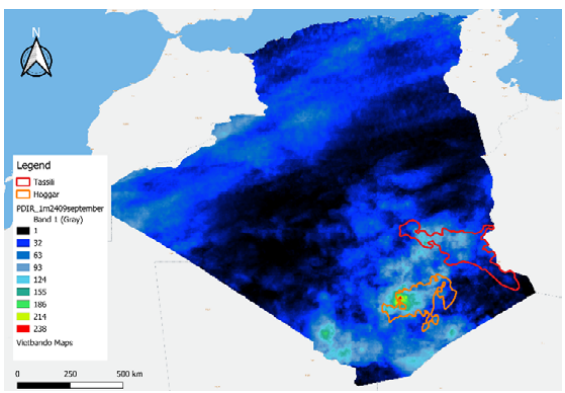
Faced with hydrological disasters, Algeria has gradually adopted a proactive risk management policy. At the national level, this approach has resulted in significant infrastructure investments – dams, retention basins, modernized drainage networks – institutional strengthening (civil protection, early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



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



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

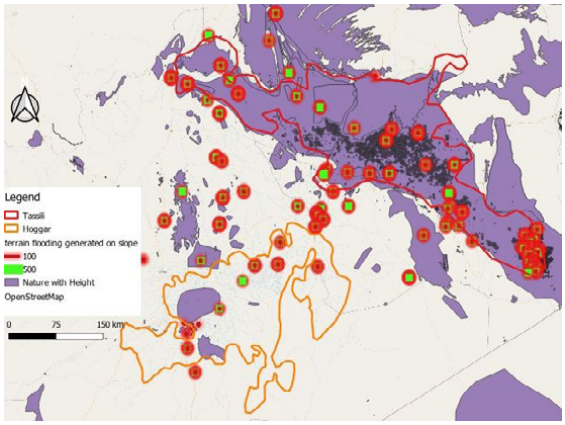


^ Fig. 8 Rainfall map of Algeria, September 2024 (Source: Amira Ghennaï and Said Madani, generated using QGIS, 2025).

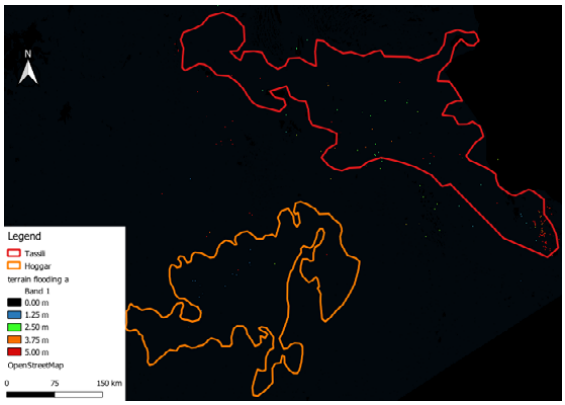
The map showcasing a simulation of potential flood risk (fig. 9–10) was generated in QGIS using the SAGA-GIS Terrain Flooding tool. This tool performs a multi-layer analysis, primarily integrating a Digital Terrain Model (DTM), a terrain slope layer and land cover data with elevation attributes. The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

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

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



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



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

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

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

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

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

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

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

Conclusion

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

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

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

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

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

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

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

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

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

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Learning from the Subak World Heritage Property: The Importance of Co-Creation for Water Management and Climate Adaptation

Diana Rahman

Abstract

The Cultural Landscape of Bali Province, a UNESCO World Heritage property in Indonesia, features ancient rice terraces and the *subak* irrigation system, reflecting a millennium-old harmony between humans, nature and the spiritual world. The *subak* landscape faces increasing challenges that threaten its sustainability. Alongside the pressure of rapidly expanding tourism, the *subak* system is increasingly vulnerable to water scarcity and shifting weather patterns due to climate change. This article examines the role of co-creation and local knowledge, advocating for the incorporation of community-led practices in the management of World Heritage properties. Co-creation can improve the effectiveness of management plans, align conservation goals with local communities' adaptive practices and enhance the resilience of the *subak* system. The article underscores the critical need for World Heritage management plans to integrate climate adaptation strategies rooted in local knowledge, ensuring a more responsive and sustainable approach to preserving the heritage landscape.

Policy Recommendations

- Integrating co-creation in heritage and water management strategies, such as those affecting the *subak* landscape, is crucial for ensuring the sustainability of cultural heritage sites and fostering resilient communities.

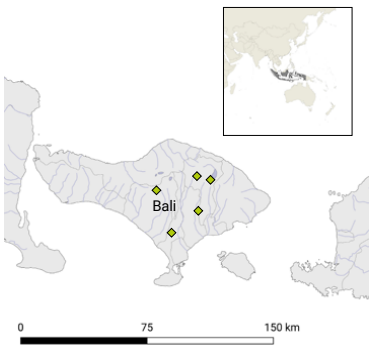
KEYWORDS

UNESCO World Heritage
Subak
cultural landscape
co-creation
local and traditional knowledge

WATER ICONS

CLIMATE

Af: Tropical rainforest climate



< Fig. 1 Rice terraces of the *subak* landscape (Source: Diana Rahman, 2023).

Introduction: The *Subak* Landscape and the Challenge of Management

In 2012, UNESCO designated as World Heritage the Cultural Landscape of Bali Province: The Subak System as a Manifestation of the Tri Hita Karana Philosophy (fig. 1). The Balinese philosophy of Tri Hita Karana emphasizes the importance of harmony between human beings, the environment and the spiritual world. Recognized under criteria (ii) and (vi) of Outstanding Universal Value (OUV), the *subak* system represents a distinctive irrigation system and a living cultural tradition (UNESCO World Heritage Centre 2025). For the Balinese, the word *subak* has several meanings: it refers to the irrigation system, the agricultural landscape, the farmers and the organization responsible for managing rice fields and the irrigation system. These various meanings of *subak* reflect the way its value extends beyond the physical landscape and the living tradition.

For it to be managed sustainably, the *subak* system must be viewed as a holistic entity that encompasses not only tangible aspects, such as rice terraces, water temples and customary villages, but also the system's intangible elements. These include traditional knowledge, the Balinese social structure, farmers and customary laws, all of which reflect a complex network of values — social, religious, environmental and cultural (Rahman 2021). Together, these elements form an interconnected system that is integral to both the landscape and the community.

The World Heritage property featuring the *subak* landscape includes six clusters of rice terraces, alongside customary villages, lakes, forests and water temples. Each landscape component plays a role in safeguarding the water supply and the farming tradition. Contributing a significant proportion of Bali's rice production, the *subak* landscape depends heavily on water, making it especially vulnerable to climate change and water scarcity.

Several challenges in the *subak* landscape are highlighted in several State of Conservation (SOC) reports, periodic assessments prepared by UNESCO and national governments to monitor factors affecting the management and preservation of World Heritage properties. The challenges include tourism development, changes in traditional ways of life, population density, land conversion and governance, all of which UNESCO identifies as threats to its OUV (UNESCO World Heritage Committee 2023). These issues, however, remain contentious as the local community considers certain changes necessary to protect the sustainability of the landscape and practices.

The SOC report did not formally recognize climate change as a direct threat to the sustainability of the *subak* landscape. While this aspect may have been overlooked by the site managers, climate considerations — particularly changes in climate patterns — have been integrated into local agricultural practices and landscape management.

Holy Water and the Climate Crisis

Water is essential not only to the *subak* landscape but also to Balinese culture. Over 80 per cent of the island's population follows the Agama Tirtha, which is formally recognized as Hinduism by the Indonesian government, although it diverges significantly from Hinduism as practiced in South Asia (Lansing 1987; Picard 2011; Vickers 2012; Wright 2015; Hobart 2016). The Agama Tirtha (religion of the holy water), as its name suggests, incorporates water into nearly

^ Fig. 2 The *subak* irrigation system is intricately connected to water temples, which not only serve as sources of holy water but also play a key role in managing the flow of water to the *subak* landscape (Source: Diana Rahman, 2021).

every aspect of traditional and religious practices. Water is central to Balinese ceremonies, including those related to birth, death, agricultural cycles and others (Lansing 1987; Eiseman Jr. 1990).

The importance of water in Balinese culture underpins the strong connection between water and temples across Bali. Water sources, such as rivers, lakes and springs, are regarded as sacred and are safeguarded by traditional customs. The holiest water usually comes from the most sacred temples, such as the Tirta Empul water temple (fig. 2), which lies within the boundaries of the World Heritage property. Water temples thus play a dual role: they not only manage water for irrigation but are also crucial for the preservation of Balinese culture and tradition. Thus, water scarcity is not only a conservation or agricultural issue; it poses a profound threat to this water-centered society, so it is critical to recognize it as an existential challenge.

In recent years, the World Heritage community has recognized the irreversible damage caused by climate change to heritage sites worldwide (Rahman 2023; Falk and Hagsten 2024). Among other challenges, the challenges posed by climate change to agricultural landscapes include increased drought, changes in precipitation patterns and more frequent extreme weather events, which disrupt traditional farming practices and water management systems globally (Agnoletti and Santoro 2022; Aktürk and Dastgerdi 2021; Furtak and Wolińska 2023). Unpredictable rainfall and extended droughts can also affect the water supply, which can disrupt the planting cycle and decrease crop yields in the *subak* landscape. Rising temperatures and

excessive rainfall can impact soil fertility, crop resilience and the availability of water resources crucial to agricultural heritage landscapes (Agnoletti and Santoro 2022; Assen et al. 2024; UNESCO et al. 2013).

Within the *subak* landscape, inadequate implementation of the World Heritage proprty management plan may be the biggest factor contributing to the landscape's deterioration. While numerous regulations have been developed by the national government – including some specifically designed to protect the *subak* landscape from land conversion and to support *subak* organizations and safeguard traditional practices – implementing them has been difficult due to the frequent turnover of government officials, lack of coordination, limited resources and site managers and local communities not sharing the same priorities. Resistance and unwillingness to cooperate are also evident among communities across various areas of the *subak* landscape.

The local community does not uphold regulations because some of them are considered disadvantageous. They have expressed their disappointment over the lack of consultation in developing the World Heritage management plan for the *subak*, which, ultimately, led to a plan that is out of line with traditional practices and communal goals (Rahman 2021). The disconnect has contributed to weak management practices that do not adequately support the farming system by addressing the supports needed and challenges faced by farmers, such as rising production costs and declining market prices, which make sustaining the agricultural sector increasingly difficult. Thus, without incentives, the agricultural sector cannot provide adequate income for the local community.

Climate change and water scarcity also have a significant impact on agricultural activities in the *subak* landscape. Climate change has altered rainfall patterns, which has led to frequent and prolonged dry weather, erratic monsoons (Falk and Hagsten 2024). Water scarcity has been identified as a challenge by farmers in the *subak* landscape, as it leads to increased competition for water between agricultural and tourism-related uses (Strauß 2011; Rahman 2021).

Co-Creation in Water Management

Strategies intended to "protect" the *subak* landscape often fail to consider the system to which it belongs, meaning not only the irrigation structures but also the farmers and their livelihoods. For example, the World Heritage management plan has primarily focused on safeguarding the physical landscape without providing financial incentives that can support farmers' well-being. The plan also has yet to adequately address the restrictive rules and regulations of the World Heritage framework that hinder farmers' ability to adapt to modern economic challenges.

Another critical yet often overlooked aspect is the relationship between farmers and water temples, which serve as spiritual and social institutions regulating water distribution through traditional practices and rituals. These temples ensure that water remains available for both agricultural needs and cultural practices by coordinating irrigation schedules, resolving disputes and maintaining equitable access to water. While they do not possess formal sovereignty over water, the water temples exercise significant authority within the *subak* system, as their traditional rules and rituals are respected and followed by the farming communities (Lansing 1987).

Many changes in the *subak* landscape are social and cultural. Some of them, such as de-

partures from traditional farming techniques, the use of different rice varieties, and changes in planting schedules, are directly related to climate change. In *subak*, the customary laws and practices of the local community offer sustainable approaches to water allocation and conservation. Farmers have been scheduling irrigation based on a rotational model, thereby preventing conflicts over water between farmers. They also synchronize planting and irrigation schedules with water availability and climate conditions, further leading to adjustments in the timing of farming-related religious ceremonies. When water is limited, farmers may shift to cultivating crops with lower water requirements, allowing them to conserve resources while maintaining agricultural productivity. These changes help farmers become more resilient in the face of uncertain weather patterns. Farmers consider them necessary to sustain agricultural activities. They also enable more effective water management in response to the growing threat of water scarcity (Rahman 2021; Rahman 2023).

Sociocultural changes reflect both challenges and adaptations within *subak* communities as they seek to find a balance between preserving traditional practices and adapting to environmental and economic changes. The communities' capacity for adaptation is reflected in their *awig-awig* – a set of customary rules that serve as a foundation for managing water resources, farmers, irrigation systems and agricultural practices. *Awig-awig*, which outlines guidelines for the *subak* landscape, is based on traditional Balinese knowledge, but it can also accommodate change within the *subak* system, highlighting a general Balinese ability to adapt to environmental changes. These customary rules have long acknowledged shifts in climate and weather patterns and have helped farmers find a way to adapt and remain resilient.

The need for co-creation between the World Heritage property managers and local communities in managing *subak*, both the tangible and intangible aspects, is crucial because there has been persistent tension between management and the local community, especially due to knowledge gaps. Since the site's inscription in 2012, local communities have called for greater involvement in management planning, but this has not been seen so far. *Subak* representatives, often leaders of *subak* organizations within the World Heritage property boundaries, are occasionally included in discussions related to *subak* management. However, the limitations of this practice are twofold: first, many voices of farmers remain unheard as only *subak* representatives can offer opinions; and second, power dynamics in official meetings often restrict the contributions of *subak* representatives.

In 2023, responding to Indonesia's SOC report, the World Heritage Committee stressed that "some areas within the serial property are subject to development pressures, and it is not clear how the traditional and institutional decision-making structures work together" (UNESCO World Heritage Committee 2023). The Committee requested further details on how the national plan will support local knowledge and the traditional decision-making process.

Effective co-creation in World Heritage management, particularly for complex systems like *subak*, requires meaningful and ongoing collaboration among various stakeholders. Integrating local communities in heritage site management fosters not only more inclusive planning but also adaptive and sustainable solutions (Millar 2006). In the case of the *subak* system, bringing together farmers, scientists and policymakers can lead to effective and innovative water management that is context-appropriate and responsive to environmental challenges.

Sharing of knowledge and co-creation between site managers, the government and the local community can bridge the gaps in understanding the sociocultural changes happening in or affecting the *subak* landscape. Co-creation can also help decrease or prevent conflicts over water and management approaches, especially by establishing mutually agreed-upon practices that benefit all stakeholders. In Bali, people have long paid close attention to local weather and ecological patterns, and their expertise should be valued. Drawing on both local knowledge and modern science will enable a more contextual and holistic approach to managing water and the *subak* system. Furthermore, co-creation can foster a sense of ownership over management strategies, strengthening the local community's commitment to implementation.

Conclusion

The challenges affecting the cultural landscape of Bali Province's World Heritage property highlight the urgent need to address climate change impacts, including water scarcity, in the *subak* landscape. Increasing droughts, unpredictable weather patterns and limited water resources make it clear that the current management approach must be revised. Challenges in implementing management plans stem from limited financial and human resources, shifting and varying priorities on the part of site managers and local communities, and a lack of effective collaboration between local communities, site managers and local and central governments.

The *subak* system utilizes traditional laws and involves the community to ensure sustainable water allocation and conservation. This includes scheduling irrigation based on a rotational system, synchronizing planting and irrigation schedules with water availability and climate conditions, and diversifying crop varieties. Water temples ensure that water remains available for both agricultural needs and cultural practices. Integrating such local approaches into formal World Heritage management could help bridge knowledge gaps and align the priorities of site managers with those of local people.

Co-creation between site managers, policymakers and local communities is also essential for incorporating climate adaptation into heritage management. Local knowledge, as demonstrated in the customary laws of the *subak* system, offers invaluable insights, making possible a tailored, adaptive approach that supports both conservation and sustainability.

To strengthen the integration of traditional knowledge, community participation, and co-creation practices in managing Bali's cultural landscape, the following policy measures are recommended: Heritage management strategies should actively involve local communities at every stage, from planning to implementation. Capturing the depth and nuance of local expertise is essential to developing informed, context-specific, and sustainable management approaches. Co-creation should become the standard practice not only in heritage and climate change management but also in water governance. This collaborative approach fosters adaptive strategies, inclusivity, and a sense of shared ownership. Specifically, it entails incorporating local observations of climate patterns into water and landscape management and using this knowledge to address competing demands from agriculture, tourism, and urban development. In addition, policies should support co-creation initiatives that provide tangible economic benefits to *subak* communities. These may include agrotourism, sustainable agriculture, innovative farming methods, and cultural education programs—all of which can

help preserve the cultural and ecological integrity of Bali's traditional irrigation system.

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The Wetland Contract as a Governance Tool to Manage Conflicts in the Venetian Lagoon

Maria Chiara Tosi, Alessia Franzese & Mette Juhl Jessen

Abstract
Venice and its Lagoon, a vulnerable UNESCO World Heritage property, requires innovative governance tools to manage its complexity amid intensifying impacts of climate change. The local community has the potential to act as a living laboratory for testing new approaches to climate change mitigation and adaptation. This article examines the participatory process behind the Wetland Contract for the Northern Lagoon of Venice, a government instrument designed to strengthen protection of the lagoon's wetlands. The initiative brings together diverse stakeholders and local actors who commit to managing, restoring and protecting wetlands in a coordinated manner. The contract aims to balance competing priorities of socioeconomic development and biodiversity conservation.

Policy Recommendations

- Provide greater support to the Wetland Contract and reduce institutional distrust. Public and political bodies should upscale this governance model to a systemic management tool capable of addressing aspects of the lagoon ecosystem that may otherwise be neglected.
- Trust the participatory process. Acknowledge the value of trans-scale and multi-actor engagement as a democratic approach that fosters the socio-ecological relationships essential for shaping the territory in a constructive way.
- Exercise patience and commit to long-term engagement. Recognize that implementing effective bottom-up governance requires a substantial and sustained investment of time.

KEYWORDS

UNESCO World Heritage
Venice
wetland contracts
collaborative planning
commons

WATER ICONS

CLIMATE

A B **C** D E

Cfa: Humid subtropical climate

< Fig. 1 The northern Venetian Lagoon, Venice (Source: Maria Chiara Tosi, 2020).

Introduction

Wetlands are essential ecosystems. They cover only 6 per cent of the earth's surface, or approximately 12 million square kilometers, but they absorb 30 per cent of the free carbon dioxide in the atmosphere and play a key role in supporting biodiversity (Pileri 2015). However, nearly 90 per cent of European wetlands – and 60 per cent of those in Italy – have been lost since the 1970s due to severe erosion related to human activities. Some wetlands are over-exploited for fish, fuel and water; others are drained and converted for farming activities and urban development. Even if safeguarded by the Ramsar Convention, wetlands are extremely delicate ecosystems. A 36 per cent decrease in plant and animal species is correlated with this erosion (Gardner et al. 2015).

The Venetian Lagoon is the largest wetland area in the Mediterranean basin (500 km^2). Like many other wetlands, it has been significantly reshaped by human activities, particularly through land reclamation for agricultural and industrial purposes. The landscape was previously characterized by extensive marshes that linked land and sea. Recent decades show a negative balance in the transformations of the salt marshes, marked by pronounced erosion. The main cause seems to be subsidence, resulting from the compaction of clay sediments and peat, followed boat traffic and natural wave motion (D'Alpaos 2010).

Spatial planning and design tools must be attentive to the diverse needs of this fragile ecosystem. They should consider the plurality of stakeholders, including both human and non-human actors, to address wetland-related and climate-driven challenges, and to advance governance systems for protection. Three primary considerations are important for spatial planning and design when dealing with wetland ecosystems. First, interventions should be guided by ecological perspectives. Second, planning should recognize the multiplicity of life forms and develop forms of representation that allow non-human entities to communicate their specific needs. Third, co-creation of social capital through strong collaboration among all actors present in the territory is essential for environmental protection.

The Wetland Contract is emerging as a governance instrument designed to address these challenges. The Wetland Contract has its foundation in the River Contract. Already tested in France, Belgium, Spain and Italy, the River Contract is a method of water management consistent with EU environmental policy (e.g., the Water Framework Directive, Floods Directive, River Basin Management Plan) that relies on the active engagement of the main stakeholders in participatory planning. The contract represents a formal agreement through which public and private territorial actors voluntarily commit themselves to realizing strategies and projects that balance public utility, private economic returns, social value and environmental sustainability. In Italy, River Contracts have been in use since 2000, taking shape through various institutional pathways across community programs and local and regional initiatives.

Following this model, the Wetland Contract brings together stakeholders within a defined region to jointly develop and share an action plan to preserve and enhance local wetland environments. This shared framework seeks to overcome governance fragmentation in wetland management, which often results in overlapping conservation goals and management practices that threaten sustainable development and biodiversity. By promoting coordinated decision-making across levels of governance, the

^ Fig. 2 The northern Venetian Lagoon, Atlante della laguna di Venezia (Source: https://www.atlantedellalaguna.it/?q=maps#tema-1-titolo).

Wetland Contract tool aims to mitigate tensions between preservation needs, economic activities (e.g., agriculture, aquaculture and tourism), natural heritage enhancement and environmental protection.

Recognizing the "hydro-social" dimension of wetlands – the spatial configuration of people, institutions, water flows, technologies and ecosystems – participatory practice must be closely aligned with decision-making structures. This is consistent with the EU Water Framework Directive from 2000 and earlier international frameworks, such as the Ramsar Convention (1975) and the Barcelona Convention (1978). This enables not only broad stakeholder inclusion but also the implementation of meaningful capacity-building and empowerment throughout the process.

The two following micro-stories draw a path, from a brief initiative to establish a Park for the Northern Lagoon to the ongoing experience of the Wetland Contract for the Northern Lagoon of Venice (WCNL) (figs. 1 and 2). They represent two different approaches, one seeking top-down approval and the other relying on bottom-up engagement, to manage the fragile and amphibious lagoon territory and to protect and promote the conflicting values supported by human and non-human actors co-existing in this territory.

The Attempt to Establish a Northern Lagoon Park

As a way to balance conservation and development in the Venice wetlands, the idea of a nature park gained momentum in the early 1970s. The great flood of 1966, which exposed the fragility of the lagoon system, catalyzed this process. Over subsequent decades, the concept of a lagoon park evolved through a series of

collaborations, initiatives and shifting priorities. Early efforts focused on physical, ecological and social degradation, and were led by Fronte per la Difesa di Venezia e della sua Laguna, an organization headed by Pino Rosa Salva (Mencini 2021). Throughout the 1980s, the idea of a lagoon park continued to develop through various conservation-focused exhibitions and publications (Mencini 2021).

In 2003, these ideas were formalized with the establishment of the Istituzione Parco della Laguna (Lagoon Park Institution). This public body aimed to safeguard the lagoon's environment and promote sustainable ways for local communities to live with and from the lagoon. It engaged stakeholders across Isola dei Laghi, Forte Mazzorbetto and Tenuta Scarpa Volo – three islands within the lagoon. A central function of the Istituzione Parco della Laguna was to support bottom-up projects by facilitating regional collaboration and assisting with fundraising (Favaro 2011).

Yet the broader goal of a nature park persisted. By 2014, political momentum for transforming the Istituzione into an official lagoon park had grown. In May of that year, a favorable vote in the Municipal Council led to the legal establishment of the Regional Environmental and Anthropological Park of Local Interest in the Northern Lagoon (Comune di Venezia 2014). After nearly half a century of development, the project appeared to have achieved firm political recognition. However, only months after the park's approval, Venice experienced a sudden shift in municipal leadership. A new administration was elected, stalling the environmental planning process mandated as part of the park's establishment. Under the new leadership, just two years later, in 2016, the designation of the park was revoked by the Municipalità di Venezia-Murano-Burano (2016).

Consequently, the media declared the park "dead" (*Live in Venice* 2016; *La Nuova di Venezia e Mestre* 2016; *Venezia Today* 2016). Opposing politicians argued that existing designations under UNESCO and Natura 2000 provided sufficient protection for the lagoon, and that establishing the park would add unnecessary regulatory layers to the management of the northern lagoon (Municipalità di Venezia-Murano-Burano 2016). Some interest organizations, including one of hunters, were also reported to be against the park (*Venezia Today* 2016). Additionally, critics questioned the park's geographic scope, contending that its effectiveness in managing the lagoon's complex socio-ecological dynamics would be limited if it covered only the northern section of the Venetian Lagoon. The attempt to establish a northern lagoon park failed because of a lack of political support and essentially because of political disagreement about how best to manage the wetland environment of Venice.

The park's long history as a concept but brief existence as an official entity reveals the complex political situation of environmental governance in Venice and the persistent challenges of developing collaborative, cross-sectoral visions. Although never formally implemented, the vision for the park promoted a holistic approach to lagoon management. It framed the lagoon as a space of integrated socio-ecological relationships, but the time was not ripe for an institutionalized framework for its management, beyond international designations.

The Wetland Contract for the Northern Lagoon of Venice: Lagoon as Commons

The Venetian Lagoon consists of three parts: the northern lagoon, the central lagoon and the southern lagoon. The northern lagoon perimeter – affected by the above-mentioned brief

institutional experience as a nature part – has been used to outline the territorial limits of the WCNLV initiative. This is a voluntary and bottom-up governance process that has been ongoing since 2021, led by Università Iuav di Venezia and co-funded by the EU through two Italy-Croatia Interreg projects, namely CREW (2018–2021) and GREW (2024–ongoing). The Iuav team focused on the northern part of the lagoon as a pilot area to test the Wetland Contract as a participatory governance tool because the 220 km² area of the northern lagoon is the best-preserved in terms of its ecological balance, boasting high biodiversity, with both sandbanks and marshlands. Moreover, it is also a field of conflict, where various projects, claims and political interests intersect (Pace et al. 2022).

The Wetland Contract aims to identify feasible actions undertaken by various stakeholders and local actors that integrate environmental protection with economic and social development from a sustainable perspective. It is a tool that primarily advocates for human and non-human subjects that are usually underrepresented, such as interest groups and third sector associations, but also flora, fauna and naturalistic site-specific values linked to this amphibious territory (De Marchi and Pace 2022).

The process began in September 2019 and consisted of five phases: (1) information sharing and intention declaration, (2) animation and listening, (3) proposal and dialogue, (4) negotiation and commitment and (5) conclusion and signature. It has involved a variety of participatory exercises, such as individual and collective meetings, a survey, several online forums, roundtables, and tours by land and water. It has involved different stakeholders (e.g., municipality representatives, associations, other public and private bodies, and institutions) to engage them in the process, collecting ideas, and positions on the most urgent topics to be implemented in the lagoon. The set of values that emerged outlined the Action Plan as the primary operational document for governance, establishing stakeholders as responsible for a wide range of activities to be carried out over the five years of the contract's implementation. In July 2021, the WCNLV was finalized, and it is currently monitored by two Lagoon Assemblies per year, where contract signatories meet and discuss the implementation of activities. Assemblies are also an arena to welcome new potential signatories and to discuss synergies and new projects.

The WCNLV has achieved several important milestones so far, including expanding its network, connecting with partners and projects and increasing mutual knowledge about the lagoon's life cycle. On the other hand, WCNLV has faced obstacles and problems during the process, mainly related to the political opposition of some public authorities like the Metropolitan City of Venice, which conditioned the involvement of some institutional partners in the project, and, in some cases, demanded their withdrawal. During the second ongoing phase supported by the GREW project, the Wetland Contract will be implemented as a climate change strategy tool with mitigation measures carried out by local stakeholders and involving very specific activities to address climate change in everyday life.

The WCNLV has generated a strong sense of shared responsibility for the lagoon in the community. In this sense, the lagoon is being recognized as a commons and the Wetland Contract is intended as a set of material and immaterial matters necessary to fulfill collective social and ecological needs (Capone 2023). Considering the lagoon as a commons encourages

a life-centered perspective in which all living beings and biodiversity are worth equal dignity and consideration. The tool is based on a new holistic and ecological concept to promote the sustainable governance of water systems.

Conclusion and Policy Recommendations

The Venetian Lagoon is an essential counterpart to Venice, the world-famous built heritage. Without the lagoon, the ancient city would lose much of its charm and beauty. The experiences mentioned above are part of a long history of efforts to protect the lagoon's fragility and biodiversity. They also reveal that a top-down approach, which established a representative governing body for just one area of the lagoon, was vulnerable to political criticism due to its lack of shared ownership.

In contrast, the Wetland Contract represents a novel, voluntary form of governance. However, because its influence has not yet been able to interact effectively with public policy to guide decisions about the lagoon, it remains a recognized but non-institutional process. While this lack of institutionalization allows for greater flexibility of involvement, it also limits its influence on formal decision-making. Being run by an academic organization rather than a government agency makes the WCNLV a unique governance model. Its current application to new problems related to climate change places it in an experimental framework where ideas can be tested as possibilities that, if accepted, could be integrated into institutional practices.

To strengthen this promising model, public and political bodies must provide the Wetland Contract with greater support and reduce institutional distrust to upscale this governance model into a systemic management tool capable of addressing less represented issues of the lagoon ecosystem. It is vital to trust the participatory process that involves trans-scale and multi-actor dimensions, as this democratic approach fosters the socio-ecological relationships essential for shaping the contemporary territory. Finally, all stakeholders must exercise patience, recognizing that bottom-up governance processes inherently have long implementation times, requiring a sustained and committed investment to achieve lasting results.

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Exploring the Venetian Lagoon: Toward A New Culture of Environmental Heritage

Maria Chiara Tosi, Luca Velo, Michela Pace & Mette Juhl Jessen

Abstract
Venice and its Lagoon, a UNESCO World Heritage property, epitomizes the challenges of water-related climate change. Historically, it has been an exemplary site of human life in close interaction with water. Today, with rising sea levels and intensifying storm surges, it offers a powerful case for developing cohesive, inclusive, and adaptive water management. The lessons emerging from Venice have relevance to other UNESCO heritage sites. In all its complexity, Venice underscores the need to recognize water's dynamic nature in governance and to avoid reliance on rigid, fail-safe solutions, instead emphasizing collaborative actions supported by political commitment. This article reframes the heritage of Venice and its lagoon as a dynamic, amphibious process, and argues that collaborative, adaptive governance is the only viable path to a sustainable future.

Policy Recommendations
- Recognize the dynamic practices and processes as central to the heritage of Venice and its Lagoon.
- Establish unified, adaptive governance models at the metropolitan level to harmonize overlapping regulatory bodies, align projects, and integrate ecological, economic and cultural strategies.
- Prioritize collaborative approaches in developing and implementing a management plan for the lagoon.
- Integrate approaches and visions across scales, from metropolitan management plans to local community initiatives.

KEYWORDS

UNESCO World Heritage
amphibious
dynamic
collaborative
contradictory

WATER ICONS

CLIMATE

Cfa: Humid subtropical climate

< Fig. 1 New implementation of the salt marshes quay in front of the northern lagoon, Venice (Source: Luca Velo, 2021).

Introduction

Venice and its lagoon exist in constant interaction with tides, sediments and storms. Climate change is intensifying and challenging these dynamics, making long-term adaptive planning urgent (IPCC 2023). The daily movement of water through canals, marshes and settlements is not only a physical process but also fundamental to life in Venice. As a UNESCO World Heritage property, "Venice and its Lagoon" challenges us to rethink heritage as more than monuments and buildings. Heritage here also includes practices, processes and relationships that adapt to shifting conditions (Riesto et al. 2022). The diverse visions, aspirations and projects related to heritage interpretation prompts reflection on what constitutes heritage – and for whom. This article examines the case of Venice and suggests how landscape and ecological systems can guide an approach to heritage that allows for uncertainty and change.

Defining the heritage of Venice and its lagoon is not straightforward. The lagoon is an amphibious environment where land and water interlace, and its value has long been contested. Multiple actors – including UNESCO, the EU, governments, local administrations, research centers, civic committees, fishers' cooperatives and cultural groups – advance competing visions. They focus on safeguarding monuments, protecting ecosystems, promoting tourism or sustaining everyday life, illustrating how narratives of memory, identity, authenticity and legacy are inherently flexible, shifting according to those who construct them and the agendas they pursue (Harvey 2001; Smith 2006). These terms have been mobilized across different contexts and periods to endorse understandings of heritage and to legitimize specific sets of values (Howard and Graham 2008). In addition, non-human actors – including tides, salt marsh vegetation and migratory birds – also shape the lagoon, but their roles are often overlooked. In this context, some local actors, such as fishing valleys, hunting associations and nature tourism promoters, play an ambiguous role: They help maintain a certain environmental balance, but deny the autonomy and agency of non-human species, treating them as profit tools. Only a few of them, such as Lipu Venezia, WWF Veneto and Laguna Viva, promote a cohabitant approach that foregrounds the ecological rights of non-human actors.

Heritage debates in Venice encompass built structures, canals, mudflats and islands, as well as the struggles, strategies and narratives of many actors. In the context of climate change, heritage becomes an arena in which questions of preservation, adaptation, ecology and the right to inhabit are negotiated, and sometimes contested.

Managing the Dynamic Environment of Venice and its Lagoon

From its origins, Venice's history has been tied to the delicate task of maintaining the lagoon's balance, a challenge that has sparked debate for centuries. The lagoon's distinctive environment shaped Venetian institutions early on, enabling the city to manage water with quite remarkable effectiveness. The Magistrato alle Acque, established in the early sixteenth century, monitored lagoon dynamics, coordinated decisions and implemented interventions such as sea defenses and river diversions (Grillo 1989; Bevilacqua 1995; D'Alpaos 2010; Bondesan and Furlanetto 2012). While today attention focuses on water levels, historically, the central concern was the balance of sediment dynamics. A well-known sixteenth-century dispute between Cristoforo Sabbadino, a hydrau-

^ Fig. 2 Canal routes, the lagoon and salt marshes (Source: Luca Velo, 2021).

lic engineer of the Magistrato alle Acque, and Alvise Cornaro, a humanist intellectual and landowner, illustrates these debates. Venice's brackish setting, where water and sediment entered from both sea and rivers, posed the acute problem of silting, particularly from the Brenta River. Both Sabbadino and Cornaro advocated diverting the Brenta outside the lagoon to reduce sedimentation. Their visions diverged however: Cornaro proposed sealing the lagoon off more firmly from the Adriatic, whereas Sabbadino argued for continued canal excavation and outward urban expansion toward the sea. In essence, the dispute contrasted a strategy of insulating Venice from natural dynamics with one of actively working with them (Tosi 2019; Bevilacqua 1995).

By the mid-twentieth century, new pressures tied to economic, industrial and residential growth emerged, clashing with the need to acknowledge the lagoon ecosystem's fragility. Industrial expansion at Porto Marghera, the excavation of shipping channels and large-scale land reclamation disrupted lagoon dynamics, accelerating the erosion of both natural and built environments (Montanelli 1969). The 1966 flood intensified concerns about flood hazards and sparked decades of debate over preservation and adaptation. The MoSE barriers, first conceived in the 1960s in the wake of the flood and only recently completed, revive the sixteenth-century question of whether Venice should be sealed off from natural dynamics or adapt to them. The MoSE project (Modulo Sper-

imentale Elettromeccanico) is a large-scale system of mobile barriers designed to protect the Venetian Lagoon from flooding caused by high tides (*acqua alta*). While the barriers promise security, they also raise concerns about ecological disruption (Benzoni and Scaglione 2020). Their limitations are increasingly evident: Barrier closures disrupt port operations, requiring ships to wait outside the lagoon and resulting in economic losses. Repeated closures also hinder the natural exchange of fresh and salt water, threatening the lagoon's ecological integrity (Umgiesser et al. 2004).

Since the 1980s, the Venetian Lagoon has been embedded in global heritage frameworks. UNESCO recognition brought cultural prestige and economic value, offering opportunities for both cultural and economic enhancement.[1] Yet climate change has highlighted how contested heritage can be. The status of environmental resources as common heritage has become a key battleground in the ecological transition, underscoring the importance of heritage within a multi-species safeguarding perspective (Celermajer et al. 2021). This has led to various mitigation and adaptation measures. For example, the protective measures taken by the EU Project LIFE VIMINE 2017-2020 (https://cigno.atlantedellalaguna.it/maps/1611/view) do not therefore appear to have disturbed the natural dynamics of the salt marsh vegetation, while fostering economic potential and social cooperation. At the same time, speculative practices – such as the privatization of some islands, and their conversion into luxury facilities including accommodations and restaurants – reveal how easily heritage can be turned into an extractive resource, generating new conflicts over ownership and accessibility.

Contemporary Governance Challenges

Since its founding in the fifth century, Venice has a long history of balancing natural and human forces that frames today's challenges. Venice still depends on managing the delicate interplay of sea, land and sediment, but climate change makes this more difficult. Rising seas, more frequent storm surges and the loss of biodiversity place new demands on governance.

Despite extensive research and reflection on management, restoration and preservation over the past few decades (Tosi et al. 2023), the lagoon paradoxically suffers from a prolonged phase of administrative inertia marked by delays and contradictions. This stagnation has been exacerbated by the scandal and protracted construction of the MoSE system, which has fueled unmet expectations and public indifference, often shaped by overly simplistic and culturally inadequate positions (D'Alpaos 2019). The MoSE project monopolized both financial resources and political attention. Initiatives such as the lagoon's Morphological Plan (Umgiesser et al. 2004) – which identified as priorities the reinforcement of port channels and other lagoon structures using shapes and materials not permitted under current regulations – failed to gain approval from the Italian Ministry of the Environment. This decision reaffirmed that environmental rebalancing remains possible and that any future development must be compatible with it. At the same time, small-scale projects such as marinas, shipyards and embankments continue to treat the lagoon as an extractive site.

Adding to the challenges, stakeholders in the region struggle to influence public opposition and local – and even national – opinion, result-

1. UNESCO declared Venice and its Lagoon a World Heritage Site in 1987, recognizing the presence of a widespread and diverse heritage: environment and landscape, archaeological, historical, architectural and ethnological (Ministry of Culture 2006).

^ Fig. 3 The entrance space in front of a traditional rowing association (Remiera), Cavallino Treporti (Source: Luca Velo, 2023).

ing in a failure to develop critical potential and informed demand for competent governance (Fabbri et al. 2020). Within this framework, numerous public and private initiatives are heavily altering the trajectory of the lagoon territory, often appearing as isolated, fragmented projects lacking a common strategy or unified perspective. Administrative frameworks, complicated by overlapping ordinary, special and commissioner-based regulations, further fragment governance, especially in key sectors such as water management and soil resources. Such issues are accompanied by interventions along the lagoon's edges, seemingly minor yet impactful, such as shipyard modifications along the Canal Salso and the new marina in Campalto, next to Marco Polo Airport.

Without shared planning anchored in common climate scenarios, responses remain reactive, often driven by short-term emergencies or entrenched economic concessions (Baldacci et al. 2022). Governance challenges connect directly to the city's social fragility. Over-tourism,

^ Fig. 4 A recent intervention: renovation for the new embankment, Punta Sabbioni, Northern Lagoon, Venice (Source: Luca Velo, 2023).

depopulation and the risk of Venice becoming a "museum city" are inseparable from ecological decline – including erosion, invasive species and salinization (De Marchi et al. 2022; Salerno 2020).

Since 2024, the new Lagoon Authority has overseen Venice's MoSE system, marking a significant change in the lagoon's governance. This authority introduces innovative and adaptive approaches to territorial and ecosystem planning, treating the Venetian Lagoon as a future laboratory for sustainable coexistence between land and water. Renewed efforts are essential today to navigate the complexity of competing projects and proposals, aligning them in cohesive strategies that address the region's fragilities while preserving its unique amphibious identity.

Stand-Alone Projects or Collaborative Actions?

Large strategic projects often dominate Venice's management, sidelining alternatives. The clearest example is the vast MoSE project, which illustrates the risk of trying to simplify lagoon management with one centralized solution. Venice's amphibious ecology depends on overlapping systems and adaptive practices. Simplification undermines resilience, and ensuring habitability, economic viability and ecological sustainability requires what Pes (2020)

calls a "difficult transition." Replacing the complexity of the lagoon's actors and projects with progressive simplification contradicts the principles underpinning one of the most fragile environments where land and water meet. Such myopia cannot safeguard the heritage of this site.

By contrast, collaborative and bottom-up initiatives show how adaptive strategies can emerge. Environmental restoration projects repopulate salt marshes, plant seagrasses and restore sediment flow. The EU Life Barene and Seresto projects have reintroduced native vegetation and promoted the spontaneous regeneration of tidal habitats, while Refresh has tested nature-based solutions for improving water quality and biodiversity. Similarly, under the EU Horizon framework, projects such as Waterland and RestCOAST explore integrated coastal management approaches, combining hydraulic engineering with ecosystem restoration to increase the lagoon's resilience to sea level rise. In parallel, governance projects foreground the cultural and ecological value of the lagoon, building alliances between professionals, communities and institutions (e.g., EU Interreg IT-HR CREW, GREW). These efforts create new forms of knowledge, care and economy, strengthening adaptation.

This broad range of initiatives reveals that there are as many Venetian Lagoons as there are projects seeking to shape it. Recognizing and engaging with this diversity can turn contestation into a resource for collaborative adaptation rather than a source of fragmentation.

Conclusion

Venice and its lagoon are more than a collection of heritage, imaginaries and challenges: They are a site of practices and processes. Preserving this heritage means recognizing historic strategies of governance and ecological dynamics that sustain amphibious life, and acknowledging the dynamic practices and processes as central to the heritage of Venice and its lagoon.

Climate change magnifies long-standing challenges, making adaptation inseparable from heritage. Salt marshes, tides and sediments are increasingly understood as heritage alongside buildings and monuments. Yet contemporary administrative inertia, combined with the prioritization of isolated safeguarding projects, places this heritage at risk. A clear articulation of what constitutes the heritage of Venice and its lagoon is becoming essential. Recent initiatives show that lagoon protection must be pursued through collaborative actions grounded in strong political commitment.

This calls for policy measures that recognize dynamic practices and processes as central to the lagoon's heritage, and that establish unified, adaptive governance models at a metropolitan level to harmonize overlapping regulatory bodies, align projects and integrate ecological, economic and cultural strategies. Such an approach would support collaborative development and the implemention of a lagoon-wide management plan, integrating approaches and visions across scales – from metropolitan planning to local community initiatives – and ensure coherent, inclusive and sustainable stewardship.

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Environmental Monitoring for Water Heritage: Innovations and Challenges for the Grand Canal of Suzhou, China

Ting Wang

Abstract

The Grand Canal in China is a regional waterway infrastructure serving multiple functions, including transportation and water regulation, and historically, it has supported economic growth and urbanization along its route. Within China's unique decentralized environmental management system, the multifaceted value of the Grand Canal presents distinct challenges, including inter-regional and inter-departmental challenges. This article examines the latest water management initiatives along the Suzhou section of the Grand Canal and explores the role of environmental monitoring in protecting this UNESCO World Heritage property. The experimental integration of underwater-surface-aerial heritage monitoring with the Joint Meeting System in Suzhou provides a nuanced perspective on the interplay between technology and sustainable development.

Policy Recommendations

- Grand Canal heritage management agencies should collaborate with private enterprise to assess available monitoring technologies and adapt them to contextual policies and environmental challenges, thereby establishing a localized heritage monitoring platform.
- The Grand Canal monitoring platform can be enhanced by expanding environmental monitoring beyond water resources to include biodiversity conservation, particularly in response to ecological crises.
- Technical environmental monitoring platforms need to be integrated into the reform of management mechanisms to develop a comprehensive governance model that effectively incorporates multiple government agencies, the private sector and the public.

KEYWORDS

UNESCO World Heritage
Grand Canal
environmental monitoring
water management
climate change

WATER ICONS

CLIMATE

Cfa: Humid subtropical climate

< Fig. 1 Cargo vessel on the Suzhou section of the Grand Canal, reflecting the canal's active transport role and the need for modern water management solutions (Source: 云在动, 2021. CC BY 4.0, via Wikimedia Commons).

Introduction: The Grand Canal in Suzhou

In June 2014, at the 38th Session of the UNESCO World Heritage Committee, the Grand Canal of China was inscribed on the World Heritage List. This joint application involved 27 cities along the Grand Canal, with the Suzhou section an integral component.

The heritage area of the Suzhou section of the Grand Canal stretches from the confluence of the Beijing-Hangzhou Canal (Grand Canal) and Shantang River in the north to the confluence of the Beijing-Hangzhou Canal and Taipu River in the south, covering an area of 642 ha, with a buffer zone of 675 ha (UNESCO n.d). The Suzhou section comprises seven heritage sites and five ancient river channels (fig. 2). These are the ancient sites that facilitated cultural activities associated with the Grand Canal.

These multiple canal segments, excavated across various historical periods from 495 BC to 1950, with a total length of about 73 km, represent one of the longest continuously used – and currently one of the busiest – inland water transport routes among the various sections of the Grand Canal (Huang and Yang 2023). Frequent water transportation and climate-related disasters, including storms and floods, contribute to riverbank erosion and water pollution issues in Suzhou. These challenges have made environmental monitoring an essential aspect of Suzhou's heritage management.

Existing literature on the Suzhou section of the Grand Canal mainly focuses on the preservation and development of historical culture. Vannoorbeeck and colleagues (2019) provide historiography detailing how the canal's evolution has influenced urbanization and territorial development in Suzhou since 514 BC. Xu and colleagues (2019) compare industrial heritage conservation along the Grand Canal in Suzhou with other sites in the Jiangnan area. Recent popular discourse and literature emphasize the development of the Grand Canal Culture Corridor, a new national policy associated with tourism revitalization (Wang et al. 2019; Chen 2019; Zhang et al. 2023; Gu et al. 2024). However, there is an absence of systematic analysis of the government mechanisms concerning water environment management related to World Heritage and its interplay with cultural preservation.

Considering that absence, this study examines the latest water management initiatives in the Suzhou section of the Grand Canal. The research questions are as follows:

1. How has the Grand Canal's World Heritage management been institutionalized in Suzhou?
2. How can new environmental monitoring technologies be integrated into World Heritage management locally?
3. What challenges hinder the technologies' implementation and how can they be addressed?

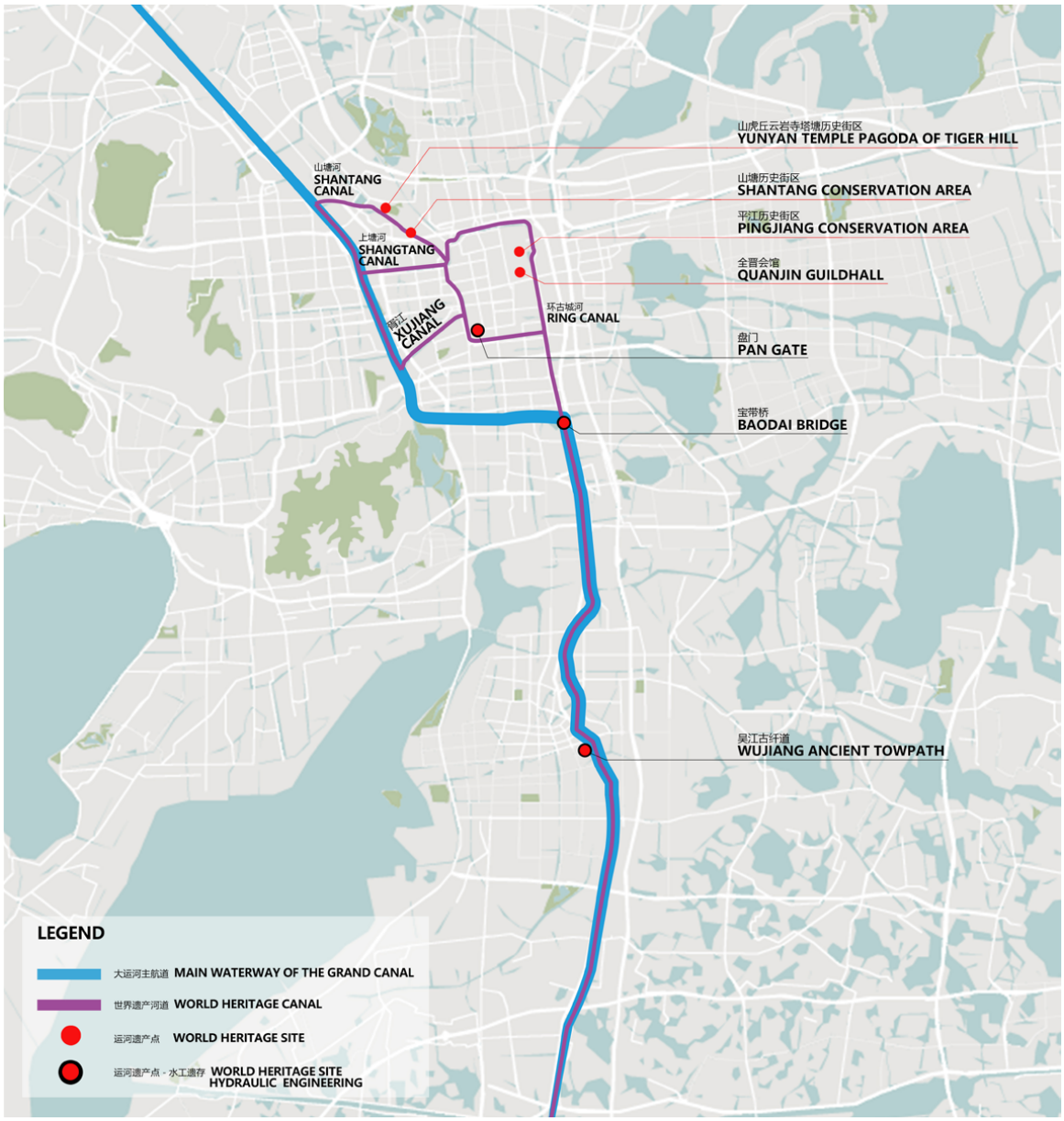
The article focuses especially on recent digital management practices along the Grand Canal in Suzhou, drawing on literature, media and interviews.

Suzhou is actively working to leverage canal water environment data monitoring as a foundation for heritage management. Issues identified through monitoring are addressed through the Joint Meeting System for the Protection of the Grand Canal – a collaborative governance framework facilitating Grand Canal management across various government functional departments. The case of Suzhou addresses the growing demand for enhanced data and knowledge sharing in the sustainable development of

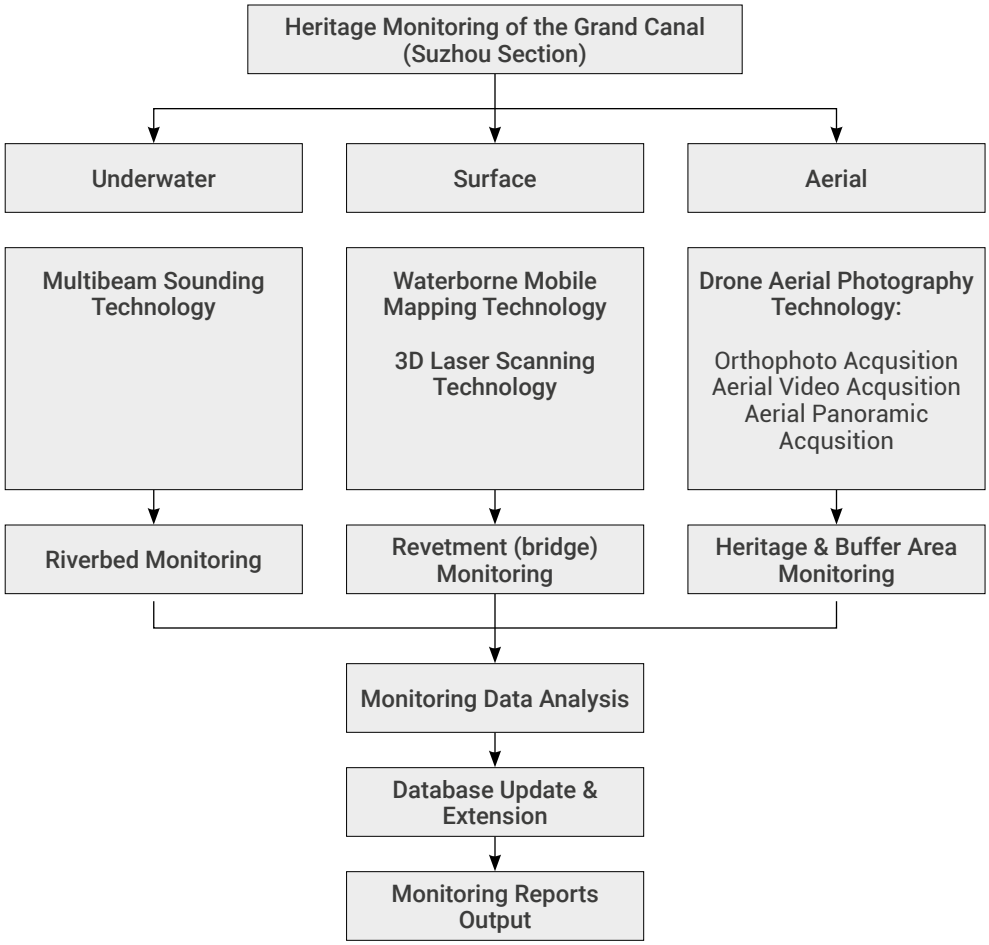
water heritage sites (Mager 2024). While Suzhou's monitoring framework has room for enhancement – e.g., involving its lack of integration with biodiversity monitoring – it highlights the potential and challenges of establishing water management practices for World Heritage properties in China and beyond.

Institutionalized Management: Data Monitoring, Platform and the Joint Meeting System

The Grand Canal Heritage Conservation and Management Office in Yangzhou, formerly the office responsible for the joint application for the World Heritage status of the Grand Canal,

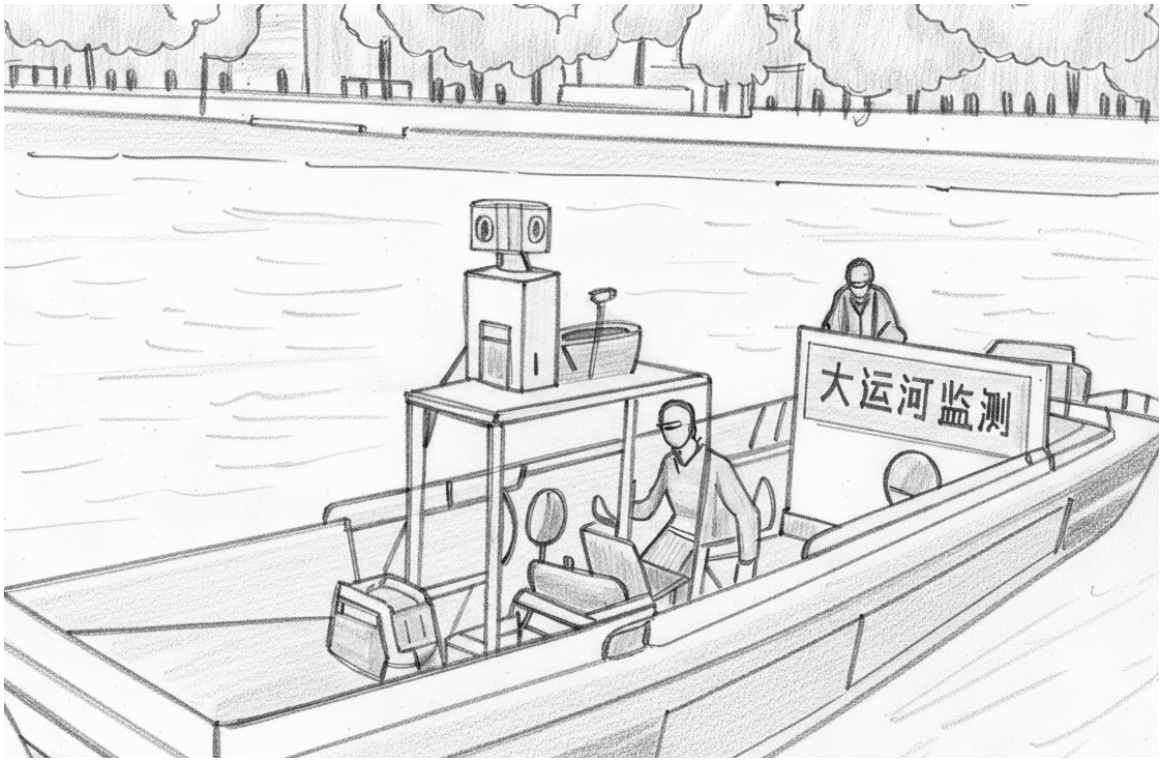


^ Fig. 2 The UNESCO World Heritage area of the Suzhou section of the Grand Canal in China (Source: Ting Wang, 2024).



^ Fig. 3 Heritage Monitoring Framework for the Suzhou Section of the Grand Canal (Source: Ting Wang, 2024).

serves as the primary institution overseeing cross-city regional heritage protection management along the Grand Canal. The management plan requires each city to have a corresponding leading management institution. In 2014, the Suzhou government established the Suzhou Grand Canal Heritage Monitoring Center (SGCHMC) under the Suzhou Cultural Heritage Conservation Institution (a subsidiary unit of the Municipal Bureau of Culture, Radio, Television, and Tourism), tasked with heritage monitoring and daily management of the Grand Canal heritage (Suzhou section). The Suzhou Cultural Heritage Conservation Institution was primarily responsible for managing architectural assets in Suzhou, but it lacked experience in handling water and environmental issues. Existing canals are managed separately by different departments related to distinct functions: the water bureau oversees water storage, the transportation department handles shipping volumes, the environmental department monitors water quality and the urban planning and construction department is responsible for tourism development. These divisions reflect the evolving culture of the Grand Canal in modern society. However, when conflicts arise between these functions, how can they be addressed?



^ Fig. 4 The Grand Canal water survey boat, equipped with a quantitative river landscape collection system including laser scanning, image capture, positioning and orientation capabilities, completes the image data collection of the water surface, embankments and bridges of the Grand Canal (Source: Ting Wang, 2025).

What is the impact of excessive cultural development on water environment conservation? How to position the new heritage management of the Grand Canal within the existing urban governance framework? SGCHMC was established to answer such questions and has proposed data monitoring to integrate cultural and water environment management in the Grand Canal heritage.

Monitoring is the first step in water environment management. Monitoring the Suzhou section of the Grand Canal involves daily manual inspection, specialized monitoring by various functional departments and heritage-specific monitoring (Suzhou Cultural Heritage Conservation Institution 2019). Since 2019, heritage-specific monitoring has included the underwater–surface–aerial three-dimensional monitoring method. "Underwater" refers to using multi-beam technology to collect depth and underwater bed morphology data, recording changes in the Grand Canal's watercourse. "Surface" involves comparing data from multiple periods to monitor changes in embankments and hydraulic structures. "Aerial" involves using remote sensing and aerial photogrammetry to survey and monitor land use changes within the protection zone. This enables monitoring of construction activities, environmental protection and landscape control along the Grand Canal.

Integrating monitoring data with existing government platforms has been a major challenge in

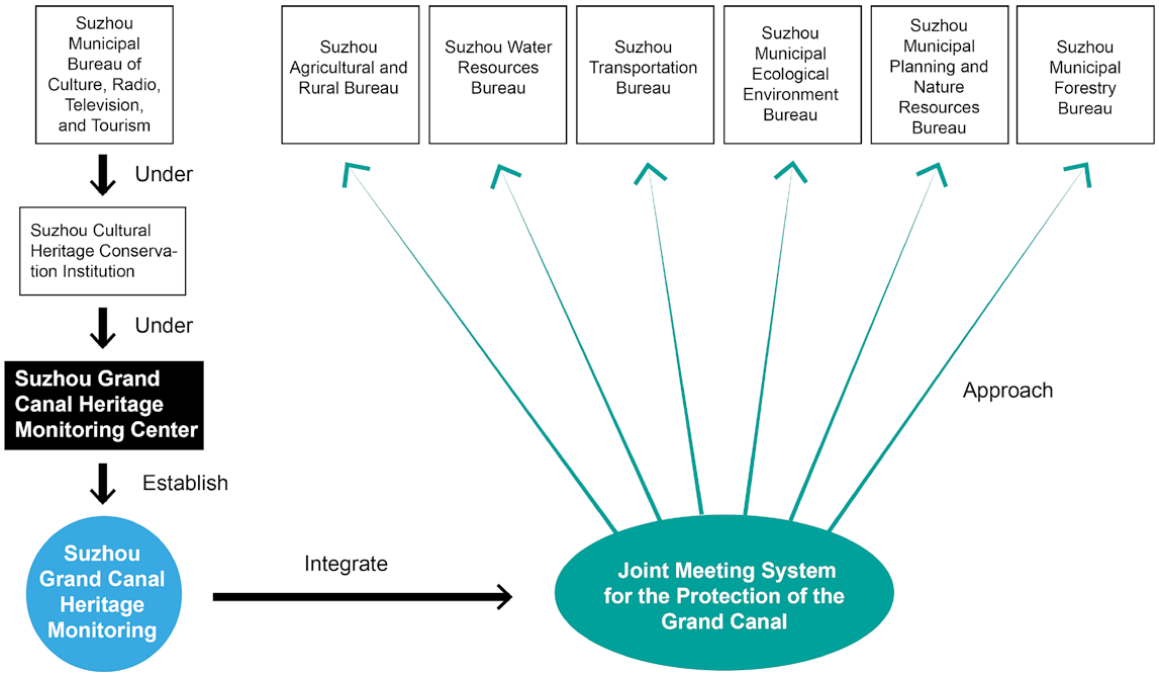
Target	Category	Indicator	Data Source
Active Canals; Historical Canals; World Heritage properties	Heritage Entity	Riverbed morphology / Structural and material stability	Underwater monitoring by SGCHMC / Aerial monitoring by SGCHMC
		Embankment preservation	Water surface monitoring by SGCHMC
		Water quality	Environmental Protection Bureau
		Water level	River Management Office
		Water surface floating objects	River Management Office
	Influencing Factors	Precipitation	Meteorological Bureau
		Natural disasters	Meteorological Bureau
		Navigation traffic	Navigation Management Bureau
		Ship collisions	Water surface and aerial monitoring by SGCHMC
		Construction projects	Aerial monitoring by SGCHMC & Planning Bureau
		Tourist volume	Tourism Administration Office
	Supporting System	Fire safety hazards	Tourism Administration Office

^ Table 1. Adapted 12 key indicators for the Suzhou Grand Canal Monitoring Platform (Source: Ting Wang, 2024).

implementing the Heritage Monitoring Framework in Suzhou. Previously, the Suzhou Cultural Heritage Conservation Institution relied on a national monitoring platform with 59 indicators, many of which were irrelevant to the management of the canal, difficult to access due to cross-departmental constraints, or unsuitable for quantitative assessment. To address this, the government institution partnered with a private technology company to develop a tailored Suzhou Grand Canal Monitoring Platform, refining the monitoring platform to 12 key indicators through fieldwork and interviewing frontline monitoring officers and other stakeholders (table 1). By leveraging drone footage and automated reporting, heritage officers can detect anomalies, such as unauthorized construction or environmental degradation, and submit digital inquiries to relevant authorities for verification and enforcement. Additionally, the platform facilitates cross-departmental data sharing through enterprise service bus (ESB) integration, allowing agencies to log in and contribute monitoring data securely. This initiative enhances localized heritage management and improves interdepartmental collaboration, streamlining administrative processes and ensuring more effective protection of the Grand Canal's cultural and environmental integrity.

To improve the utilization of environmental monitoring data in addressing conflicts between cultural development, in 2014, the Suzhou government established the Joint Meeting System for the Protection of the Grand Canal Heritage.

Unlike the vertical management model used in Canada's Rideau Canal, where a specific department handles administration and enforcement for the Canal (Parks Canada 2005), Suzhou's



^ Fig. 5 The heritage management mechanism of the Grand Canal of China (Suzhou Section) (Source: Ting Wang, 2024).

"Joint Meeting System" operates horizontally, coordinating the management of the canal across different departments. Representatives from 14 government functional departments, such as Ecology, Water Affairs, and Forestry, participate in preserving and utilizing the Grand Canal's cultural heritage. This system involves holding regular interdepartmental meetings to address issues related to illegal construction, water use conflicts and data sharing that cannot be resolved through the online platform (Xiong 2019). Starting as a pilot program in Jiangsu Province, the Joint Meeting System was officially legitimized at the national level in 2019, involving different ministerial leaders managing the China Grand Canal (State Council Office 2019).

The integration of the Joint Meeting System and data monitoring serves as a reference for developing water management in relation to the Grand Canal heritage. China's water management challenges have long been known as "Nine Dragons Run the Water" (Hou 2001; Xing 2015). While the Water Affairs Bureau oversees rivers, the issues of waterways and their adjacent spaces also involve responsibilities across various management departments, such as those devoted to urban planning, ecological environment, forestry, transportation and cultural relics. Land ownership on the sides of the canal also varies, further complicating water management efforts. Monitoring data in the Suzhou section of the Grand Canal helps to visualize water management issues primarily related to water pollution, degradation and erosion of embankments, and unauthorized construction in buffer zones around the waterway. In 2020, the Suzhou Grand Canal Heritage Monitoring Center issued 28 management letters to territorial government departments addressing the identified issues with data support (Suzhou Gov-

ernment 2021), convening multiple joint meetings with relevant departments to resolve these issues. Meanwhile, data from riverbed scans in heritage-specific monitoring supported the river dredging process initiated by the Water Affairs Department.

Biodiversity Monitoring and Multiple Actors Involved in Platform Governance

The impacts of climate change on the Grand Canal are multifaceted. Climate disasters like storms, typhoons, and floods directly impact the canal, along with changes in precipitation patterns that affect water levels and flows (Fu 2022). Meanwhile, some slow-onset impacts of climate change – e.g., riverbank weathering, erosion, changes in groundwater levels, and foundation settlement – also pose a danger to cultural heritage sites (Lefèvre 2014). Suzhou Grand Canal heritage monitoring has tackled the drastic and less visible impacts of climate change by including data on water level and quality submitted by the Water Affairs Department – such as (temperature, total suspended solids, total nitrogen, total phosphorus and chlorophyll a), as well as river spatial data (riverbed topography, depth ratios and water depth changes) (Suzhou Cultural Heritage Conservation Institution 2023).

It is important to note that climate change also affects the biodiversity of canals and their surroundings, in a process of "slow violence" (Nixon 2011). The Grand Canal not only serves as a national corridor for economic and cultural exchanges but also as a biodiversity corridor. Shifts in temperature can alter habitat conditions within and around the canal, affecting the

^ Fig. 6 A white heron standing on the Wujiang Ancient Towpath with naturally growing weeds. The towpath divides the canal into two different wetland ecosystems (Source: Ting Wang, 2024).

species that can thrive there, such as water microorganisms and birds. Warmer temperatures and altered water patterns can create more favorable conditions for invasive species (Zhang 2022). The natural decay of the canal heritage also creates a site for spontaneous plant growth, which lacks proper monitoring (DeSilvey 2017; fig. 6).

There remains a significant gap in the collection of biodiversity data for the Grand Canal and its adjacent areas. The Suzhou Grand Canal Heritage Monitoring Center can further explore how to link biodiversity data with monitoring efforts in other connected areas, such as rivers and wetlands managed by other departments. This effort will enhance environmental conservation management in Suzhou on a broader scale.

The newly enacted Regulations on the Protection, Inheritance, and Utilization of the Grand Canal Culture in Suzhou City in 2023 emphasize the importance of involving diverse actors in heritage management (Suzhou Government 2023). As China advances the development of the Grand Canal Cultural Corridor, the need for effective management coordination will increase, necessitating greater involvement from non-governmental entities such as community residents, local businesses and international organizations. Exploring reforms to the Joint Meeting System that might make it a more inclusive platform for governance of the Grand Canal is a direction worth considering.

Conclusion

As a continuous and dynamic landscape, the Grand Canal presents complexity in spatial and cultural conservation. Suzhou's management of the Grand Canal illustrates how data and technologies can be integrated with managerial innovation. The combination of the underwater-surface-aerial monitoring platform and the Joint Meeting System exemplify Suzhou's innovative approach to Grand Canal heritage management. The applicability to other parts of the Grand Canal system and to UNESCO Heritage assets worldwide merits investigation. While technological advancements have made data monitoring the primary step in management, it is important to note that heritage conservation should not solely rely on technological fixes (Huesemann and Huesemann 2011; Fomin and Laužikas 2024). Designing collaborative management systems involving diverse participants effectively prompts reflection about what data to collect and how to utilize it, highlighting the key to World Heritage management, especially in the field of water.

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Modern Water Management and the Challenges of Climate Change at the World Heritage Property Upper Harz Water Management System

Manuela Armenat, Christian Bellak & Andreas Lange

Abstract

The Upper Harz Water Management System is an outstanding example of effective water management over the centuries. Through historical development and adaptive change over centuries, a multifunctional system has evolved that remains in active use today. Since the site's UNESCO designation as a World Heritage property in 2010, continuous monitoring and maintenance have been integral to its management. In recent years, challenges arising from climate change and safety-related hydraulic engineering issues, as well as financial constraints, have put the monument under increasing pressure. With the common goal of ensuring that the historic elements and their operation continue to contribute to a wide range of Sustainable Development Goals (SDGs) and provide essential public services in the future, changes are necessary. World Heritage management that incorporates the importance of water management is therefore essential, just as, conversely, the World Heritage and the monument play a supporting role and basis for the management of water in the Upper Harz Water Management System.

Policy Recommendations

- Maintain constant communication and coordinated, integrated management to balance hydraulic engineering, economic, World Heritage, and sustainability requirements, fostering a willingness to compromise and find future-oriented solutions.
- Recognize that a Living World Heritage property is subject to change, and as for this, it is important to clearly define the non-negotiable features to ensure the preservation of its Outstanding Universal Value (OUV).

KEYWORDS

UNESCO World Heritage
energy
recreation and tourism
mining history
integrated management

WATER ICONS

CLIMATE

Cfb: Oceanic climate

< Fig. 1 Hirschler-Pfauenteiche pond cascade (Source: Stiftung Welterbe im Harz 2018, photographer: Stefan Sobotta).

Introduction

The Harz low mountain range is located in the center of Germany. Due to its geological development, it is particularly rich in ore deposits. Mining was carried out in the region for many centuries, particularly for the non-ferrous metals lead, silver, copper and zinc. Upper Harz ore mining reached depths of 300 m as early as the seventeenth century. An energy supply was essential for pumping the sump water and transporting ore, materials and personnel. Water played an important role as a source of energy. Over the course of 800 years, a highly complex surface and underground water power system developed in the high altitudes of the western Harz. Even today, the water and the historic facilities are still used in various ways. The status of the Rammelsberg mine, the old town of Goslar and the Upper Harz Water Management System as an ensemble of monuments and, since 2010, as a joint World Heritage property, entails a particular responsibility for the protection and preservation of these facilities under changing conditions, including climate change.

The Upper Harz Water Management System: Elements and Function

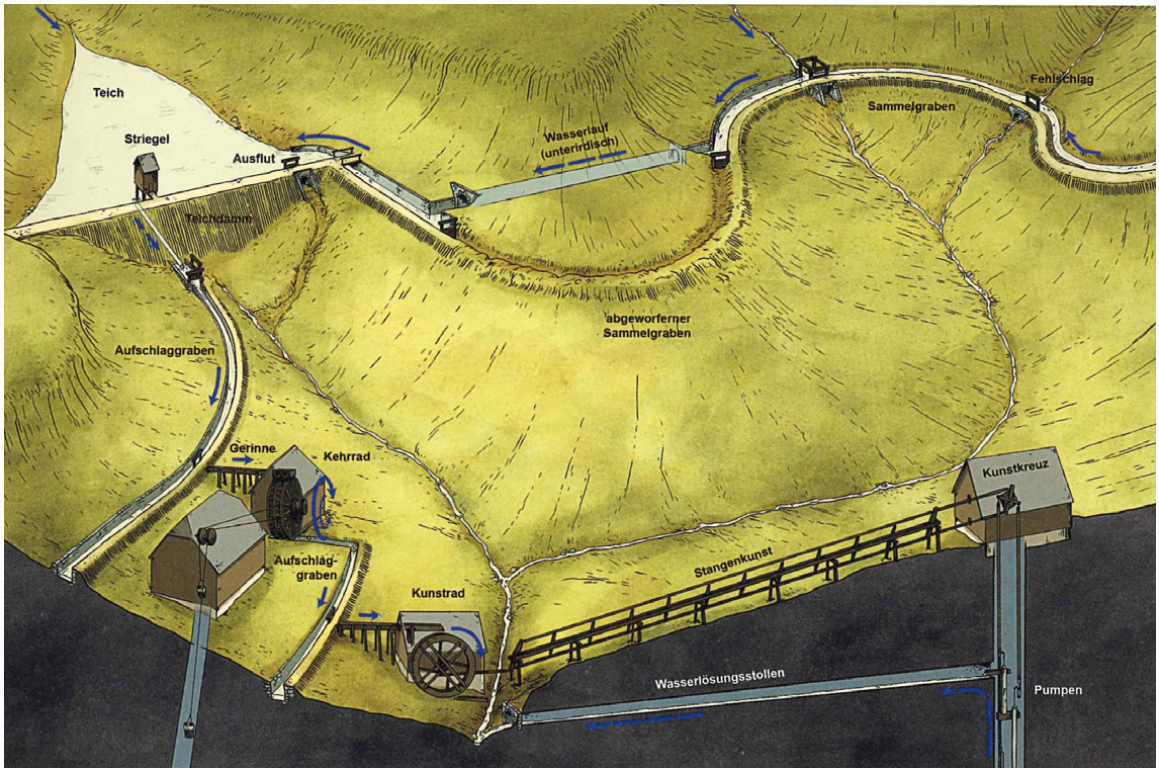
The aim of the world's largest pre-industrial energy supply system was to provide the Upper Harz mining industry with water on a permanent basis and, if possible, all year round. Its function and components are briefly described below (see fig. 1; also Harzwasserwerke 2011, Malek-Custodis 2022, 81–9).

The water was channeled parallel to the slope from the distant areas and raised bogs via collecting ditches, starting from streams. In order to shorten a ditch or overcome the unfavorable topography of the terrain, so-called water tunnels were driven into the mountains. This not only shortened the route, but also prevented the water from freezing in winter. The water was directed into the storage ponds. These artificial ponds were mainly constructed with dams made of earth and turf sods. The only exception to this construction method is the Oderteich, near Sankt Andreasberg. This dam was built from granite stones, with granite grit used as sealing material. The excess water was drained via the outlets. The water flowed from the ponds to the wheel pits via surcharge ditches. There it drove sweep wheels or waterwheels, which were used for transportation or for pumping and driving stamp mills (for crushing ore). Finally, after being used several times, the water ran out of the mountain through so-called water drainage galleries to receiving watercourses. To supply as many users as possible with the same water, "keeping the water high" became a central principle.

Today, a large number of these water management facilities (see fig. 2; table 1) are still in operation and are used for various purposes. The operational water-bearing infrastructure has been managed and maintained by Harzwasserwerke GmbH, the regional water utility, since its transfer was completed in 1996 (a process initiated in 1992).

Living World Heritage and Climate Change

The Upper Harz Water Management System has been in continuous use for centuries. Since the 1980s, it has undergone a significant change in importance: from being a focal point of the energy supply system to a recreational and tourism attraction. However, many of the old functions are still in use today (see fig. 3, also Harzwasserwerke 2011, 18–19). Climate change is currently playing an increasingly im-



^ Fig. 2 Functional diagram of the Upper Harz Water Management (Source: H. J. Boyke in the 1990s, colored by J. Bintakies in 2013).

portant role in management and operation (Armenat 2022). Various measures for the Upper Harz Water Management System are therefore being discussed, for reasons that include safety. Solutions are being sought that reconcile monument protection, World Heritage conservation and water management concerns. The various uses, challenges and possible measures are presented below.

Recreation and tourism

Of the sixty-three ponds in operation today, ten ponds have been designated as bathing ponds by the Harzwasserwerke GmbH and four have camping facilities. Fishing is permitted as a recreational sport at more than half of the ponds. The water management elements characterize the landscape of the Upper Harz and are a flagship for the region, combining culture and nature. The Upper Harz is a popular hiking destination. The facilities contribute directly to SDG 3 (good health and well-being). In addition, the mining museums in the region and guided tours for locals and visitors fulfill the educational and public outreach mission of the World Heritage property and SDG 4 (quality education).

Ecological niche

Over the centuries, special flora and fauna have developed in the ponds due to the changing water levels caused by the operation. Red-listed species (at risk of extinction) such as the European crayfish can be found in the nutrient-poor

^ Fig. 3 Overview of water management in the northwestern Upper Harz (Source: A. Dumreicher, 1866).

Element	In total	In operation	Archaeological monument
Pond	95	63 (10 Mio. m³)	32
Ditch	309.3 km	69.7 km	239.6 km
Water tunnel	30.7 km	21.3 km	9.4 km
Water drainage gallery	92.2 km	4.5 km	87.7 km

^ Table 1. Elements of the Upper Harz Water Management System (UNESCO 2010).

and cool still waters. These species can survive here thanks to the favorable habitat and isolated location. Some of the ponds around Clausthal-Zellerfeld are also Flora Fauna Habitat (FFH) areas (LAVES 2011, 4). However, climate change and rising water temperatures are also causing problems for plant and animal communities. The nature conservation authorities have agreed on plans with the the site's operators, Harzwasserwerke GmbH, to ensure the survival of plants such as the whorled knotted chickweed, the stag's head, the beach lily and the small sedge reeds in the affected water bodies. Plans include regulating the water levels in the ponds. In this way, the ponds also contribute to SDG 14 (life below water - bodiversity in water bodies).

Power generation

Until the early 1980s, numerous Upper Harz ponds continued to be used to generate electricity despite the cessation of mining. Today, five hydroelectric power stations are in operation in the World Heritage property. The largest and historically significant plants are located underground as cavern power plants in the Samson mine in Sankt Andreasberg and are operated by Harz Energie GmbH. Frequently, private individuals consider constructing additional small plants in the Upper Harz water management area. This development is positively supported by Harzwasserwerke and the monument conservation authorities, provided the monument is not impaired. In this way, the

World Heritage facilities contribute directly to SDG 7 (affordable and clean energy).

Drinking water supply

Another current use of the facilities in operation is the provision of drinking water. In six of the sixty-three ponds, drinking water is used directly by communities in the Upper Harz region, which are facing growing challenges due to climate change. The water supply is becoming increasingly scarce and for longer periods of time and it is often necessary to treat surface water at great expense in order for it to be used as drinking water and thus contribute to SDG 6 (clean water and sanitation). The necessary interventions in the monument are carried out in consultation with the conservation authorities and in such a way that they are as reversible as possible. For example, floating deep-water aeration systems were installed at the drinking water pond Hirschler Teich to stabilize the ecological balance (Schrader et al. 2023, 14–19). In addition, the increased input of sediments due to the current climate-induced forest conversion and the increase in extreme weather events is leading to further measures being taken to treat drinking water (Schrader et al. 2023, 14–15).

Indirectly, additional ponds can also be used to supply drinking water in times of extreme drought. This primarily concerns the supply of localities outside the Harz via the supply line to the large reservoirs of the Harzwasserwerke GmbH located on the edge of the Harz. The ponds only have a very limited significance and use for the Harzwasserwerke in terms of drinking water production in regular operation, but are an important component when it comes to adapting to changing climate conditions, including with flood protection, in keeping with SDG 13 (climate action – adaptation to climate change).

Flood protection

The ponds have always been part of flood protection. Today, numerous ponds (16, as of 2011) are used directly for flood protection, while all others contribute indirectly to flood attenuation via their retention areas (Harzwasserwerke 2011, 18). Changes in use, climatic changes and the increase in extreme events are increasing the pressure on the monument. As the ponds are legally classified as dams under water law, the Harzwasserwerke, which own and maintain the components in operation, are also confronted with new and in some cases increased demands on the dam structures and their stability.

Due to climate change and changing hydrological conditions, it is necessary from a hydraulic engineering perspective to make appropriate structural adjustments to the facilities in order to minimize the risk of failure – i.e., dam failure – in extreme cases. For example, the Harzwasserwerke has proposed redesigning some spillways in order to increase their capacity as a way to meet water law requirements. The relevant laws pertaining to water make no distinction between historical and modern dams. The World Heritage nomination document (UNESCO 2010) and the management plan already assume that the constantly evolving system must continue to change and adapt. A viable solution for future challenges must be found in a joint process of mediation between national monument protection law, UNESCO World Heritage standards, and water law.

In addition to the above-ground facilities, flood protection planning is now also incorporating the underground facilities of the Upper Harz Water Management System that can be incorporated in plans for flood protection. Care must also be taken to ensure that the substance of the

monuments is not damaged in the long term. Extreme flooding and the constant ingress of surface water promote the instability of underground mine sections that have not been flooded for long periods of time. This structural instability can lead to increased subsidence and collapse due to washout. The situation requires regular monitoring and, if necessary, permanent rock stabilization to prevent further damage to the structure. Extreme amounts of water can severely damage the tunnels and carry away existing cultural assets such as historical fixtures. A possible countermeasure here could be to salvage the assets after emergency documentation of the condition on site.

Monitoring and management

An important aspect of the operation, preservation and safety of the Upper Harz Water Management System is monitoring the facilities. The system of the Upper Harz ponds is very complex and is now only monitored and controlled by a small number of employees. To meet today's safety requirements for such systems, it is necessary to use as many automated measuring points as possible. The location and number of measuring points are always agreed on in advance with the monument preservation authorities. Hence, the installation of these measuring points ideally involves only very limited interference with the substance of the protected facilities. The water level measurements are already largely automated and allow targeted deployment planning in the event of flooding. Work is also underway to make key measurement data available automatically and online for pond monitoring. This further development in operation, which is necessary from a water management perspective, is currently focused on stability. The aim is to carry out as little intervention as possible and only as much as necessary in the monument and World Heritage property. Innovative applications and new monitoring options are also required. These can be part of preventive risk management that includes aspects relevant to World Heritage as well as hydraulic engineering.

Conclusion

The Upper Harz Water Management System has evolved over 800 years and is still changing today, not only due to changes in use, but also in operation and its requirements. As a result of the climatic changes that have already occurred and those that are expected as well as the increasing importance of the water supply, adjustments to the facilities will also be necessary in the future, just as they were in the past, and not least because many of the system's functions also contribute to achieving sustainability goals. It is crucial to define the framework conditions, both legal and financial, to coordinate new approaches and solutions with the monument protection authorities, the World Heritage management and also the supervisory authorities for dam operation. A more comprehensive view of water management in the World Heritage property is therefore an essential building block.

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Water Management in a UNESCO Biosphere Reserve: The Village of Pampaneira at the Barranco de Poqueira Heritage Site

Luis José García-Pulido

Abstract

Recent changes in how water resources are managed in the Alpujarra – a vulnerable region on the southern slopes of the Sierra Nevada in Andalusia, Spain – are contributing to the degradation of formerly lush landscapes, which are now becoming increasingly arid under the pressure of global climate change. Poor water management practices risk pushing the environment beyond a point of no return, making recovery impossible unless the current climate emergency is addressed. It is therefore necessary to learn from the millennia-old culture and traditional processes of adaptation and resilience that have enabled communities in this region to thrive without overexploiting or depleting natural resources. This paper examines the village of Pampaneira, located in the Barranco de Poqueira, a heritage site within the Sierra Nevada UNESCO Biosphere Reserve. The village has historically practiced a unique and sustainable approach to water management, supporting human consumption, agriculture, daily activities, energy production and bioclimatic mechanisms established in the municipality.

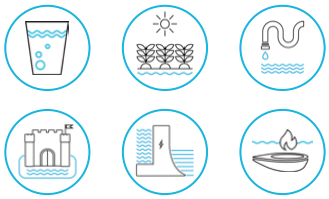
Policy Recommendations

- Promote sustainable water management in inhabited heritage sites to mitigate the effects of climate change and ensure environmental value and comfort for residents and visitors.
- Learn from the historical management of heritage systems in sensitive high mountain environments that adapted to available resources and minimized human impact. Draw on this knowledge to inform future practices.

KEYWORDS

UNESCO Biosphere Reserve
historical uses of water
Andalusian channels
bioclimatism
heat dissipation

WATER ICONS



CLIMATE

Csa: Mediterranean climate

< Fig. 1 Ravine from Castillejo de Poqueira; Pampaneira, Bubión and Capileira are in the background (Source: Luis José García-Pulido, 2021).

Introduction

Rising temperatures are making cities in southern Spain increasingly uninhabitable during the summer months. According to the Heat Action Day report by World Weather Attribution (Giguere et al. 2025), human-induced climate change has contributed to an average of 30 additional days of extreme and dangerous heat over the past year. This intensification of heat is particularly severe in urban areas due to the urban heat island effect. However, rural environments are also beginning to experience similar conditions, especially where traditional practices that once helped regulate temperature are being neglected or replaced.

Precipitation over the Iberian Peninsula shows significant variability across different time scales, as demonstrated by the evolution of annual accumulated rainfall from 1900 to 2010 (AEMET 2024). Since the 1960s, a noticeable decline has been observed in peak values, resulting in the most recent figures being the lowest in the historical record. The region has experienced an average temperature rise of 0.1 to 0.3°C per decade since the 1960s, with summer temperatures now more than 2°C higher than historical averages, largely due to climate change. Data from 1965 to 2010 indicates a consistent upward trend in annual average temperatures, especially since the mid–1970s.

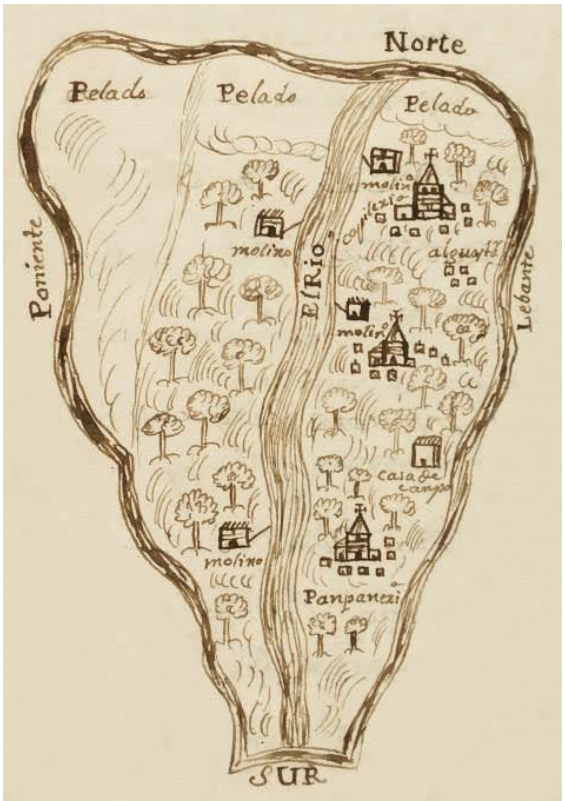
Rainfall data available since 1996 (Dirección General de Infraestructuras del Agua de la Junta de Andalucía 2024) illustrate the high variability typical of the continental Mediterranean climate in the Alpujarra region. Some years receive double or even triple the average rainfall, while the wettest years can receive up to nine times as much rainfall as the driest years. In any case, rainfall records for villages in this region show an increasing number of years with below-average precipitation since 2009–2010, which was the year with the highest recorded rainfall in the series. Consequently, the amount of water available on the region's slopes has been gradually declining.

In addition, reduced snowpack and earlier snowmelt have altered the hydrological regime, resulting in reduced river flows, vanishing springs and decreased freshwater availability. This affects both local ecosystems and downstream water users. These threats are giving rise to several additional challenges, including:

- The Sierra Nevada, a biodiversity hotspot, is experiencing severe impacts on its flora and fauna. Endemic plant species are especially vulnerable, with habitat suitability projected to decline by up to 80 per cent under severe climate change scenarios.
- The breakdown of traditional agricultural resource management systems leading to the deterioration and abandonment of terraces surrounding the villages and the landscape.
- Changes in water management tend to be appropriated and overexploited by large agricultural enterprises rather than small producers or the community as a whole.
- Surface water availability has been reduced, as water is often diverted through long pipelines instead of open channels that facilitate local consumption. This practice dries out normally humid areas and contributes to an increase in temperatures.

The Poqueira Ravine, a Cultural and Environmental Protected Area

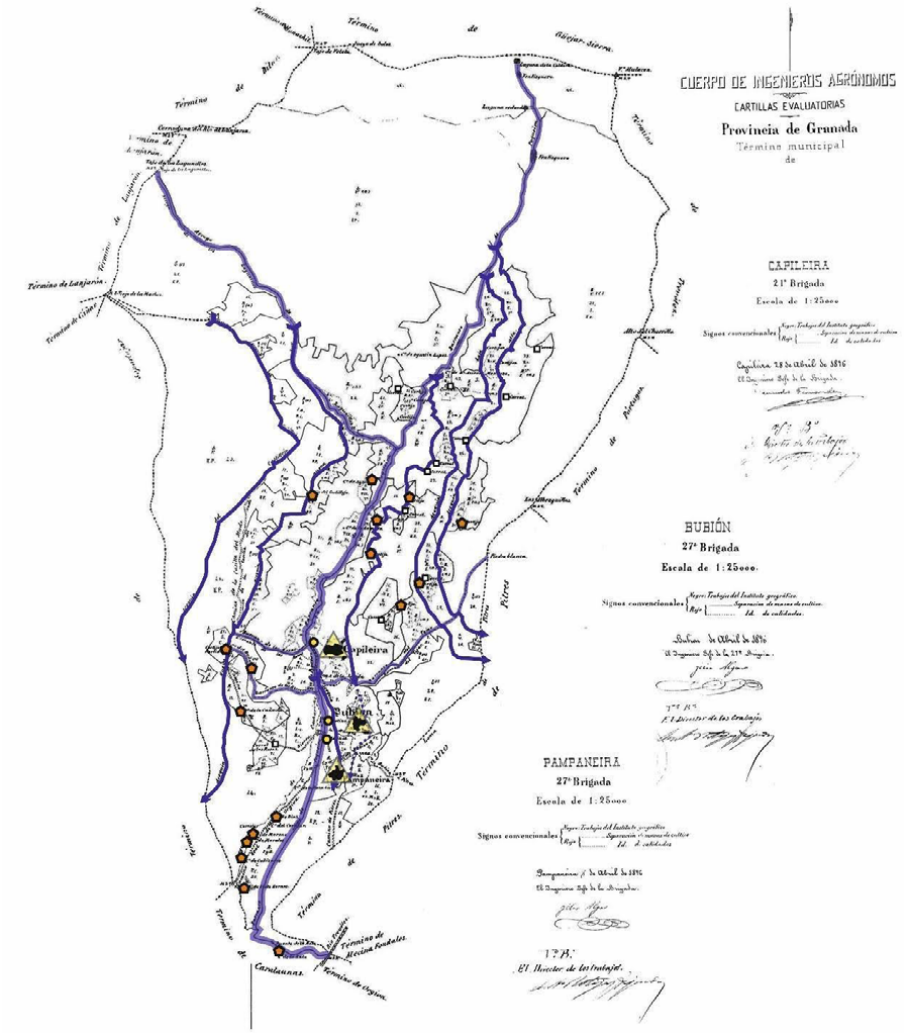
The Barranco de Poqueira heritage site (fig. 1) is located in the western Alpujarra region, just south of Mulhacén and Veleta, two of the highest peaks on the Iberian Peninsula (3,479



^ Fig. 2 Sketch of the Poqueira ravine included in the documentation of the Ensenada Cadastre from 1752 (Source: Instituto de Estadística y Cartografía de Andalucía. Archivo Histórico Provincial de Granada. Hacienda/Administración de Rentas Públicas/ Catastro de Ensenada. Libro 1046, f25r. CC BY 4.0).

and 3,392 m AMSL). The lower section of the Poqueira ravine, where the local population resides, lies within the Sierra Nevada Natural Park, a UNESCO Biosphere Reserve since 1986. In 1999, the upper section of the site (above 1,800 m AMSL) was also incorporated into the Sierra Nevada National Park. The Poqueira watercourse descends through a steep ravine dotted with pastures and scattered holm oaks (*Quercus ilex*), making it one of the most distinctive features of Spain's stratified mountain landscapes. Today, the entire gorge forms a part of the Natura 2000 ecological network. Human activity has played a decisive role in shaping the region's ecological and cultural diversity. The Natural Resources Management Plan (Plan de Ordenación de los Recursos Naturales, PORN 2011) for the Sierra Nevada National and Natural Parks recognizes the landscape as a fundamental part of both the natural and cultural heritage. The designation of the Historic Site of the Middle Alpujarra (Sitio Histórico de la Alpujarra Media Granadina y La Tahá) in 2007, along with the creation of the Inventory of Cultural Heritage of the Sierra Nevada (Inventario de Bienes Culturales de Sierra Nevada) in 2011, adds further layers of protection through varying levels of regulation. The Master Plans for Use and Management (Planes Rectores de Uso y Gestión, PRUG 2011) of the Sierra Nevada National and Natural Parks define the instruments and actions required to enforce protection, conservation and recovery of environmental and cultural values. In 1982, when Pampaneira, Bubión and Capileira, three traditional mountain villages located in the Barranco de Poqueira, were declared Sites of Cultural Interest (Bienes de Interés Cultural), their urban regulations were integrated into the management framework of the natural park. These provisions aim to preserve the historical integrity of the villages and safeguard the surrounding ravine landscape (Instituto Andaluz de Patrimonio Histórico 2016, 12–14).

Some of the village names in the Poqueira ravine – Pampaneira, Bubión and Capileira – suggest that settlements may have existed here as early as late antiquity. Others, now disappeared, are believed to have been established during the al-Andalus period (eighth to fifteenth centuries), when much of the Iberian Peninsula was under Muslim rule; these include Arrabal, Beniodmín, Alguazta and Benzeyt (Trillo San José 2014, 37). All the settlements were located on the eastern slope of the Poqueira ravine (fig. 1), where the terrain is less steep and receives more sunlight from the west.



^ Fig. 3 Montage of the maps of the municipalities of Pampaneira, Bubión and Capileira (yellow triangles), showing the main irrigation channels (dark blue), farmhouses (*cortijos*, orange pentagons) and farmyards (*corrales*, yellow circles) (Source: Instituto de Estadística y Cartografía de Andalucía. Gerencia Territorial del Catastro de Rústica de Granada [folders of Pampaneira and Bubión, Busquistar, Cañar and Capileira]. Authors: Eduardo Fernández [Pampaneira] and Félix Algar [Bubión and Capileira], 1896).

A hydraulic system, likely dating to the tenth or eleventh centuries, has survived to the present day, largely due to continuous use and maintenance by the local population. Although it gradually expanded over the centuries, significant degradation has only occurred in recent decades. A shared irrigation channel, known as the Acequia de los Lugares, connects the villages within the ravine, running just above them as it descends the slope (fig. 3). Of the three villages, Pampaneira lies at the lowest altitude in the Poqueira ravine, between 1,130 and 1,040 m AMSL. It features a unique and sustainable water management system, presenting an exceptional case of utilizing water and other methods traditionally employed on these mountain slopes to regulate

^ Fig. 4 Water running slowly in an acequia alongside the fast current riverbed downstream of the Poqueira ravine (Source: Luis José García-Pulido, 2025).

temperature and protect humans and animals from excessive heat. The techniques are both passive (use of water and vent flows, orientation of the municipality and materiality of the buildings), as well as active (infiltration in the aquifers, regulation of fountains inside the municipality, conduction of surface water, creation of fixed shaded spaces, such as porches and passageways, and temporary ones such as trellises and communal awnings). Analysis of these systems allows for a better understanding of why their conservation is a priority and how their methods can be applied in other municipalities. Pampaneira receives water from two irrigation ditches, which enables to replenish and sustain several natural springs within the hamlet. In addition, it is the only village in the Alpujarra that still allows the excess water from these springs to flow through the streets in open channels, separated from the sewage systems, rather than having it run through pipes. The moving water provides the village with a bioclimatic device shared by the entire community, while contributing to its sensory, acoustic and optical well-being.

In the past, the settlements in the Barranco de Poqueira obtained their drinking water from fountains fed by irrigation channels that ran above the population centers. This suggests that the canal system may have been constructed after the villages were first established (Delaigue 1995, 144). The name Pampaneira is derived

from the Latin word *pampinarius*, meaning "land of vines," referring to a type of dry crop likely cultivated during the village's foundation in late antiquity. During the Islamic period, however, these dry crops were replaced by irrigated agriculture. The introduction of terraced cultivation around the village enabled the integration of orchards within the settlement, helping to moderate local temperatures. Water for these gardens was supplied by diversion channels or by overflow from nearby springs.

The highest channels collect water from snowfields or high-altitude springs. As the water descends the slopes, it travels along irrigation channels that pass through areas with cracks in the walls or permeable soils. In these sections, water seeps through and infiltrates the ground, contributing to the recharge of underground aquifers.

This technique of replenishing water tables, known in the region as *careo*, is still in use and promotes the growth of vegetation and pastures, slowing the transit of water from the peaks to the bottoms of the valleys. With this method, it is possible to maintain the flow of springs downhill during periods of low water levels and increase the concentration of salts in the water, thereby improving its quality for consumption (Pulido-Bosch and Sbih 1995). This water management is a clear example of symbiosis between humans and their environment, as its maintenance is essential for conserving soil, vegetation and fauna (Plaza-García and García-Rubia 2010). It is an ingenious aquifer recharge system developed over centuries (Martos-Rosillo et al. 2019, 1–4). It regulates the transit of water from the high mountains to the sea, raising the water table from the bottom of ravines and valleys to the slopes, which would otherwise dry out quickly once the dry season (from May to October) begins.

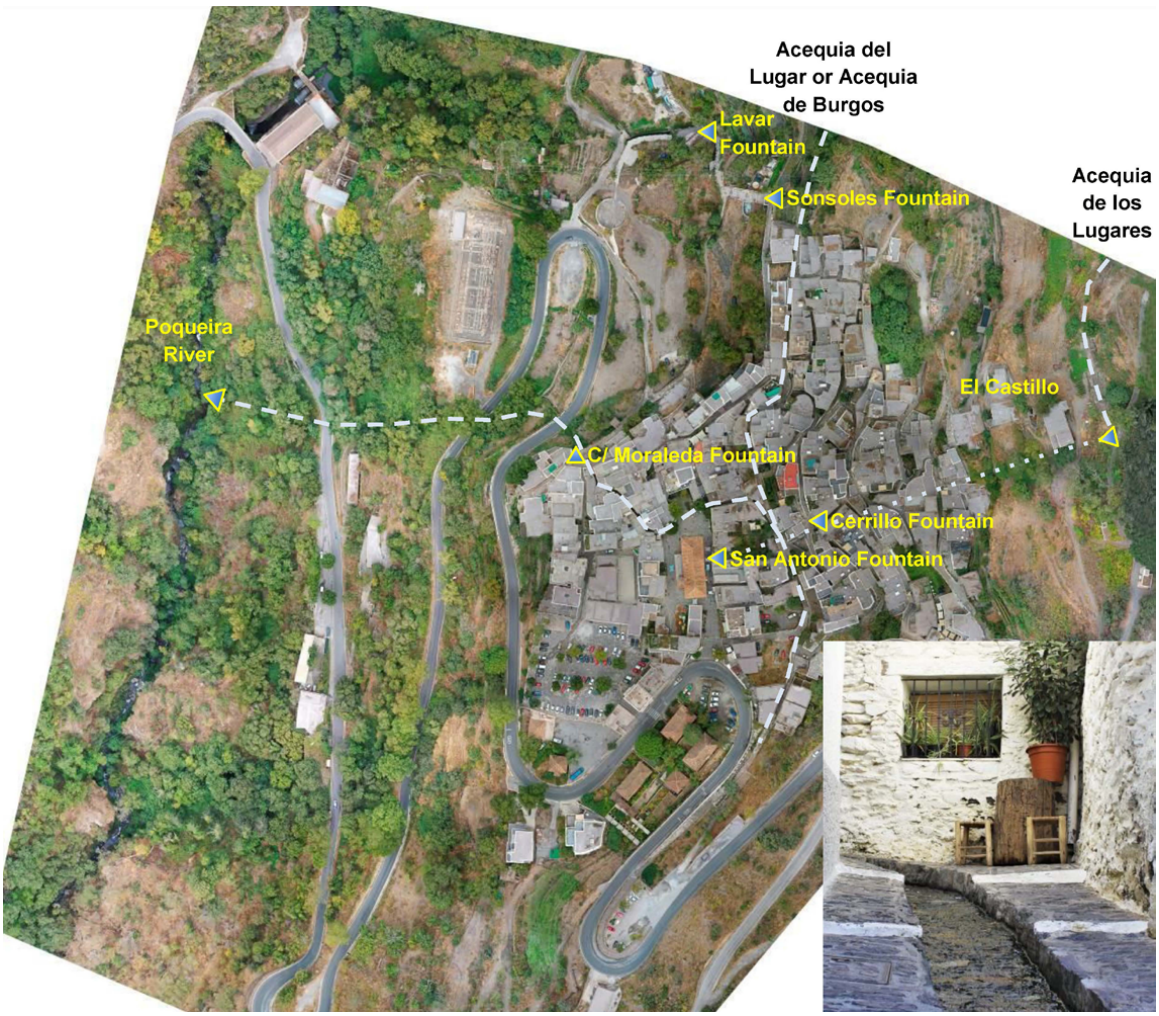
The Unique Use of Water in Pampaneira

During the Nasrid period (part of the al-Andalus era between the thirteenth and fifteenth centuries), the area experienced considerable economic and social development, largely due to its agricultural wealth and thriving silk industry (Padilla Mellado 2019, 56–60). After the Alpujarras Rebellion (1568–1571) and the subsequent expulsion of the Moriscos (former Nasrids, who were forced to abandon their religion, language and traditions), Christian settlers arrived in the region from various parts of the Iberian Peninsula. In general terms, they continued the sustainable water management practices and bioclimatic architecture. The regulation, use and maintenance of the network of irrigation ditches (fig. 4) continued and even expanded, with new *careo* channels that contributed to retaining water on the slopes instead of letting it rush down the ravine after the thaw. Diversified crops were reestablished, in contrast to other regions where monoculture eventually prevailed, a consequence of the hydraulic network and land arrangement established during the Islamic period. Natural springs were continuously maintained, and their recharge was supported through the use of *careo* water channel systems. The increase in the use of this snowmelt catchment in the modern period, especially in the seventeenth and eighteenth centuries, could be related to the greater cooling experienced during the Little Ice Age, when the snow on the high peaks of the Sierra Nevada became perennial again.

This relationship with water is not only evident in agricultural and hydrological systems but is also embedded in the Pampaneira's urban layout, which facilitates the flow of water into the very heart of the village (fig. 5). The most significant hydraulic structures are connected to different water sources linked to the infiltration

system from the Acequia de los Lugares, coming from Capileira and Bubión. Additionally, the Acequia del Lugar, also known as the Acequia de Burgos, runs directly into Pampaneira, possibly marking an upper boundary of the village. Today, this hamlet is the only settlement that has maintained excess water flow from the fountains through its streets without covering the water course. This helps maintain a fresh and humid environment in summer, while in winter, the quick evacuation of water reduces humidity problems caused by water infiltrating the area under the houses. To the west of the village, the water flows into the Poqueira riverbed, which is surrounded by riparian plants, blackberries, chestnut trees and pastures.

The settlements of the Alpujarra region typically developed around one or more springs, which were often valued and even ranked based on the quality of the water or their specific uses. In Pampaneira, several sources can be found (Baena Fernández 2009, 303–8), each serving different functions. Some springs are used for drinking water. The main one is located at the San Antonio Fountain (1,060 m AMSL), which



^ Fig. 5 Aerial view of Pampaneira with the main water sources and the routes of water on the surface and underground (Source: Luis José García-Pulido, 2024).

has three spouts and is next to the church and the site of the former mosque (Castillo Martín and Sánchez-Díaz 2006). Other springs are used as washing places. The Cerrillo Fountain (1,080 m AMSL) has four spouts that pour water into a small basin below (Robles-Arenas 2009) and feed the Lavadero del Cerrillo, a washhouse elevated on a podium above the hamlet (López-Osorio et al. 2020, 403–4). The Lavar Fountain (1,040 m AMSL) has also been used as a washing site and is located to the north of Pampaneira, in a small ravine (Sánchez-Díaz and Peinado Parra 2015). There are also springs with mineral-medicinal properties. The Sonsoles Fountain (1,065 m AMSL) is divided into two individual terraced springs. The water flowing from its spouts is slightly ferruginous and carbonated. Next to it, there is another source with normal mineralization (Castillo Martín and Sánchez-Díaz 2006).

The point where all these springs are recharged is located above Pampaneira, in the area known as El Castillo ("The Castle," 1,150 m AMSL), a name that likely refers to a historical site of control over this vital hydraulic resource.

Today, the modern water tank that supplies drinking water to the entire village is filled from this same irrigation channel, highlighting its continued importance for the settlement's survival. However, the future of this ancestral water system faces significant challenges due to declining rainfall, reduced snowfall and increased evaporation driven by rising temperatures. In addition, the overexploitation of local water resources in other Alpujarra's areas, especially through intensive monoculture and groundwater extraction for commercial greenhouses, is leading to the collapse of traditional systems that had remained sustainable for centuries. It is therefore urgent to preserve and maintain these networks, both to prevent further degradation and to ensure that they can continue to be used sustainably in the future.

The surplus water mixes with the flow from the irrigation ditch. It continues along open channels running through various main streets of the village before exiting the municipality and heading toward the Poqueira River. Downstream, it passes beneath a more recent infrastructure development: the Poqueira Ravine Hydroelectric Power Plant, built in 1957. Its intake point is located at 1,520 m AMSL. From there, the diverted channel runs approximately 6 kilometers along the eastern slope of the ravine until it reaches a reservoir situated above Pampaneira at 1,502 m AMSL. The water is then released through a pressurized pipe to 952 m AMSL, where the engine room of the Pampaneira Power Plant is located. This facility generates electricity for the entire population of the valley (García Moreno and Arredondo Garrido 2007). In the future, the industrial use of water in the hydropower plant should be combined with efforts to replenish the aquifers around the municipalities, rather than returning it directly to the river.

Conclusion

The communities of the Poqueira ravine still benefit from a hydraulic system that has transported water to the upper edge of the urban area for over 1,000 years. As this water descends the slopes through irrigation ditches and terraced fields, it promotes infiltration, reduces surface runoff and limits soil erosion, helping to prevent landslides. Within the villages, the water continues its journey, supplying fountains, feeding washhouses, flowing through streets and ultimately draining into nearby hydrological basins. This dynamic system exemplifies the principles of "integrated aquifer management" (Vivas et al. 2009) within a living cultural heritage land-

scape. The history of the management of these hydraulic systems allows us to understand how this management has been carried out in harmony with available resources and the populations' adaptation to their environment, minimizing human impact in these sensitive high mountain areas.

Despite growing tourism and environmental pressures, Pampaneira has managed to preserve its unique character and its historical connection to water. Keeping the full hydraulic cycle active, from snowfields to channels, terraced fields, aquifers, urban fountains and ultimately to the Poqueira River, ensures that water is retained in the highlands during the dry season. This, in turn, helps cool the ecosystem, allowing a wide variety of plants and animals to thrive. Distributing water across the slopes instead of at the bottom of the ravine also provides another benefit in summer, as evaporation contributes to cloud formation. Ultimately, rain from those clouds and storms over the mountains restarts the water cycle. However, pressures on the system are intensifying as reduced rainfall, declining snowpack, increased evaporation, and overexploitation by commercial agriculture and wells threaten both water availability and the traditional resilient management practices.

Preserving this ancestral network requires recognizing the human dimension of water governance. The role of the irrigation communities, and in particular of the *acequiero*, or channel keeper, is essential, along with the role of environmental groups, researchers, Sierra Nevada National Park technicians and local initiatives of municipal authorities. Equally important is the intergenerational transfer of traditional agricultural knowledge and land-use practices, to prevent the adoption of intensive or harmful practices that overexploit and deplete the system. In a region where tourism is a major economic driver, promoting greater awareness of the shared responsibility for water resources among visitors is also important. Active policies are required at all levels for the local actors involved in their use to safeguard and promote the sustainable use of these resources, ensuring that these systems can remain interconnected and flexible, and preventing overexploitation of the aquifers.

Ultimately, the protection and sustainable management of these heritage water systems offer one of the most immediate and locally controlled strategies for adapting to climate change, particularly in the face of reduced water resources and increased pressure for their exploitation. The continued use of this hydraulic system demonstrates how human societies can live in balance with their environment, drawing on centuries of knowledge.

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Watermills as Cultural-Natural Ecosystems: Tangible and Intangible Heritage for Sustainable Water and Energy Management in a Changing Climate

Maria Carmela Grano

Abstract
Watermills are not remnants of obsolete technologies but dynamic socio-ecological systems in which hydrology, craftsmanship, landscape processes and community knowledge have co-evolved for centuries. Although mills appear in many UNESCO World Heritage and Intangible Heritage inscriptions, their ecological functions and climate-adaptation potential remain largely underrecognized. This article demonstrates how historic mill infrastructures – by regulating flow, managing sediment, supporting biodiversity and generating low-impact energy – embody long-standing forms of water governance that anticipate today's nature-based solutions. Drawing on recent evidence, the article shows that active or revived milling practices strengthen landscape resilience, whereas abandoned mills deteriorate rapidly under climate stress, amplifying environmental risks.

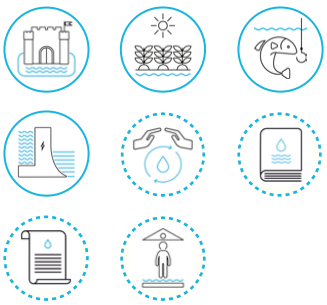
Policy Recommendations

- Integrate historic mills – both UNESCO and non-UNESCO – into climate-resilience strategies and landscape management frameworks, recognizing their capacity to provide ecosystem services such as water retention, flood regulation, biodiversity enhancement and low-impact hydropower.
- Strengthen community-based and intersectoral governance by supporting miller associations, local heritage NGOs, and volunteer networks through participatory models, co-design processes and long-term capacity-building programs.
- Expand interdisciplinary studies, applied research and interoperable digital platforms that integrate hydrological, ecological, cultural and energy data.
- Remove regulatory barriers and harmonize procedures among cultural heritage, environmental, hydrological, and energy authorities, simplifying authorizations for maintenance, ecological upgrades, hydraulic reactivation and sustainable micro-hydropower.

KEYWORDS

UNESCO World Heritage
climate adaptation
regenerative development
clean energy
landscape management

WATER ICONS



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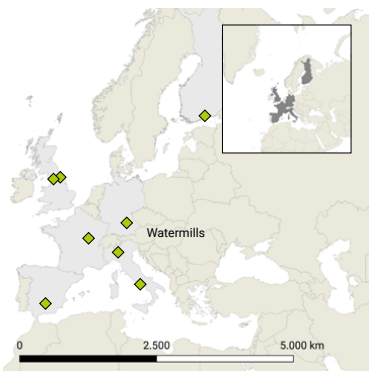

< Fig. 1 Noria, along the Guadalquivir River in the Historic Centre of Córdoba – UNESCO Cultural Landscape (Spain). The vertical waterwheel, once used to lift irrigation water to the Huertas, shows continuity from Roman to Islamic hydraulic traditions and the city's multicultural legacy (Source: Kiko León, 2014. CC BY-SA 4.0, via Wikimedia Commons).

Introduction

Watermills have historically functioned as more than mechanical devices. Embedded in monastic complexes, industrial settlements, irrigation systems and rural districts, they have served as multifunctional infrastructures where water management, social organization and technological innovation have converged. Historically, these sites functioned as dynamic systems, integrating water regulation, energy production and community practices. By analyzing UNESCO-listed and non-listed mill landscapes, this article connects cultural heritage research with ecological and hydrological sciences, energy and water resilience. It shows how heritage assets can actively inform nature-based and community-driven adaptation strategies in the context of climate change.

The article calls for a reinterpretation of historic watermills as socio-ecological systems (SES) – integrated systems in which human societies and ecosystems interact dynamically and shape one another through continuous feedback processes (Berkes and Folke 1998). In this perspective, watermills represent local SES, where communities, hydraulic technologies and intangible knowledge have co-evolved over centuries in close interaction with river ecosystems. These long-lasting relationships have produced distinctive biocultural landscapes and sustained practices of adaptive and resilient resource management.

The interwoven relationships between people – embodying cultural, educational and identity values rooted in place (Hernández-Morcillo et al. 2022) – and their environments reveal adaptive strategies that can inform integrated policies for climate resilience and sustainable territorial governance. Reframing watermills in this way reconnects nature and culture, restoring their historical role as infrastructures that serve both communities and landscapes (Grano 2025).

UNESCO World Heritage inscriptions capture only the tip of this global heritage. Inventories such as the European RESTOR Hydro database (~27,000 sites), TIMS (The International Molinological Society) and some national Intangible Cultural Heritage lists confirm the scale and diversity of milling traditions worldwide. Yet, most of these sites survive only as ruins, and in many places their memory has faded and they are treated as fragments of the past with little relevance to the present.

Ecologically, contemporary ecohydrological research shows that small-scale hydraulic infrastructures enhance biodiversity, sediment retention and groundwater recharge, functioning as "sponge landscapes" capable of buffering both droughts and floods (de Mars and Bleumink 2023; Meire 2022). At the same time, although historic weirs and millraces have altered river continuity and can hinder fish migration, their indiscriminate removal risks erasing biocultural landscapes and the very ecological functions they helped sustain. The challenge is therefore not to frame heritage and ecology as opposing forces, but to calibrate scale and density – mitigating the impacts of large or clustered barriers while adapting small, low-head structures with fish passages, adjustable sluices or seasonal regulation (Quaranta et al. 2020; Dodd et al. 2018). Recognizing and restoring these ecological roles aligns closely with the objectives of the EU Water Framework Directive and the EU Biodiversity Strategy for 2030, demonstrating how historic watermill systems can contribute to contemporary environmental and climate goals.

^ Fig. 2 Derwent Valley Mills – UNESCO Industrial Heritage (United Kingdom). View of the River Derwent weir at Masson Mills, part of the hydraulic system that powered textile factories shaping the factory model of the Industrial Revolution. Current studies explore its reuse for micro-hydropower within heritage frameworks (Source: John M, 2013. CC BY-SA 2.0, via Wikimedia Commons).

Watermills as Socio-Ecological Systems and Governance Challenges in Sustainable Development

Recent studies show that mills have shaped landscapes through centuries of water regulation, sediment control and agro-industrial production. Far from being passive infrastructures, they demonstrate how local communities translated hydro-geomorphological constraints and agricultural needs into sustainable resource use across diverse environments (Downward and Skinner 2005; Bishop and Muñoz-Salinas 2013; Grano et al. 2016; Brykała and Podgórski 2020). As multifunctional nodes, mills stood at the intersection of geomorphology, hydrology, river ecology and energy production, influencing both cultural and ecological systems. Their technological diversity – including horizontal and vertical wheels, chute- and tower-fed systems –reflects centuries of adaptation to local conditions and anticipates principles of modern low-impact energy solutions (Barceló 2004, Grano and Bishop 2017).

These examples underscore the multifaceted role of watermills as socio-ecological infrastructures. Their potential contributions span several key domains, including:

- Hydrological regulation: Traditional mill dams and channels buffered floods and stabilized groundwater levels, ensuring reliable water supply across both drought-

prone regions and arid environments, and providing enduring models of resilience. By regulating flows, trapping sediments and fostering riparian vegetation, they mitigated hydro-geological risks in temperate landscapes, while in drylands, traditional water-harvesting techniques helped societies cope with scarcity and desertification, maintaining fertile agricultural valleys (CAG and DCIH 2023; Grano et al. 2016).

- Biocultural and socio-ecological system services: Mill landscapes, when maintained as living heritage systems, function as strategic resilience assets. They enhance water retention, create diverse habitats and support wetland micro-ecosystems, strengthening biodiversity and local environmental stability. Evidence from two Dutch–Flemish projects – Water and Land and Watermill Landscapes for Climate Adaptation – shows that these sites provide key regulatory and cultural services: For example, they buffer extreme flows, support riparian species and contribute to community well-being (CAG and DCIH 2023). Ensuring ecological connectivity is essential: Even small historic weirs can obstruct fish passage and disrupt habitat continuity, reinforcing the need for adaptive solutions that balance ecological requirements and heritage conservation (Quaranta et al. 2020).
- Renewable energy: Historically, mills powered grain milling, papermaking, textiles and forging. Today, their infrastructures can be repurposed for micro-hydropower, supporting the EU Green Deal and community-led renewable initiatives (Quaranta et al. 2023; RESTOR Hydro Project 2015; Interreg RENEWAT 2024).
- Collaborative governance and cultural resilience: Millers and local communities regularly maintained weirs, cleared sediment and reinforced riverbanks with hydrophilic vegetation such as willows and poplars, ensuring long-term resilience of both the infrastructure and the surrounding farmland (CAG and DCIH 2023; Genovese et al. 2024; Grano 2025). These practices illustrate how intangible heritage – knowledge of flows, materials and the rhythms of water – was inseparable from tangible structures, making mills socio-ecological infrastructures.

At the same time, watermills occupy a complex governance space where heritage conservation, agricultural use, ecological requirements, community expectations and renewable-energy interests intersect. Fragmented responsibilities among cultural, environmental, water and energy authorities often hinder adaptive reuse, despite growing recognition of mills as pivotal nodes linking tangible and intangible heritage with ecological processes. Their multifunctionality means that decisions regarding flows, sediment and infrastructure maintenance frequently involve negotiation among stakeholders with differing priorities. Addressing these tensions is an important step in developing coherent and equitable policies aligned with climate resilience objectives.

To connect these interdependent dimensions – hydrology, ecosystem services, renewable energy, and intangible heritage – policy innovation is essential. Platforms such as IHP-WINS (Water Information Network System), promoted by UNESCO's International Hydrological Programme, show how open-access geospatial and hydrological data can strengthen evidence-based water governance, fostering citizen participation and multi-stakeholder collaboration. Similarly, the World Water Assessment Programme (WWAP) integrates gender-disaggregated data and localized knowledge to design more inclusive and context-sensitive water policies.

Building on such approaches, the creation of inter-ministerial registers of historic watermills, supported by interoperable databases linking heritage inventories, scientific networks and water-management systems, would provide a coherent foundation for restoration and sustainable territorial planning. Citizen science, training programs and the integration of heritage, tourism and climate policies can further reinforce the role of watermill landscapes as active socio-ecological infrastructures for adaptation and innovation.

Watermills in the UNESCO Frameworks and Challenges in the Climate Change Context

On the World Heritage List, watermills rarely appear as isolated monuments; rather, they are embedded within broader cultural systems that link technology, society, and landscape. In the earliest cases, mills are part of monastic complexes, as at the Abbaye de Fontenay (France, 1981), and Studley Royal Park including the Ruins of Fountains Abbey, where the Cistercian watermills embodied ideals of self-sufficiency and technical ingenuity.

They are found as parts of cultural landscapes, such as the Amalfi Coast's Valle dei Mulini in Italy, inscribed in 1997, or the Córdoba Historic Centre (Spain, 1984/1994), where hydraulic infrastructures shaped river valleys and urban development.

Watermills also appear within industrial districts with strong social value, including San Leucio Complex (Italy, 1997), Saltaire and New Lanark (United Kingdom, 2001), both conceived as utopian communities combining production,

^ Fig. 3 Abbey of Fontenay – UNESCO Monastic Site, France. Hydraulic wheel driving the trip hammer in the Cistercian forge, illustrating medieval monastic water management and the integration of technology and spiritual life within a self-sufficient economy (Source: Draceane, 2013. CC BY-SA 4.0, via Wikimedia Commons).

^ Fig. 4 Vallone dei Mulini, Sorrento – Costiera Amalfitana, UNESCO Cultural Landscape, Italy. A natural canyon where watermills began operating in the thirteenth century, showing the interaction between geomorphology, vegetation and historic hydraulic systems for paper production; the site vividly illustrates the sophisticated pre-industrial water network that sustained Amalfi's paper industry within a dramatically sculpted landscape (Source: Mentnafunangann. CC BY-SA 3.0, via Wikimedia Commons).

welfare and education as well as the Verla Groundwood and Board Mill (Finland, 1996), a perfectly preserved pulp and paper factory that illustrates the role of waterpower in Europe's industrial heritage.

The Derwent Valley Mills (United Kingdom, 2001) further exemplify this industrial dimension. Here, waterpower was canalized through an extensive system of weirs and channels to drive the first large-scale cotton mills, laying the foundations of the modern factory system. This hydraulic network was not only central to production but also to environmental regulation, and today it offers opportunities for community-led micro-hydropower within a landscape preserved as industrial heritage (Jackson 2024).

The Upper Harz Water Management System (Germany, 2019) demonstrates technological continuity from medieval watermills and canals to modern hydropower and water-supply infrastructure.

An overview of all UNESCO sites containing watermills or watermill-related practices is provided in Table 1, which summarises inscription criteria, historical functions, current roles, challenges and regeneration opportunities.

^ Fig. 5 Verla Groundwood and Board Mill – UNESCO Industrial Heritage, Finland. Guided group in the pulp-processing room of a nineteenth-century water-powered mill complex, an exceptionally well-preserved example of early rural industrialization maintaining its original machinery and buildings (Source: UPM Image Bank, Verla Groundwood and Board Mill Image Collection; Courtesy of UPM-Kymmene Corporation, n.d.; https://materialhub.upm.com).

The chronological evolution of inscriptions (1981–2020) reveals a shift from monastic and agrarian uses to industrial, hydropower and socio-technical heritage values. Yet these sites face increasing vulnerability to climate change. Mills located in river valleys – including those in Córdoba, Amalfi and the Derwent Valley – experience reduced flows, sedimentation, floods and hydro-geological risks. In addition, inactive mills face heightened vulnerability, as the absence of routine hydraulic management accelerates structural deterioration, increases sediment accumulation and reduces the system's capacity to buffer extreme events. Tourism pressures (Amalfi, Fontenay) and ecological conflicts over fish migration further complicate conservation efforts. As Jackson (2024) shows, the Derwent Valley Mills continue to exemplify long-standing tensions between hydropower and ecological continuity: Historic weirs affected fish migration but also incorporated early adaptive solutions such as seasonal hatches and sluice openings, offering insights for today's sustainable hydropower redevelopment.

UNESCO sites also illustrate the socio-ecological and cultural versatility of ancient watermills across diverse environments. Beyond Europe, systems like the Persian Qanat (Iran, 2016), the Aflaj (UAE, 2020), and the Foggara (Algeria, 2018) represent historic techniques of water mobilization closely connected to milling traditions and water distribution governance. Although windmills are not the focus here,

UNESCO Convention & Criteria	Year of inscription	Country	Site (Element)	Historical Function of the Mill
WHL (iv)	1981	France	Cistercian Abbey of Fontenay	Milling and forging
WHL (i)(ii)(iii)(iv)	1984 / 1994	Spain	Historic Centre of Córdoba (11 Molinos del Guadalquivir)	Grinding; water lifting
WHL (iv)(v)	1995	Italy	Crespi d'Adda	Industrial cotton spinning
WHL (i)(iv)	1995	United Kingdom	Studley Royal Park including the Ruins of Fountains Abbey	Corn grinding
WHL (iv)	1996	Finland	Verla Groundwood and Board Mill	Pulp and paper production
WHL (ii)(iv)(v)	1997	Italy	Costiera Amalfitana – Valle dei Mulini	Paper production
WHL (ii)(iv)(v)	1997	Italy	Royal Palace of Caserta & San Leucio Complex	Silk production; utopian industrial welfare

Current Role (with museum/institution in brackets); State	Climate Change Challenges & Other Pressures	Opportunities (for regeneration of site or practices/knowledge)
Private ownership; open to public; excellent and intact	Tourist pressure; environmental stress on Romanesque hydraulic features Inactive mills deteriorate faster under flooding, drought, sedimentation, and hydro-geological stress	Regeneration of monastic water-management knowledge through eco-tourism and interpretation of historic self-sufficiency
Mixed: Museo Hidráulico – Molino de Martos; Molino de la Alegría – Museo de Paleobotánica; other mills in ruin; ecological riparian functions; variable state	Flooding; reduced river flow; sedimentation; drought Inactive mills deteriorate faster under flooding, drought, sedimentation, and hydro-geological stress	Regeneration of hydraulic knowledge and riparian culture through multifunctional reuse (museums plus ecological nodes)
Mill buildings reused as apartments/offices; Workers' Village partly residential and partly museum-oriented; well preserved. The Hydroelectric Power Plant (built in 1909) is fully functioning, converting water energy into electricity for the factory and village; open to guided visits; example of industrial hydraulic evolution	Urban pressure; demographic change; maintenance of historic structures	Regeneration of industrial and social heritage through climate-aware cultural tourism and interpretation of welfare models
Abbey Corn Mill functioning as interactive museum (National Trust); abbey ruins; preserved designed landscape	Increased flooding of River Skell; visitor pressure on fragile landscape	Regeneration of monastic hydraulic knowledge for contemporary flood-awareness and water stewardship
Verla Mill Museum; intact machinery; excellent state	Water infiltration; forest fire risk from prolonged dry periods	Regeneration of industrial know-how through education on sustainable paper processes and heritage engineering
Mixed: one active mill (Mulino dei Punzi); Museo della Carta di Amalfi; multiple ruins	Hydro-geological hazards; extreme weather; slope instability; tourism pressure Inactive mills face accelerated deterioration due to flooding, drought, sedimentation, vegetation growth, and hydro-geological instability	Regeneration of artisanal papermaking and ecological valley-management knowledge via restoration and eco-tourism
Restored cultural district; Museo della Seta; excellent state	Increased heat and drought; stress on the historic Acquedotto Carolino requiring complex maintenance	Regeneration of utopian socio-technical heritage as a model for sustainable community districts

UNESCO Convention & Criteria	Year of inscription	Country	Site (Element)	Historical Function of the Mill
WHL (ii)(iv)	2001	United Kingdom	Derwent Valley Mills	Industrial textile production
WHL (ii)(iv)(vi)	2001	United Kingdom	New Lanark	Industrial cotton spinning
WHL (ii)(iv)	2001	United Kingdom	Saltaire	Wool spinning; planned workers' village
ICH	2009	Spain	Irrigators' Tribunals of the Spanish Mediterranean Coast	Governance of irrigation; resolution of water-related disputes among farmers and millers
ICH	2017	Netherlands	Craft of the Miller operating windmills and watermills	Operation, management, and training in the use of windmills and watermills for milling
WHL (ii)(iv)	2019	Germany	Water Management System of Augsburg	Canal- based hydropower

^ Table 1. Comparative overview of European watermill heritage in the UNESCO World Heritage List (WHL) and the Intangible Cultural Heritage (ICH). The table traces the chronological sequence of inscriptions and highlights diverse criteria for their recognition. It also illustrates conservation issues, climate-related threats and opportunities for regeneration. Mills emerge not as isolated monuments, but as components of hydraulic, industrial, cultural and social systems. They reflect social innovation, technological adaptation and long-term hydrological management. Yet their recognition remains primarily cultural, overlooking ecological and resilience potential. The table also highlights a key distinction between inactive and operational mills under climate change. Environmental risks threaten not only tangible structures but also intangible practices. When mills fall into disuse, the loss of routine hydraulic management – knowledge of flows, seasonal adjustments, sediment control, emergency responses – amplifies climate impacts. Conversely, active or revived practices help reduce risks by stabilizing water levels, preventing blockages, mitigating erosion and enhancing ecological performance. This demonstrates that the intangible heritage connected to mill activity is simultaneously vulnerable to climate change and essential for adaptive, community-based water management (Source: Maria Carmela Grano, 2025).

Current Role (with museum/institution in brackets); State	Climate Change Challenges & Other Pressures	Opportunities (for regeneration of site or practices/knowledge)
Partly museums (Cromford Mills); partly reused industrial buildings; good preservation	Urban pressure; limited renewable-energy integration; variable river flow; ecological conflicts related to fish migration due to historic weirs; mandatory modern fish passages significantly increase costs of low-head hydropower redevelopment (Jackson 2024)	Regeneration of hydropower heritage through micro-hydro reuse and community-led industrial landscape revitalization Opportunity to revive historical flow-management solutions (e.g., seasonal hatches, sluice gates) as heritage-informed ecological enhancements for fish mobility and sustainable hydropower (Jackson 2024)
Restored village; New Lanark Visitor Centre; Mill Hotel; excellent state	Gorge instability; maintenance pressures on hydraulic system	Regeneration of social-industrial knowledge through welfare-model interpretation and sustainable tourism
Salts Mill hosting the 1853 Gallery and offices; excellent adaptive reuse	Urban pressure	Regeneration of industrial community identity through creative industries and heritage-driven place-making
Active institutions: Tribunal de las Aguas de Valencia; Consejo de Hombres Buenos de Murcia	Water scarcity; floods; semi-arid pressures. Reduced opportunities for intergenerational transmission	Regeneration of traditional water-governance knowledge for adaptive water justice and participatory drought management
Active craft; supported by the Gilde van Molenaars; strong volunteer networks	Altered water flows; siltation; urban pressure. Reduced opportunities for intergenerational transmission	Regeneration of milling skills and landscape knowledge through intergenerational training, tourism, and education
Original hydropower function maintained; managed by municipal authorities (Stadtwerke Augsburg); excellent state	Urban canal-system pressure; integration with renewable energy planning	Regeneration of historical hydropower knowledge as a model for modern low-carbon energy planning

^ Fig. 6 Saltaire Mill Complex – UNESCO Industrial Heritage, United Kingdom. View looking south over the weir on the River Aire, showing the New Mill within the nineteenth-century model industrial village of Saltaire; the site exemplifies paternalistic social planning and innovative industrial architecture, providing insight into the social transformations of the Industrial Revolution (Source: The joy of all things, 2018. CC BY-SA 4.0, via Wikimedia Commons).

water-related examples such as the Kinderdijk-Elshout network (Netherlands, 1997) highlight climate-related risks to low-lying polder landscapes.

Conclusion

Historic watermills are not static monuments but socio-ecological infrastructures where hydrology, technology, landscape processes and intangible knowledge co-evolved. UNESCO recognizes their cultural and industrial values, yet their ecological and climate-resilience functions remain largely overlooked. Although watermills appear in multiple inscriptions, only two sites – the Verla Groundwood and Board Mill (Finland, 1996) and the Derwent Valley Mills (United Kingdom, 2001) –include the term mill in their names, confirming that in these cases the watermill infrastructure itself constitutes the core of Outstanding Universal Value.

The comparative analysis shows that mills historically regulated flows, stabilized soils, maintained wetlands and supported agro-industrial economies – functions aligned with today's climate-adaptation and nature-based solutions agendas. A critical distinction emerges: Inactive mills deteriorate rapidly and lose routine hydraulic management, while active or sustainably reused mills continue delivering ecosystem services and community resilience. Recognizing mills as socio-ecological systems highlights their relevance for integrated water governance, renewable energy and participatory management. A shift from passive conservation to functional regeneration is essential

^ Fig. 7 Amalfi Paper Museum – Costiera Amalfitana, UNESCO Cultural Landscape, Italy. Wooden sluice gates regulating the water-powered papermaking process, exemplifying the artisanal hydraulic ingenuity that defined the Amalfi Coast's long-standing role in European paper production (Source: Derbrauni, 2014. CC BY-SA 4.0, via Wikimedia Commons).

to empower both UNESCO and non-UNESCO water mills as contributors to climate-resilient territories. As governance hubs, UNESCO sites create structured spaces where cultural, environmental and water-management institutions collaborate; these frameworks not only enhance the resilience of listed mills but also serve as transferable models for non-UNESCO sites. In this way, UNESCO recognition becomes a catalyst for broader, landscape-wide strategies of sustainable development and adaptive water governance.

To operationalize this shift from passive conservation to functional regeneration, the following policy actions are critical. First, integrate historic mills – both UNESCO and non-UNESCO – into climate-resilience strategies and landscape management frameworks, recognizing their capacity to provide ecosystem services such as water retention, flood regulation, biodiversity enhancement and low-impact hydropower. This integration should include technical solutions that reconcile ecological continuity with sustainable reuse, including fish ladders, bypass channels, adjustable sluices and environmentally compatible micro-hydropower. Second, strengthen community-based and intersectoral governance by supporting miller associations, local heritage NGOs and volunteer networks through participatory models, co-design processes and long-term capacity-building programs, ensuring continuity of hydraulic management practices and the transmission

^ Fig. 8 A miller and the millstone at Calbourne Watermill, Isle of Wight, United Kingdom. The carved millstone represents traditional technical craftsmanship, an aspect of the intangible cultural heritage linked to historic milling (Source: Garry Knight, 2011. CC BY-SA 2.0, via Wikimedia Commons).

of traditional knowledge. It is also important to expand interdisciplinary studies, applied research and interoperable digital platforms that integrate hydrological, ecological, cultural and energy data. These tools – enhanced through citizen science, open-access monitoring and training – should support shared decision-making among cultural, environmental, water and energy authorities as well as local communities. Finally, remove regulatory barriers and harmonize procedures among cultural heritage, environmental, hydrological and energy authorities, simplifying authorizations for maintenance, ecological upgrades, hydraulic reactivation and sustainable micro-hydropower. Clearer and more coordinated regulation would enable mills to function effectively as components of climate-resilient landscapes.

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Useful Links

World Heritage List is available at: https://whc.unesco.org/en/list/.

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The Water Management System of Augsburg: UNESCO World Heritage Property, Global Practice Example and Role Model

Christian Schaller

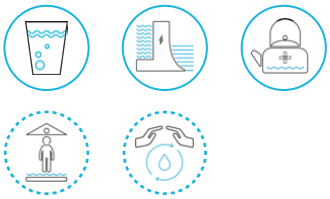
Abstract
The buildings and infrastructure of the UNESCO World Heritage property, the Water Management System of Augsburg, document the use of water resources over the course of 800 years. The system embodies sustainability and is recognised for its innovative solutions. The foundation for its management is the 2019 management plan, developed for the site's UNESCO nomination. Building upon this foundation, the City of Augsburg implemented its Klimawandelanpassungskonzept (Climate Adaptation Plan) in 2022. This subsequent program focuses on urban resilience and sustainable development, linking directly to the World Heritage property by identifying "water" as a key action field. Current responses to climate challenges, closely connected to the Augsburg World Heritage property, include three EU projects: Licca Liber, LIFE, and Contempo2, which aim to restore the Lech River and surrounding floodplain habitats.

Policy Recommendations
- Use Augsburg's proven 2019 management plan as a model for developing new transregional and international water strategies.
- Leverage historical water heritage sites to promote public awareness and foster the cross-border dialogue needed to address water challenges.
- Scale up innovative local solutions and pilot projects to create implementable measures for global water management.

KEYWORDS

UNESCO World Heritage
water management system
urban water landscape
water stewardship
sustainable hydropower

WATER ICONS



CLIMATE

A B C **D** E

Dfb: Humid continental climate

< Fig. 1 Around 1879, the Waterworks at Hochablass was put into operation, and the abundance of water was used to drive the state-of-the-art turbines of the time (Source: City of Augsburg/Martin Augsburger).

Introduction

Representing a historical heritage, the UNESCO World Heritage property listed in 2019 as the Water Management System of Augsburg can be regarded as a best practice example with relevance to the future of sustainable urban water stewardship and climate-resilient city planning. The site represents a unique urban water landscape, consisting of 22 unique and interconnected elements that illustrate the local use of water resources over 800 years. These include a network of canals and watercourses, dating from the fifteenth to the twentieth century, that divide spring and river water, as well as monumental fountains, water towers with their associated infrastructure, and 10 power plants. Together, the elements serve as testaments to technological progress, the evolving aesthetics of water features in Augsburg, and the sustainable management of water resources.

The system is particularly remarkable for its continuous use, development and expansion over time. For many centuries, water has been a fundamental part of Augsburg's character, and throughout the city's over 2000-year-long history, the water management system has aligned with modern principles of sustainability and a focus on innovative solutions. This article presents the water-related and climate challenges and current projects addressed within the management of the Water Management System of Augsburg, as well as the use of water for power generation and human consumption.

Measures and Projects Connected to the World Heritage Management Plan

In developing the proposal for the site's inclusion on the World Heritage List in the 2010s, the City of Augsburg compiled an extensive nomination dossier, which involved extensive research into its 22 individual elements. This dossier offers a thorough description of the site, justifies its Outstanding Universal Value (OUV), and includes a comprehensive global comparative analysis. A core component of this dossier, the management plan, serves as a key planning tool, outlining guidelines for the preservation and, an aspect that deserves special focus, the careful and sustainable development of the World Heritage property, all while maintaining high technological and design standards (Stadt Augsburg 2019, 33–35).

The management plan lists conservation measures, identifies potential conflicts and synergies, and establishes formal procedures for administration, monitoring, and stakeholder engagement. The plan operates within a legal framework defined by acts and ordinances concerning water pollution, nature conservation, heritage protection, and building. In the case of Augsburg's site, an important objective was to ensure that the protection of the World Heritage property was consistent with other goals integral to the City of Augsburg's concept of urban planning. This was a key consideration because the property's 22 individual elements are scattered throughout the city and linked by a watercourse system that covers the entire urban area. The water resources and the water management system are closely connected to the urban landscape and the city's livability. Consequently, the site's architectural and technological monuments are not lifeless relics of the past, but essential components of present-day life.

Water-Related Challenges

The management of The Water Management System of Augsburg involves addressing com-

plex water-related challenges within the heart of a modern Bavarian city of over 300,000 inhabitants. The World Heritage Office's ongoing tasks, therefore, include monitoring quality assurance of water resources and monument conservation, ensuring compliance with local, state, and federal heritage and environmental law, and balancing the interests of various urban stakeholders, including municipal utilities (*Stadtwerke*), private mill owners, environmental groups, and residents. Consequently, new measures and projects are subject to negotiation, and their feasibility must be aligned with the needs of the contemporary urban environment.

The management plan addresses these specific urban challenges in depth. This includes guiding the further development of technical components, such as hydropower plants, which must comply with evolving safety, environmental, and energy efficiency standards, while also accommodating inevitable infrastructure additions, such as new roads or streetcar lines.

In response to these challenges, it outlines guidelines that align with numerous United Nations and UNESCO charters and documents. Most importantly, this includes compliance with the *Zukunftsleitlinien für Augsburg* (Future guidelines for Augsburg), adopted by the Augsburg City Council in 2016, in accordance with the 2030 Agenda for Sustainable Development. In the context of Augsburg's World Heritage property, SDG 6 ("Ensure availability and sustainable management of water and sanitation for all"), SDG 7 ("Ensure access to affordable, reliable, sustainable and modern energy for all") and SDG 11 ("Make cities and human settlements inclusive, safe, resilient, and sustainable") play a central role (Stadt Augsburg 2019, 68–70).

Additionally, the *Erklärung zur Erhaltung historischer Stadtlandschaften* (Recommendation on the Historic Urban Landscape), adopted by the UNESCO General Conference in 2011, is of particular importance. The recommendation emphasizes that the maintenance of historic heritage within conurbations can only be ensured if the heritage is viewed not in isolation but rather within the existing urban context. The City of Augsburg accordingly defines its World Heritage property as an integral and central component of urban development and the urban social fabric (Stadt Augsburg 2019, 130). Thus, the definition of the World Heritage Status of the Water Management System of Augsburg is closely aligned with international framework documents.

In the 2019 management plan for The Water Management System of Augsburg, the outlined challenges and guidelines for addressing them result in specific projects. These include measures to make Augsburg's watercourses and canals more attractive to residents and visitors, to maintain and restore individual elements and to implement protective measures and educational frameworks. The plan also initiates projects that go beyond the preservation, presentation and further development of the site. In addition to the establishment of the World Heritage Info Center in the town hall square, the construction and inauguration of the Umweltbildungszentrum (environmental education center) is noteworthy. Located on the grounds of the Augsburg Botanical Garden, it was completed in 2023 and provides the Umweltstation Augsburg, an officially recognized institution for environmental education, which opened in 2007, with offices and adequate facilities for workshops, seminars and exhibitions. The center is located between the Western Forests Nature Park and the inner-city area. Its tasks include providing education concerning the connection

between the brooks in the city forest and the history of Augsburg's drinking water supply system (Stadt Augsburg 2019, 110).

"The Water Management System of Augsburg" Management Plan and Climate Change Challenges

The 2019 management plan for the property proactively considers the potential effects of environmental changes, including water shortages, flooding, and utilization pressure from tourism (Stadt Augsburg 2019, 54–111).

In 2022, three years after the site was inscribed on the World Heritage List, these efforts to address new challenges culminated with the adoption of the City of Augsburg's climate adaptation plan (*Klimawandelanpassungskonzept der Stadt Augsburg*). This strategic plan focuses on promoting urban resilience and sustainable development, and it is closely linked to the World Heritage property through its identification of "water" as a key area for action. In the Augsburg area, numerous systems – both natural and man-made – depend on water. The plan identifies particular areas of concern: groundwater and drinking water, high and low water levels in surface water, and urban area drainage, especially where heavy precipitation events lead to flooding. These concerns, common to many other cities and regions worldwide, pose even greater challenges for Augsburg, with its abundance of water. On the other hand, educational programs and public presentation of the World Heritage property can increase public awareness, encourage international networking, and stimulate scientific and political discussion (Herrmann 2024, 116–20).

Current responses to climate challenges that directly support the goals of the Augsburg World Heritage management and adaptation plans include three EU-funded projects: Licca Liber, LIFE, and Contempo2, which aim to restabilize the Lech River and surrounding floodplain habitats. An important project that extends beyond the city limits is Licca Liber, which aims to return large stretches of the Lech to their natural state and to stabilize the river, which has been canalized over the past 200 years, with its depth regulated by numerous barrages. The project "LIFE. Stadt-Wald-Bäche" (hereafter LIFE) is intended to last from 2019 to 2027 and is funded by the City of Augsburg and the Bavarian State Ministry of the Environment and Consumer Protection. It focuses on the Lechauen, the floodplain habitats in the city forest extending along the banks of the Lech River, which are an important part of the wildlife corridor of Lechtal (Lech Valley). With a budget of over EUR 6,640,000, the project covers an area of more than 2,250 hectares. The entire city forest is part of the buffer zone of the World Heritage property. The goals of LIFE are to restore uninterrupted ecological continuity within the city forest area, reconnect the brooks in the city forest to the Lech, restore the alluvial forest habitats, and provide environmental education and public relations support to raise awareness of the network of protected areas called "Natura 2000," which includes the project area. Another EU-funded project, Contempo2, spans from 2022 to 2028 and is coordinated by LEW Wasserkraft GmbH, a subsidiary of the power supply company Lechwerke AG. Contempo2 analyzes the effects of climate change on the Lech, and the Lechkanal (Lech Canal) north of Augsburg is one of its focal points. The canal, an artificial diversion of the Lech, as well as the three hydropower plants located on the canal, are included in the World Heritage property. The project aims to investigate how the ecosystem of the Lech can be strengthened despite the utilization of waterpower (Settele 2024, 121–34).

^ Fig. 2 The Hochablass waterworks, a 19th-century element of Augsburg's World Heritage system, supplied drinking water using sustainable hydropower (Source: City of Augsburg/ Martin Augsburger).

Water for Power and Consumption

In addition to the projects mentioned above, both drinking water production in the city forest and the generation of electricity in hydropower plants are closely connected to the World Heritage property, due to their use of water as well as their location. The City of Augsburg has been pursuing a sustainable water policy for centuries. Its efforts allow high quality drinking water to continue to be supplied from resources in the city forest. The vast expanse of woodland belongs to the City of Augsburg, which means Augsburg is among the cities with the largest publicly owned forests in Germany. In Augsburg, the development of a supply network and the quality assurance of the drinking water – initially supplied by canals constructed to carry spring water, and since the nineteenth century by pumps and pipelines – were matters of key importance. The pioneering role in water management Augsburg assumed in the Middle Ages runs like a golden thread through the city's history and still holds true today. In strict accordance with the highest quality standards, the Stadtwerke Augsburg, a subsidiary company of the City of Augsburg, supplies the conurbation with drinking water sourced from the protected area, which is, for the most part, located in the city forest. The untreated drinking water is directly obtained from groundwater. It is a pure natural product characterized by a very low level of nitrate and a desirable mineral content, and is therefore suitable for use in baby food. The quality of Augsburg's drinking water is rated among the best in Europe. The drinking

water supply relies on the use of sustainable energy sourced from waterpower – generated by the Stadtwerke Augsburg, for instance, at the Waterworks at Hochablass, an element of Augsburg's World Heritage property. Drinking water is available free of charge at numerous fountains scattered throughout the city. As far as the supply to households is concerned, apart from a base rate, the Stadtwerke offers citizens of Augsburg the so-called Regenio-Tarif, which includes a customized drinking water analysis and co-funds conservation projects in the region. Introduced in 2009, the Regenio-Tarif combines health protection and quality assurance, water and nature protection, and the use of renewable energy in a way that is almost unique (Ottilinger 2017, 228–33).

With numerous plants on the city's watercourses, Augsburg has always been renowned for its intensive use of hydropower. In the nineteenth century, premodern waterwheels and pumping stations were gradually replaced by turbines and modern power plants, which still count among the primary features of the cityscape. In Augsburg, hydropower supplies a significant amount of electricity. Renewable energy is produced in the 10 plants (such as Hochablass waterworks, see fig. 2) located in and around the city that are elements of the World Heritage property and a dozen others, which are mainly under private ownership, but feed surplus electricity into the public power grid (Häußler 2015, 11–84).

Conclusion

In the 2010s, in addition to the nomination dossier, an extensive management plan was completed as part of the proposal for the Water Management System of Augsburg to be considered for inclusion in UNESCO's World Heritage List. The tasks outlined in the plan aim to preserve the World Heritage Property and its inherent value, to support appropriate presentation and education efforts and enable sensitive and sustainable further development while maintaining high technological and design standards. Another important objective is to promote the sustainable use of water resources on the local, national and international levels, positioning the Water Management System of Augsburg as a role model. Thanks to the intensive work and research carried out when preparing the nomination file and, even more importantly, in the years since the site's inscription, the management plan has proven to be a vital reference and guiding tool. It supports not only the site's day-to-day management, but also its long-term protection, development and transmission to future generations.

Consequently, the proven success of the 2019 management plan offers key lessons for broader water strategies. It demonstrates that historical water heritage sites can be powerful catalysts for public awareness and the cross-border dialogue needed to address water and climate challenges. Furthermore, Augsburg's experience shows that local, context-specific solutions and pilot projects can provide innovative and implementable measures for sustainable water management on a global scale.

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Ancient Wood and Climate Resilience: Prehistoric Pile Dwellings around the Alps

Cyril Dworsky & Barbara Fath

Abstract
As climate change threatens heritage sites, modern settlements and landscapes around the world through flooding and rising sea levels, closer examination of prehistoric innovations may inspire solutions based on practices that have been tested for over 7000 years. Elevated architecture, natural ventilation systems and minimal hydrological impact provide actionable blueprints for sustainable building and planning today. By integrating these time-tested strategies with modern technology, the UNESCO World Heritage property of Prehistoric Pile Dwellings around the Alps can contribute to achieving the United Nations Sustainable Development Goals, transforming ancient techniques into modern climate adaptation tools.

Policy Recommendations

- Ratify and implement the 2001 UNESCO Convention in Austria and Germany to protect underwater cultural heritage from development and climate change threats.
- Create specialized archaeology programs by establishing permanent university and institutional programs focused on underwater and wetland archaeology to ensure expertise in conserving waterlogged artifacts.
- National and international agencies should provide funding to interdisciplinary research teams (archaeologists, architects, hydrologists, climate scientists) to develop integrated strategies for cultural preservation and climate resilience.

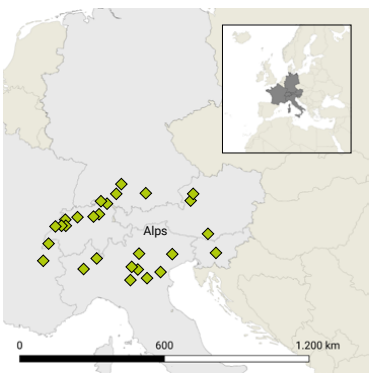
KEYWORDS

UNESCO World Heritage
prehistoric archaeology
water-adaptive architecture
climate resilience
cultural transmission networks

WATER ICONS

CLIMATE

Cfb + Dfb/Dwb/Dsb:
Temperate oceanic climate and humid continental climates (with dry winter or dry summer variants)



< Fig. 1 Remains of the wooden stilts of the pile dwelling site of Bevaix, Lake Neuchâtel, Switzerland (Source: Béat Arnold, with photographer's permission).

Introduction

A remarkable archaeological example of water management in the history of mankind has survived, thanks to the water itself. The remains of hundreds of prehistoric villages now submerged in lakes, bogs and rivers around the Alps serve as a testament to human ingenuity, technological progress and resilience, as well as adaptation to past environmental crises (fig. 1). Dating from 5000 to 500 BCE, these ruins provide unparalleled insights into the lives of prehistoric communities, because in comparison to mineral soil sites, the waterlogged conditions aid the preservation of organic material – especially the wooden construction piles. They are such outstanding archaeological treasures that a carefully selected collection of 111 sites across six countries (Switzerland, Austria, France, Germany, Italy and Slovenia) as of 2011 constitutes the transnational and serial World Heritage property "Prehistoric Pile Dwellings around the Alps" (UNESCO 2011). A common feature of these settlements is their deliberate location near or even within water bodies to benefit from a stable supply of freshwater and food (fish), and strategic defensive advantages while also remaining accessible to residents. This environmental context has played a crucial role in their preservation, architectural design and cultural development. This article explores the significance of water management in these prehistoric villages through three key themes: preservation, transmission and adaptation.

Preservation of Organic Material

Archaeologically, one of the most distinctive aspects of prehistoric pile dwellings is the ex-

^ Fig. 2 Model of an underwater pile dwelling excavation at the Musée archéologique du lac de Paladru, France (Source: Kuratorium Pfahlbauten/Cyril Dworsky, 2022).

ceptional preservation of organic materials, which is a direct result of the waterlogged conditions in which they were buried. The anaerobic environment created by these conditions inhibits the growth of microorganisms that normally decompose organic matter. This unique preservation condition has allowed for the survival of materials rarely found in terrestrial archaeological sites (Hafner et al. 2022; Hafner 2024; fig. 2). The range of preserved materials from these sites is vast and includes wooden piles, plant fibers, food remains, textiles and tools. For example, wooden piles used to support buildings – hence the term "pile dwellings" – have been found in remarkable condition, providing detailed information about the types of wood used, woodworking techniques employed and about the use of trees as a resource in general. Plant fibers, such as those used in basketry and cordage, have also been preserved, providing insight into the daily lives and technological capabilities of these communities.

Food remains, including seeds, nuts and animal bones, have been found in abundance, shedding light on the diet and subsistence strategies of the inhabitants (Antolín et al. 2022). Textiles, rarely conserved in other contexts, have been found at numerous sites, revealing information about clothing and textile production. Tools made of wood, bone and antler have also survived the millennia, providing evidence of the technological sophistication of these prehistoric communities. This exceptional preservation of organic materials at these sites contributes to their Outstanding Universal Value (OUV), as recognized by UNESCO. The detailed information gleaned from these materials allows archaeologists to reconstruct the daily lives, changes in social structure, and technological advances of prehistoric communities with a level of detail unparalleled in most other archaeological contexts. This preservation not only enhances our understanding of prehistoric life but also provides a unique window into the environmental conditions and changes that have occurred over millennia (Rey et al. 2025).

Transmission of Culture

Given the historical environmental challenges of non-regulated water bodies with regular changes of high water and low water and the mundane nuisance of mosquitos, the bold strategic decision to build pile dwellings in a wet environment close to the bank of waterbodies was not only a practical choice for construction but also a key factor in the economic and cultural development of the early settlers' circumalpine region. The lakes and rivers provided a reliable source of food and freshwater and aided the development of early trading routes, making them ideal locations for prehistoric settlements. The pile dwellers certainly participated in the extensive commerce networks that spanned the Alps and beyond during prehistory, starting in the fifth millennium BCE and ending in the first millennium BCE. Waterways allowed for highly efficient transportation of goods such as flint, amber and metal ores, which were traded over considerable distances (Rosenstock et al. 2016). For example, flint tools and ax-heads from the Alps have been found in prehistoric sites as far away as Northern Europe, for example in Scotland and Denmark, indicating the extensive reach of these trade networks (Pétrequin et al. 2008). Such connectivity played a crucial role in the exchange of skills, knowledge and cultural transmission between various communities, significantly contributing to the technological and cultural development of prehistoric pile-dwelling communities (Kowarik et al. 2020; Archäologisches Landesmuseum Baden-Württemberg 2016; fig. 3). The movement of people and goods along established routes enabled

^ Fig. 3 Reconstructed model of a Bronze Age dugout from Carinthia/bog of Sattnitz (Source: Kuratorium Pfahlbauten, Michael Tavernaro, 2014).

the sharing of technological innovations, such as new tool-making techniques, early metallurgy and agricultural practices. It also potentially allowed for the rapid spread of burial customs, artistic styles and religious beliefs. While there is no uniform "pile dwelling culture," this transmission certainly contributed to similar elements of cultural expression among prehistoric pile-dwelling communities across the Alpine region, reflected in similarities in material culture and technologies found at different sites (Affolter et al. 2023; Bahss and Bleicher 2023).

Adaptation to the Environment

The use of stilts in construction is a major defining characteristic of prehistoric pile dwellings, although this technique is also quite common in other archaeological contexts and is not the decisive argument for its OUV. Nonetheless, this architectural approach allowed the inhabitants to build their homes at levels high enough to stay dry, providing protection from floods and pests (Swierczynski 2017). In addition, building on the sparsely vegetated shores of the lakes meant that laboriously cleared areas inland could be used as potential farmland.

Wood as a building material is not only easy to work with, but was then, and is now, a renewable and easily accessible raw material. The use of wooden piles driven into the lake or riverbed provided a stable foundation for the structures, which were typically made of additional wood and other organic materials (fig. 4).

^ Fig. 4 Construction details of a reconstructed pile dwelling grid foundation at the Parco Archeo Natura a Fiavé, Italy (Source: Kuratorium Pfahlbauten, Cyril Dworsky, 2025).

Among the many pile dwelling structures that existed from the Neolithic to the early Iron Age, there were a variety of construction types. Houses were built with flat floors near shorelines, and even log constructions have been found. The landscape as well as regional building traditions influenced the architecture of these buildings (Bleicher 2018, fig. 5). Nevertheless, the architectural adaptation of elevated houses allowed both prehistoric and modern communities to thrive in challenging environments with changing water bodies, demonstrating the enduring relevance of this building technique.

The architectural features of wooden stilts as foundations certainly invite comparisons to modern settlements built in similar environments. One of the most well-known examples may be the city of Venice in Italy. Although the use of piles in Venice is more connected to the stabilization of the building ground by compression of the subsoil and reaching more stable and sound strata, the technique made it possible to build in unfavorable wet conditions, which are geographically important. As a result of millions of wooden piles driven into the soft, waterlogged soil of the lagoon, Venice was able to become a conveniently located and important center of commerce.

The comparison highlights the contemporary relevance of the architectural strategies employed by prehistoric pile dwellers in terms of dealing with difficult settlement areas. This is particularly becoming important in the context

^ Fig. 5 Interpretative life-size models of Neolithic houses in the Pfahlbaumuseum Unteruhldingen at Lake Constance in Germany (Source: Kuratorium Pfahlbauten, Cyril Dworsky, 2015).

of climate change, when rising sea levels and increased weather extremes pose significant challenges to modern communities and a decline in settlement space. Along with storms, floods are the most common and devastating natural disasters worldwide. The resilience of the prehistoric settlers and how they survived the periodic flooding of their villages is documented in layers of lake sediment (Swierczynski et al. 2017). This can inform and stimulate contemporary architectural responses. Although common practice in many regions and in history, modern housing development quite often ignores the danger of climate change. One of the key lessons from prehistoric pile dwellings is in fact the effectiveness of elevated building designs in mitigating the impact of flooding. While diverse modern examples of stilt constructions exist, architects today are increasingly exploring the use of elevated structures in flood-prone areas and may draw inspiration from the pile-dwelling strategy (Eck 2020).

In addition to flood protection, the pile-dwelling strategy offers benefits in terms of heat management in times of global warming. The elevated structures allowed air to circulate better than structures built directly on soil, helping

to regulate indoor temperatures. This principle is being applied in contemporary architecture using raised foundations and open floor plans, which enhance natural ventilation and reduce the need for artificial cooling (Bartolini 2021). The building strategy for waterlogged or unstable soils also offers inspiration for addressing other modern challenges of water management. Modern settlement areas frequently face issues related to soil surface sealing, where impermeable surfaces prevent water infiltration, leading to increased runoff and flooding. Building on stilts is a potential solution that can make it possible to develop contaminated sites and expands the amount of land available in growing societies. More and more land is being covered with impermeable materials, like asphalt and concrete, as well as buildings. This prevents rainwater from infiltrating the soil, leading to higher flood risks, reduced groundwater recharge, and impaired soil function. Sealed surfaces also intensify the urban heat effect, reducing biodiversity and fragmenting natural habitats. Creating minimally invasive foundations with piles reduces the impact on natural hydrology.

Conclusion

The UNESCO World Heritage property Prehistoric Pile Dwellings around the Alps offers a unique window into the lives of prehistoric communities and their ability to adapt to and manage natural resources. The exceptional preservation of organic materials at these sites provides unparalleled insights into the daily lives, social structures and technological advancements of these communities. The lessons learned from these ancient settlements continue to inform and inspire modern approaches to water management, architecture and cultural exchange. The architectural strategy of building on stilts, which has historically enabled inhabitants to thrive in challenging environments, remains highly relevant today, especially in the context of climate change.

The lessons learned from these ancient settlements must inform modern policy. Of primary importance is the implementation of the 2001 UNESCO Convention on the Protection of Underwater Cultural Heritage: The exceptional preservation of organic materials in waterlogged conditions in the prehistoric pile dwellings proves that underwater archaeological heritage contains irreplaceable evidence of human environmental adaptation. To protect this submerged cultural heritage from development and climate threats, countries should ratify and implement the 2001 convention. Austria and Germany must prioritize ratifying the convention in the coming years, as the other four the four other countries that are home to the Prehistoric Pile Dwellings have already done.

It is also crucial to establish underwater and wetland archaeology programs: The OUV of pile dwelling sites requires highly specialized conservation techniques for waterlogged materials and underwater excavation. Research institutions, universities and heritage agencies should create permanent positions for archaeologists and conservators trained in underwater archaeological methods to ensure continuous knowledge transfer.

Finally, we need transsectoral collaboration frameworks: The 7,000-year success of the pile dwellings in flood management, waterway networks and environmental adaptation underlines that such archaeological sites offer multi-sectoral perspectives and can provide valuable lessons. National and international funding agencies must support interdisciplinary teams – including archaeologists, architects, hydrol-

ogists and climate scientists – to develop integrated approaches that address both cultural preservation and climate resilience challenges within the SDGs.

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An Integrated Water System: The Cultural Landscape of Honghe Hani Rice Terraces

Tianchen Dai & Carola Hein

Abstract
The Cultural Landscape of Honghe Hani Rice Terraces, inscribed on the World Heritage List in 2013, integrates traditional farming, irrigation, water management and the Hani people's spiritual relationship with nature. It embodies traditional ecosystemic practices and provides a model for sustainable development aligned with the United Nations' Sustainable Development Goals (SDGs). The terraces exemplify a comprehensive water management system (SDG 6), grounded in resilient communities (SDG 11), efficient traditional farming (SDG 12) and climate-resilient water management (SDG 13). This article examines this traditional approach to water management to offer insights regarding the challenges involved in conserving and (re)creating holistic water systems. In the context of climate change, safeguarding this cultural landscape against flooding, drought and socioeconomic pressures is of critical importance.

Policy Recommendations

- Public and private stakeholders – including local farmers, returnees, governments, entrepreneurs and experts – should strengthen climate resilience by reinforcing irrigation canals, dams, ridges and other water conservancy facilities, and by integrating this infrastructure into the daily lives and agricultural practices of nearby communities.
- Local governments should enhance farmers' capacity to adapt to extreme weather by offering training in water-saving irrigation techniques and disaster-resistant crops, and by investing in upgraded monitoring systems, including advanced weather stations and real-time water-flow sensors to facilitate implementation.
- The local government should establish an ecological compensation budget to raise farmers' income, promoting rice–fish co-cropping, reducing reliance on chemical fertilizers, and encourage farmers to plant water-retaining forest species.

KEYWORDS

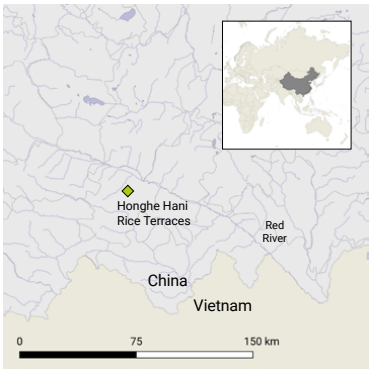
UNESCO World Heritage
Water system
Cultural landscape
Honghe Hani Rice Terraces
Ecosystem

WATER ICONS

CLIMATE

A B **C** D E

Cfa: Humid subtropical climate



< Fig. 1 The terraced landscape system in Honghe Hani Rice Terraces in Yuanyang County, Honghe Prefecture, Yunnan, China (Source: Fanghong, 2013. CC BY-SA 3.0, via Wikimedia Commons).

Introduction

The Cultural Landscape of Honghe Hani Rice Terraces in Southern Yunnan is a unique, comprehensive water system that integrates farming, water management and the Hani people's spiritual connection with nature. It was added to the World Heritage List in 2013 (UNESCO World Heritage Centre 2013). The case of the Honghe Hani Rice Terraces illustrates the importance of integrating both tangible and intangible water practices as a holistic spatial, social and cultural system (Dai and Hein 2023; Dai, Hein, and Baciu 2023; Dai and Hein 2021). This complex system of channels and forests exemplifies an ecosystem approach that secures a reliable water supply for rice terrace irrigation and household needs, supporting SDG 6 (Clean Water and Sanitation). The integration of the traditional "mushroom" house (A unique traditional Hani dwelling, named for its mushroom-like roof, is typically composed of earthen walls, bamboo and wood frames, and thatched roofs) – typology into the rice terrace landscape promotes sustainable living, aligning with SDG 11 (Sustainable Cities and Communities). Using locally sourced, biodegradable materials like wood and thatch, the design of the compact, resource-efficient village minimizes environmental impact, supports the terraces' agricultural and water management systems and strengthens community cohesion. An effective farming system that uses buffalo, ducks and fish to maximize resources and reduce waste in red rice production speaks to the values of SDG 12 (Responsible Consumption and Production). The terraces' strong resilience to climate change and drought makes this landscape a model of ecological sustainability in line with SDG 13 (Climate Action). This ingenious system also highlights the important role of water in preserving and protecting these traditional sites at a time of climate change.

The Honghe Hani Rice Terraces exemplify human creativity in adapting to climate challenges. Their construction originated with the multi-ethnic people (Luo and He 2023), who originally inhabited the Qinghai and Tibetan Plateau. They were highly skilled pastoral nomads with mainly agricultural skills. By the ninth and tenth centuries, they left their homeland and moved to China's Yunnan Province due to pressures from neighboring groups and severe living conditions. In Yunnan Province, starting in the ninth and tenth centuries (UNESCO World Heritage Centre 2013), the Hani people used water from the high mountains to create a terraced landscape system that provided water for drinking, cleaning and irrigation downhill (fig. 1).

The region's steep slopes, heavy rainfall and elevations approaching 3,000 m made it suitable for terracing from forested uplands to valley floors. By reshaping the terrain, the Hani created a resilient agricultural landscape that still functions today and includes mountains, trees and villages (fig. 2).

A crisscross network of irrigation channels directs water into ditches. The Hani people meticulously plan the layout of rice terraces, positioning them on sunny, mid-slope locations at around 800 m above sea level to optimize irrigation and environmental conditions for rice cultivation. Forests, located at the top of the hill, play a vital role by capturing and regulating the water needed for the terraces. A network of channels efficiently distributes water both horizontally and vertically, with sills in terrace bank walls guiding water flow from one level to the next. Sites are selected in winter and spring, when warmer weather and drier soil allow initial dryland cultivation. After three to four years of leveling the terrain, these sites are converted into permanently flooded irrigated terraces.

During winter, the Hani reinforce terrace bank walls using mud from the fields to maintain the system.

The Hani people also developed social structures for water management, as captured in the saying: “Dividing water with woodcuts." According to the respective number of terraces belonging to each household and the amount of water needed, water was supplied through a piece of wood with several notches to indicate a controlled amount of water that was allowed to flow into the terraced fields, making full use of the mountain springs and minimizing water waste. This method of “dividing water with woodcuts" greatly helped maintain the agricultural system of the terraced fields. Similar water management structures — designed to divert water and regulate the amount allocated to each household — can be found in villages throughout the Honghe Hani Rice Terraces (fig. 3).

The rice-growing process is sustained by elaborate socioeconomic systems that strengthen people's relationship with the environment through obligations to both their own lands and to the wider community. It is also sustained by religious practices that inscribe natural processes in spiritual activities, emphasizing the sacredness of nature. The relationship between individuals and their community, as well as between people and their gods, has persisted for at least a millennium and is still a living cultural tradition.

A sustainable agricultural system built on fairness and rationality can inspire contemporary societies. Climate change, modern infrastruc-

^ Fig. 2 Villages above the Honghe Hani Rice Terraces (Source: Tianchen Dai, 2024).

^ Fig. 3 A water diverting and management structure in a village in the Honghe Hani Rice Terraces (Source: Tianchen Dai, 2024).

ture and socioeconomic shifts threaten the ecological and cultural integrity of this UNESCO World Heritage property. Preserving this living heritage requires innovative, community-driven strategies that balance tradition with adaptation, offering a replicable model for global sustainable development.

Current and Future Challenges to this Water System

Today, this sophisticated traditional water management practice faces multiple challenges. Fewer people and communities are willing to follow the traditional way of life, leading to a decline in terraced fields that cannot be adapted to mechanical production methods. Furthermore, traditional communities are disappearing as the area has seen an influx of new immigrants who have settled to work in the local tourism and leisure sectors (Zhang et al. 2017). Tourism has also disrupted the Honghe Hani Rice Terraces by adding road and parking infrastructure—which in turn alters traditional settlement layouts—transforming social relationships and resource allocation within villages, and upsetting the ecological balance.

Extreme droughts and floods are exacerbated by climate change and the destruction of the forests that traditionally capture and regulate water for the Honghe Hani Rice Terraces. The internal structure of the terraced fields has been damaged by newly built viewing platforms for tourists, ditches and rivers and other water conservancy facilities have been damaged, and problems have arisen with the natural irrigation system structure. These artificial changes have severely impaired the inner balance and the ecological and cultural integrity of the traditional irrigation system, thereby compromising its ability to sustain the natural and cultural landscape.

Current Approaches to Preserving and Managing Water Heritage

Terraced farming is a climate-resilient practice that plays a vital role in the sustainability of the Cultural Landscape of Honghe Hani Rice Terraces. The protection of the cultural landscape relies heavily on sustaining terraced farming, which requires a comprehensive understanding of the natural and cultural nexus supporting the local practice and its potential evolution in the face of climate change and shifts in consumption patterns, economic structures, demography and information dissemination. Given the awareness of the values of terraced farming and the heritage status of Honghe Hani Rice Terraces, multiple stakeholders have been interested in and have been making efforts to protect the site. Local government, academic institutions, cultural foundations, tourism organizations and agricultural institutions (Zhang 2023), have all

become involved in the conservation and management of the Honghe Hani Rice Terraces.

A notable example is a project focused on one of the nominated villages within the UNESCO property boundary, the Azheke Village. The Cultural Landscape of Honghe Hani Rice Terraces includes eighteen villages within the property's designated boundary, and five additional villages that have been nominated. Other villages lie in the properties' buffer zone. The Azheke Plan, launched in 2018 by a team from Sun Yat-sen University, focuses on tourism-driven poverty alleviation for heritage preservation (Zhang 2023). The project established a village-run tourism company, funded partly by the government (30 per cent) and the villagers' resources (70 per cent), with 30 per cent profits of the profits supporting operations and 70 per cent to preserving traditional homes and rice terraces. This innovative model avoids external investment, directly linking income to the upkeep of cultural and ecological resources, while experts from Sun Yat-sen University guide operations and train villagers.

Tourism interventions, as part of the Azheke Plan, include cultural experiences such as terrace hikes and Hani song performances, promoting living heritage. More young farmers have returned to the village for tourism development and to the terraced fields for traditional farming, attracted by the profits generated by the plan. This self-reliant, community-led approach combines protection with development, offering a replicable model for sustainable rural revitalization in China and beyond. The plan is both successful and innovative in terms of heritage protection, as Sun Yat-sen University has recognized that the villages inhabited by local people are key to preserving and revitalizing the Honghe Hani Rice Terraces, serving as a vital link between the tangible and intangible elements of the agricultural and water management system. However, the commercialization of cultural practices risks commodification, potentially diluting authenticity if not carefully managed to prioritize community values over profit.

In addition, to protect the environment, the Honghe Prefecture Committee, the Prefecture Government and Yuanyang County have promulgated and implemented a series of regulatory documents such as the "Regulations for the Protection of Honghe Hani Terraces" and the "Guidelines for the Preservation, Restoration and Environmental Management of Traditional Hani Houses in Honghe" to facilitate converting farmland back into forests and restricting access to certain mountains to allow forest recovery. These efforts have significantly expanded forest cover in the region, which is essential to the functioning of the Hani rice terrace system. Furthermore, the local government has strictly protected the terraces to maintain the traditional rice farming method and the agricultural cultural landscape; therefore, the cultivated land area in the core area of Hani Terraces remains intact (Ma et al. 2024). The substantial increase in forest area enhances landscape connectivity and reconnects to the historic landscape pattern of the Hani Terrace core area. This not only improves the stability and security of the Hani Terrace ecosystem but also enhances its aesthetic landscape function, which plays a positive role in protecting Hani Terrace's cultural heritage and the development of ecological tourism.

Since 2020, several institutions have provided diverse non-fiscal funding sources for the preservation of both tangible and intangible heritage related to the ancient agriculture system of Honghe Hani Rice Terraces. For instance, the China Foundation for Poverty Alleviation has backed the establishment of the Heritage

Protection and Inheritance School. Academic institutions, including Yunnan University, Yunnan Normal University, Honghe University, the Chinese National Academy of Arts and the Yunnan Academy of Social Sciences, have conducted extensive research on the intangible cultural heritage of Yuanyang County, including Pu'er tea-making skills, a ceremony to honor the village's patron saint "Angma" and the nature god and the traditional multi-voice folk singing. The research has led to publications (Zhang 2023), as well as audio and digital materials planned for publication, featuring Hani folk literature and art, with the goal of promoting the inheritance and development of Yuanyang County's farming culture to the world. Publication projects include "On the Fields of Hope: An Ethnographic Documentary on Green Agricultural Development in Yunnan" and "The Collection of the Musical and Dance Traditions of the Hani and Yi Ethnic Groups on the Southern Bank of the Red River." Such actions effectively enhance the visibility and recognition of terraced fields as a living product of human culture. This process of cultural empowerment and branding can facilitate the transformation of terraced rice farming into a high-value-added compound agricultural culture system, thereby increasing the income from agricultural production and sustaining its development.

Local farmers, who consider themselves the creators and custodians of this heritage (Wu and Sun 2022), should be at the center of the region's sustainable development. Their participation is essential in maintaining terraced agriculture, improving agricultural marketing, promoting heritage tourism and supporting related cultural industries. This can be facilitated through capacity-building programs as well as by reforming local economic and environmental policies and restructuring community governance.

Policy makers can help address ecological degradation and promote ecological compensation by encouraging farmers to engage in traditional agricultural practices, modify their planting choices, and reduce chemical use, thereby improving forest water retention and minimizing chemical pollution (Liu et al. 2020). As a practical example, Yuanyang County Government distributed fish seedlings as part of physical ecological compensation to promote the rice-fish co-cropping mode in the Honghe Hani Rice Terraces. The economic benefits of this action were considerable, and the net income to the Hani terrace area was greatly increased compared with that of rice mono-cropping between 2020 to 2021 (Xu et al. 2024). This co-cropping mode is beneficial for improving the income and living quality of local farmers, alleviating the outflow of the rural labor force to a large extent, and thereby maintaining the unique four-element isomorphic agricultural ecosystem of the Hani Terraces and ensuring the stability of the terrace landscape.

As part of community restructuring, it is important to attract and support talented, educated young people, especially those with entrepreneurial skills and experience in digital media, who are interested in the terraces. Some university graduates, drawn by the unique culture and lifestyle of the Hani Rice Terraces, have already joined local communities and initiated new forms of entrepreneurship that integrate culture, agriculture and tourism. The People's Government of Honghe Hani and Yi Autonomous Prefecture has also introduced policies to encourage university graduates to return to their hometowns in Honghe Prefecture to start businesses. These include measures such as guaranteed loans and one-time startup subsidies for entrepreneurs (People's Government of Honghe Hani and Yi Autonomous Prefecture 2025).

By weaving together culture, agriculture and tourism, these approaches can transform everyday life in the locality. This reimagined way of life in revitalized communities ensures that the cultural landscape not only endures but thrives, boldly adapting to the dynamics of climate, environment and society with resilience and innovation. However, the success of these strategies ultimately depends on their active engagement, motivation to improve their livelihoods and commitment to preserving the land and water.

In terms of capacity building, training sessions and lectures can enhance local farmers' awareness of extreme weather and improve their ability to manage agricultural production, including techniques for water-saving irrigation and the cultivation of crops resistant to disasters like droughts and heavy storms. To counter the decline in terraced farming and boost income from agricultural products, farmers can be taught skills in advertising and packaging, and how to expand sales through e-commerce (Lu 2012), thereby adding commercial value to their agricultural products. In 2017, Honghe County nd launched a large-scale terraced red rice–processing plant as part of an "e-commerce poverty alleviation project." Online sales of e-commerce not only revitalize the idle assets of old red rice–processing plants but also broaden the sales of red rice (Zhang 2023). Such approaches can also be inspirational for institutions that promote the preservation of terraced landscapes more generally, notably the International Terraced Landscape Alliance (https://www.itla.si/art-home-page.html).

Current Approaches to Preserving and Managing Water Heritage

The Hani Rice Terraces will benefit from future-oriented engagement through capacity building, ecological compensation and support for young entrepreneurs, all of which will also aid community revitalization. These strategies should be further promoted and financed by the local governments. In addition, the governments should improve meteorological and hydrological monitoring in the Honghe Hani Rice Terraces area by installing advanced weather stations and real-time water flow sensors across key terrace zones; improve the extreme weather warning system with a dedicated mobile app and SMS alerts for farmers; repair and reinforce existing irrigation canals, dams, ridges, and other water conservancy facilities by enhancing flood control and drought resistance capabilities and initiate new water conservancy projects to increase water storage capacity, ensuring sufficient supply during droughts and effective drainage during heavy rainfall.

Recommended Future Approaches

The government could set up a fund to continuously provide entrepreneurship guaranteed loans and one-time subsidies to university graduates annually who return to Honghe Prefecture to start ventures in heritage tourism, cultural industries, or social media focused on the terraces. They could establish a mentorship network, pairing returnees with local leaders and businesses, aiming to retain them in the region for the long term. Finally, the government could expand the rice–fish co-cropping initiative by distributing fish seedlings to terrace farmers, backed by an annual ecological compensation budget, increasing net income, and introduce policies for reducing chemical fertilizer use and planting water-retaining forest species, with the goal of improving forest water retention across the terrace region.

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Resilience Value and Recovery: The Symbiotic Relationship between Classical Gardens of Suzhou and the Historic Urban Water System

Yapeng Ou, Zhen Cai & Qingzhou Wu

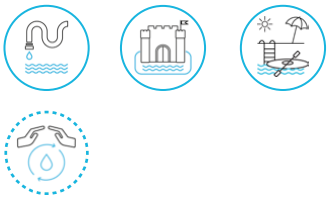
Abstract
The World Heritage property Classical Gardens of Suzhou (CGS) comprises water-focused cultural landscapes closely integrated with the historic urban water system (HUWS) of the ancient city of Suzhou in China. Historically, the gardens and the water system developed together, influencing and complementing one another in a symbiotic relationship. In response to the combined pressures of climate change and rapid urbanization, the resilience value – that is, the inherent capacity to adapt to and withstand environmental stresses – embedded in this relationship offers critical insights for urban planners, ecologists and cultural heritage agencies working to improve the flood and ecological resilience of gardens and ancient cities. This article surveys relevant scholarship and draws on field visits and interviews. It focuses on the resilience value of the symbiotic relationship that developed between the gardens and the urban water system and reviews key policies and practices since the 1950s. It summarizes efforts that have helped revive the symbiotic relationship and proposes strategies to further promote the recovery of this relationship by drawing on its embedded resilience value to enhance the resilience of both the gardens and the city of Suzhou.

Policy Recommendations
- Treat CGS and HUWS as a single organism and comprehensively restore their symbiotic relationship.
- Ensure the connectivity of gardens, rivers, lakes and wetlands, and strengthen the exchange of ecological materials and the functions of risk transmission between CGS and HUWS. Enhance the restoration and, when necessary, rebuild historic waterways, reconnect isolated waterways to improve long-term water system connectivity, and restore the ecological systems of gardens and urban water bodies.

KEYWORDS

UNESCO World Heritage
Classical Gardens of Suzhou
historic urban water system
symbiotic relationship
resilience value

WATER ICONS



CLIMATE

Cfa: Humid subtropical climate

< Fig. 1 Pond in the eastern garden of Couple's Retreat Garden, Suzhou (Source: Yapeng Ou, 2025).

Introduction: Classical Gardens of Suzhou and Historic Urban Water System

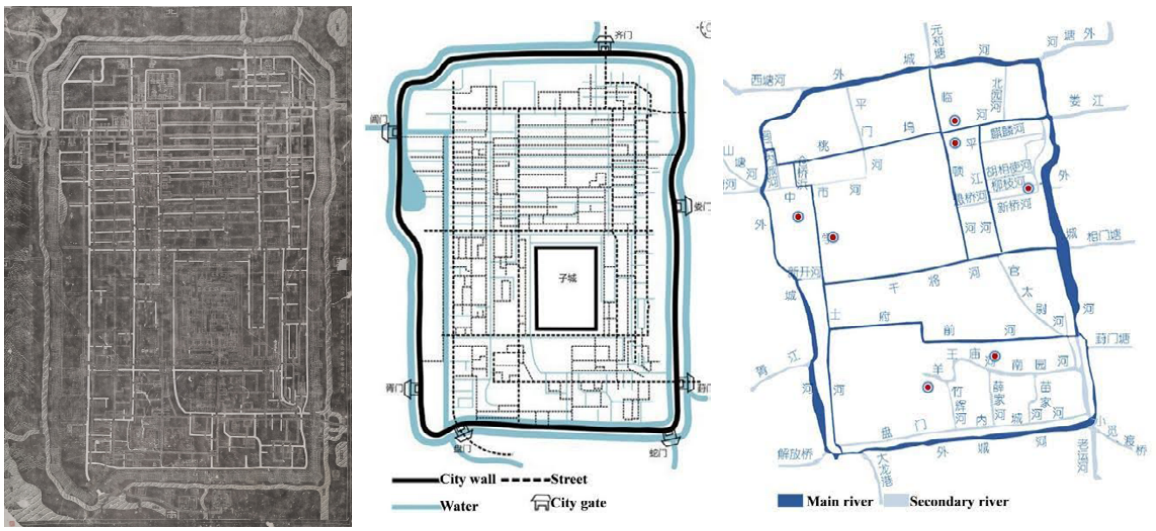
Classical Gardens of Suzhou, added to the World Heritage List in 1997, comprises "complex landscapes of pavilions, terraces, towers, rocks, hills, streams, and pools" created with "great subtlety and skill in a small area, re-creating natural beauty and harmonizing natural and human aesthetics" (ICOMOS 1997). Renowned for being "artificial yet comparable to a natural wonder," the gardens mark the pinnacle of Chinese classical "mountain and water gardens." Today, nine gardens[1] are included in the UNESCO World Heritage property. Mimicking the natural world, the gardens incorporate natural elements like water, rocks, plants and cultural elements such as buildings of aesthetic, literary and poetic significance (fig. 1). Together, they reflect the unique design philosophy of Eastern classical gardens, which revolves around the core principles of "emulating Heaven and Earth" and "water management and landscaping." They embody the concept of a living environment centered around "mountains and waters" and "unity of Heaven and Humanity" (Zong 1981). Historically, the gardens' formation and development were closely related to the highly developed water system in the ancient city of Suzhou (Wu 1991; Zheng and Li 2009). The city follows the design and construction concept of water–city integration, with a spatial pattern shaped by excavated canals (Wu 1991; Yu 1986). Since the Song Dynasty (AD 960–1279), Suzhou has been one of the Chinese cities with the largest and most comprehensive urban water networks and densest waterways.

Throughout history, this well-developed urban water system established the foundation for water landscaping in CGS (fig. 2). As a result, CGS co-evolved with HUWS. Overall, through the coordinated construction of urban water networks and gardens, Suzhou has achieved city–water harmony, city–landscape integration, and resilient development based on the connectivity of its water system. The inherent symbiotic relationship between CGS and HUWS, along with its associated resilience value, provides a fundamental basis for coordinated protection of the gardens and HUWS in the face of climate change. They also provide a model of water system planning for flood resilience (Zhu 2018).

However, since the early 1900s, modern urban construction has undermined the symbiotic relationship and co-evolution between CGS and HUWS. Amid urban economic growth and rapid population increase, waterways were filled in to create roads and housing throughout the Ming and Qing dynasties (AD 1368–1912). The density of waterways has continued to decrease (fig. 3), with a reduction from 5.8 kilometers per square kilometer in the Song Dynasty to 2.5 kilometers per square kilometer in the 1990s (Wu 1991).

Since large-scale urban construction started in the 1950s, this problem has progressively worsened. For various reasons, most of the water sources in CGS were disconnected from the external urban water system (Chen et al. 2014; Wu et al. 2012). Meanwhile, large-scale infrastructure construction has disrupted groundwater connectivity, while overextraction has caused a significant decline in its volume and level (Wu et al. 2012). This has led to the disconnection of both internal and external water sources, including underground and surface water sources of CGS. The water bodies in the gardens face

1. The nine gardens are the Humble Administrator's Garden, Lingering Garden, Net Master's Garden, Mountain Villa with Embracing Beauty, Canglang Pavilion, Lion Grove Garden, Garden of Cultivation, Couple's Retreat Garden, and Retreat and Reflection Garden.



^ Fig. 2 From left: a) Pingjiang Prefecture Map Stele (平江府图碑) from AD 1229 showing temples, bridges, rivers and city walls of Pingjiang (Suzhou) during the Southern Song Dynasty (Source: Suzhou Museum of Inscribed Stone Tablets); b) Plan of Pingjiang in the Song Dynasty (AD 960–1276) (Source: redrawn based on Hanchu Yin, 2021); c) Suzhou's current urban water system with seven classical gardens within the city wall inscribed as World Heritage (Source: redrawn based on Sha Shi, 2017).

difficulties not only in obtaining water from the urban water system, but also in discharging (rain)water outward. In addition, their small size and poor self-purification ability have compromised their ecological stability, leading to varying degrees of eutrophication. This has affected the expression and presentation of garden landscape aesthetics (Chen et al. 2014; Wu et al. 2012) and weakened the gardens' flood and ecological resilience, as evidenced by the severe inundation of Canglang Pavilion following a heavy storm in 2024. Considering the growing climate crisis, restoring the symbiotic relationship between CGS and the urban water system is essential for the sustainability of CGS.

Academic and other authorities have long overlooked this symbiotic relationship, let alone its embedded resilience value. Existing research predominantly focuses on the heritage value of CGS and their conservation. At the same time, the limited studies addressing Suzhou's HUWS remain confined to isolated examinations of its structural morphology, construction techniques, landscape aesthetics and historical evolution. Meanwhile, within cultural heritage conservation practice, there is a notable absence of integrated approaches that coordinate the conservation of CGS and HUWS. To fill this dual gap, this research aims to reveal the resilience value embedded in the symbiotic relationship that once existed between CGS and HUWS and propose strategies to restore it. To this end, we first examine the nature and resilience value of the symbiotic relationship between CGS and HUWS. We then review the policies and practices of CGS and HUWS since the 1950s and identify shortcomings. Finally, we summarize the efforts made so far that have been conducive to restoring the symbiotic relationship between CGS and HUWS. On this basis, we propose strategies to promote the relationship's recovery by leveraging the embedded resilience value in response to the urgent need to enhance the resilience of both gardens and city.

Our research employs a qualitative methodology that first entailed a review of journal articles, monographs and government documents concerning CGS and HUWS of Suzhou. We then visited representative gardens, including Canglang Pavilion and Couple's Retreat Garden, as well as historic districts of Pingjiang, Humble Administrator's Garden and Changmen Gate to investigate current water body conditions, connectivity between CGS and HUWS and water ecological restoration practices. During field visits, interviews were conducted with elderly and long-term residents to gather information on changes in HUWS, community-water relationships and neighborhood flooding. Finally, we interviewed a senior planner and water conservancy engineer, who provided an expert perspective on the evolution of HUWS, restoration practices and ongoing planning initiatives.

The Symbiotic Relationship between Classical Gardens and the Historic Urban Water System and Its Resilience Value

Connotation of the symbiotic relationship

The gardens in the World Heritage property not only embody traditional Chinese gardening art but also form a comprehensive water cultural landscape closely integrated with Suzhou's unique urban water system. Historically, the two have been closely connected and have influenced and complemented one another, forming the "bloodline" of Suzhou (Lv 2017). First, CGS's water system and Suzhou's water system shared the same source, forming the urban water environment. The water sources of CGS fell into two categories: 1) direct water intake from the urban water system, and 2) water intake from wells drilled at the bottom of ponds (Wu et al. 2012; Zheng and Li 2009; Zhu 2018).[2] In both cases, garden water bodies were connected with urban surface water or urban groundwater. This is due to the site selection characteristics of CGS, which emphasize the presence of water bodies and water systems within or around the site, as well as proximity to or connection with waterways (Xu and Ma 2021).

Second, CGS and HUWS were not merely physically connected but formed a co-evolving system, reflecting a symbiotic relationship shaped by mutual adaptation (Zheng and Li 2009). Specifically, the overall layout, building placement and vegetation arrangement of the garden were not determined solely by the preferences of the garden owner. Instead, they developed in response to the urban water system, evolving alongside its historical transformation (Zheng and Li 2009). On one hand, CGS benefited from being connected to HUWS, which offered favorable conditions for water-focused garden design and landscaping. This also influenced the location and distribution of gardens, as their development and decline closely followed changes in the urban water networks (Lv 2017). Meanwhile, different water environments (e.g., canal morphology, water flow direction) also stimulated the development of various garden water landscaping methods and aesthetic pursuits. On the other hand, the construction of the gardens also changed the distribution of urban waterways. For example, in Suzhou's urban fringe, where gardens are concentrated, waterways became sporadic (Zheng and Li 2009).

Finally, the integrated construction of CGS and HUWS as a holistic system has not only enhanced aesthetic and ecological functions but

2. According to Zheng and Li (2009), 60–70 per cent of the water sources of CGS come from the urban waterways diverted from the Grand Canal, 30–40 per cent from groundwater, and only a few from underground springs (Zheng and Li 2009).

^ Fig. 3 Evolution of Suzhou's historic urban water system from AD 1229 to AD 1797 (Source: Hanchu Yin, 2021).

^ Fig. 4 Scheme of the connection between the water system of the Couple's Retreat Garden and the urban water system (Source: Google Maps; photos by Yapeng Ou, 2025).

also strengthened the resilience of both the gardens and the city. Territorial, urban and garden water systems together form a "primary-secondary-branch" network (Zhu 2018), ensuring that both gardens and the city could play a long-term role in ecological and flood resilience.

Resilience value of the symbiotic relationship

Owing to the integrated construction and complementary relationship between CGS and the city, they have become a "resilient ensemble" capable of coping with external pressures such as

extreme weather and habitat disturbances. This is one of the reasons why Suzhou, despite being surrounded by numerous water bodies outside the city and low and flat internal terrain, has seldom suffered from floods in its history (Yu and Liu 2018). CGS and the urban water system have undergone thousands of years of adaptive co-evolution, forming a relatively stable overall structure that has sustained a multifunctional system capable of regulating microclimates and water ecology and of avoiding water disasters.

Historically, the stable operation of this system enabled CGS and the city to not only cope with natural disasters such as floods and droughts but also to respond flexibly to the needs of urban development, creating a highly adaptive and livable environment. First, thanks to the connected waterways, clean water flowed continuously into the city, reducing pollution (Wu 1991). This not only purified the urban water environment but also provided a reliable water source for the gardens. Second, ponds and channels in the gardens were connected to the urban water system (fig. 4), forming a comprehensive drainage and water storage system that could regulate runoff, alleviate floods, and enhance the overall disaster resistance of the city. Additionally, the symbiotic relationship between CGS and the urban water system helped regulate the microclimate and provided diverse habitats, thereby maintaining biodiversity.

Protection of Classical Gardens and Historic Urban Water System

Stage of protecting garden architecture while neglecting the urban water system

Beginning in the 1950s, municipal and CGS management authorities began to overlook the symbiotic relationship between CGS and the urban water system. Until the 1990s, although the gardens were protected, the urban water system and water environment suffered continual damage. In 1952, the Suzhou Garden Management Office was established and arranged for folk craftsmen from Xiangshan to restore the gardens. The period from 1953 to 1957 saw the first wave of garden restoration. In 1979, fourteen gardens were restored, marking a new wave of restoration (Xia 2021). These early efforts to conserve the gardens mainly focused on maintaining individual buildings and garden elements, emphasizing the stability of the structures and preserving the building style. They prioritized well-known gardens due to financial limitations and a "monument-centric" historic preservation ideology. Regarding the protection of garden water systems, given their limited connection to external water sources that saw declining water quality due to pollution, measures were widely implemented to disconnect the gardens from the urban water system. This was seen as necessary to prevent pollution from outside sources and to keep the water bodies within the gardens manageable (Chen et al. 2014). In sharp contrast, since the 1950s, as many as 23 waterways have been filled in, totaling 16.32 km (Shi et al. 2017), and domestic and industrial sewage have been discharged directly into these waterways. The integrity of the urban water system was damaged, and the water's ecological environment continued to deteriorate. From the 1970s to the late 1990s, the urban water system experienced problems such as water pollution, stagnation, continuous shrinking of waterway length and an increase in silted sections and dead-end waterways (Zhou and Ruan 1998).

Prioritizing the protection of the gardens over that of the urban water system has resulted in a loss of the resilience value of their symbiotic relationship. This isolated individual protection

method obscured the importance of the relationship between the gardens and HUWS, weakening their organic connectivity. For instance, the loss of waterway connectivity reduced the city's capacity to regulate floods and microclimates, thereby exacerbating its vulnerability to extreme weather events, such as heatwaves and sudden rainstorms (Wu 1991). With the gradual destruction of Suzhou's HUWS, characterized by the loss of waterways and deteriorating water ecology, as well as the replacement of waterways with drainage pipe networks, its regulation and storage capacity have decreased, leading to frequent inundation during typhoon seasons (Yu and Liu 2018).

By the late 1990s, the fragmented approach had already proven ineffective, prompting a paradigm shift toward integrated water system planning that recognized the interdependence of heritage preservation and ecological resilience.

Stage of highlighting the garden water body management and historic urban water system protection

Since the late 1990s, the protection of urban water systems has emerged as a new focus of urban heritage conservation. At this stage, the municipality introduced a series of regulations, measures and plans aimed at strengthening the protection of the HUWS. The "Regulations on the Protection of Urban Rivers in Suzhou City" (1996) stipulates that urban waterways must be protected, with priority given to their historical features. Following CGS's designation as a UNESCO World Heritage property in 1997, the city prioritized water system protection and restoration as a cornerstone of its heritage management strategy. In particular, HUWS protection has become a crucial lever for promoting the preservation of historical and cultural heritage (Jin 2024). The *Suzhou Urban Water Environment Governance Plan* (2007–2020) mandates reconnecting existing dead-end waterways to create a continuous network of flowing urban waterways. Additionally, *Protection Measures for Historical and Cultural Cities and Towns in Suzhou City* (2003) emphasizes the importance of maintaining the integrity and connectivity of the water system, as well as restoring the main waterways in key neighborhoods. With the advancement of protection concepts and the strengthening of an enabling environment, comprehensively implemented measures include water system restoration, urban water diversion projects, sewage treatment, waterway dredging and flood control facility construction.

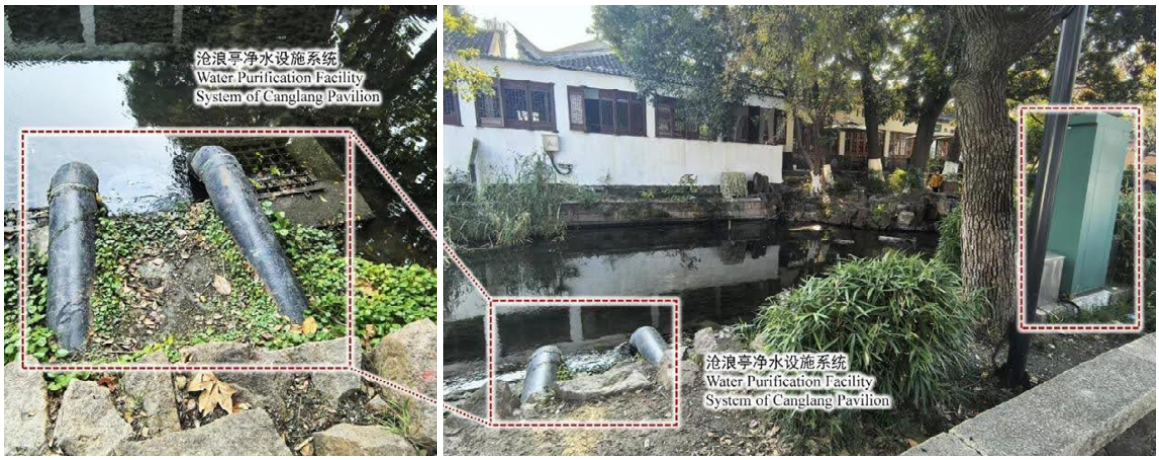
During this stage, the water quality, safety and connectivity of the HUWS were improved, and many dead-end waterways were reconnected. The first historic waterway reconstruction project, the Mid-Zhangjia Alley Waterway reconstruction,[3] was implemented and completed in 2020 (fig. 5), which has to some extent improved the connectivity of the urban water system. The layout of the backbone waterway system, namely, three horizontal and three vertical primary waterways within the ancient city of Suzhou and one surrounding moat system (as shown in fig. 2), has been protected. However, concurrently, some large-scale infrastructure construction and renovation projects have also damaged the integrity of the urban water system. With the renovation of Ganjiang Road, the connection between Ganjiang Waterway and the backbone water system has been interrupted (Qiu 2009).

3. It took the municipality of Suzhou 15 years to reconstruct this 607-meter-long waterway at a cost of over 20 million RMB (about US$2.74 million) (Jin 2024).

^ Fig. 5 Comparison of Mid-Zhangjia Alley Waterway before (top) and after reconstruction (bottom) (Source: Black-and-white photos were taken in 2020 by Jinshuai Zhang of the Suzhou National Resources and Planning Bureau; color photos by Yapeng Ou, 2025).

Meanwhile, CGS protection has also been strengthened, especially following their nomination and listing as a World Heritage Property. A framework has been established for protecting the intrinsic value of key heritage elements, including historic buildings, plants, water bodies and rockeries. It has now become widely accepted that water bodies are a fundamental part of the gardens. However, with the destruction of HUWS during the period of rapid urbanization, the accumulation of non-point source pollution and the overall decline in the quality of the urban water environment, the pressure of water management in the process of garden protection has become increasingly severe (Chen et al. 2014). Since the 1990s, a widespread problem of deteriorating water quality and aquatic ecology has been observed in gardens, resulting in turbid water bodies and adverse landscape effects. Therefore, the significant new progress in garden protection at this stage is the strengthened management of garden water bodies. The *Regulations on the Protection and Management of Suzhou Gardens* (1996) not only requires that the original layout of gardens should not be changed to maintain the original appearance of rockeries and water bodies but also puts forward a new requirement for water protection, stipulating "no discharge, infiltration of sewage, or dumping of solid waste into gardens."

To improve the water quality of CGS and HUWS, a "nature-based and engineering-supported" approach has been increasingly adopted since the first decade of the twenty-first century. CGS water body treatment generally adopts in situ ecological restoration methods to enhance the self-purification ability of garden water bodies and to optimize the landscape aesthetic. Common measures include adding biofilm self-purification devices and microbial agents to the water body, introducing aquatic animals and plants,



^ Fig. 6 Water purification facility system of Canglang Pavilion, composed of an artificial water circulation system and a distribution box (Source: Yapeng Ou, 2025).

installing artificial water circulation systems (fig. 6), and dredging sediment (Chen et al. 2014; Wu et al. 2012). Alternatively, underground infiltration treatment systems (such as those in Humble Administrator's Garden) or sand filters (such as those in the Garden of Cultivation) were constructed next to the ponds or outside the gardens to purify the water. While these practices have improved the water landscapes to a certain extent, they also have several drawbacks, including high management costs and long-term energy consumption, which contradict the low-carbon and green concepts (Chen et al. 2014).

Regarding HUWS water quality management, a helpful example is the Pingjiang Waterway, which in recent years has become well-known for its clear and clean water; it also combines nature-based solutions with engineering technology (fig. 7). First, ongoing efforts have been made to dredge the waterways. Since 2018, large-scale dredging has been carried out on the Pingjiang Waterway and its surrounding waterways, restoring natural water flow (China Environment Network 2023). Second, its self-purification ability has been enhanced by restoring the aquatic ecosystem. Aquatic plants with strong adsorption capacity have been planted in all nine waterways within the Pingjiang Historic District (*Jiangsu News* 2024). Furthermore, an underground water purification plant was built to extract and purify water from the nearby moat and then inject the purified water into the waterways and gardens within the district. Finally, water quality has been improved through water diversion. The efficient regulation of seven sluices within the district has achieved precise management of water bodies. These measures, since 2018, have improved water quality and ecology. However, persistent challenges remain, such as gaps between policy and local enforcement.

However, despite the progress made in the water body governance of CGS and HUWS in recent years, little attention has been paid to restoring their symbiotic relationship. The problem of isolated management remains due to institutional silos, lack of awareness and technical challenges. Still, there have been calls from society and academia to recover this relationship (e.g., by restoring the hydrological connectivity between CGS and HUWS). Therefore, adopting an integrated approach to protecting both is essential.

^ Fig. 7 The current state of water bodies following the introduction of aquatic plants and dredging in Pingjiang Historic District (Source: Yapeng Ou, 2025).

Existing Practices Conducive to Recovering the Symbiosis between Classical Gardens and Historic Urban Water System

CGS generally suffer from various ecological problems involving water, including small water bodies, low environmental capacity, disconnection from groundwater and surface water sources, weak self-purification ability and malfunctioning aquatic ecosystems (Wu et al. 2012). Integrated city water management and planning on a larger scale is imperative to solve this problem. In 1982, Suzhou was listed in the first batch of Chinese Historical and Cultural Cities. Based on this protection system, in August 2012, the municipality of Suzhou took the innovative step of establishing a National Historical and Cultural City Protection Area (hereafter, Protection Area) (Jiangnan Forum 2018), currently the only management mechanism in China that fully links protection and management. A specialized joint management office for CGS and HUWS has been established in the Protected Area, breaking down institutional silos between authorities responsible for garden management, water conservancy, environmental protection and urban planning. This has promoted inter-departmental information sharing, collaborative decision-making and concerted action (Fan 2023).

Regarding protective planning, Suzhou focuses on the water network between gardens and optimizes their layout based on urban development needs and ecological protection goals. The aim is to ensure that the water system can provide a stable water supply and ecological support for the gardens, which can be integrated into the urban water ecosystem, thereby enhancing the overall ecological resilience of the city (Suzhou Natural Resources and Planning Bureau 2013). The *Suzhou Historical and Cultural City Protection Plan* (2013–2030) emphasizes the protection of the "double chessboard layout of waterways and roads." It also emphasizes specific protection requirements and long-term development goals for the ecological, cultural and landscape aspects of CGS and the urban water

system, clarifying their connectivity and ecological needs. Under the guidance of the planning system, the ancient city of Suzhou implemented a waterway dredging project, completing the dredging of 26 waterways by 2020, with Phase 2 involving the dredging of 30 additional waterways. The River Management Authority aimed to universally improve the transparency of the 56 waterways in the historic districts by approximately one meter through a series of integrated water management measures (Suzhou Water Authority 2020).

Conclusion: Transmitting the Resilience Value of the Symbiotic Relationship to Promote Its Recovery

CGS and Suzhou's HUWS have coexisted in a symbiotic and resilient relationship, adapting together to external pressures such as extreme weather and habitat disruption. In the context of the ongoing climate crisis and growing environmental pressure, this resilience value provides a fundamental focus for the overall protection and preservation of CGS and the ancient city of Suzhou, facilitating climate adaptation. However, since the early 1900s, this symbiotic relationship between CGS and HUWS has been undermined due to modern urban construction. This, in turn, has led to the loss of its embedded resilience value, which is especially needed at a time of climate change.

Fortunately, since the early twenty-first century, preservation priorities for CGS and HUWS have evolved from an architecture-centric approach that marginalized water heritage to a "pro-water paradigm" emphasizing garden water landscape stewardship and the protection of historic waterways and the associated cultural heritage. To improve the water quality of CGS and HUWS, a "nature-based and engineering-supported" approach has been adopted. Some of the existing practices have also leveled the ground for the recovery of the symbiotic relationship between CGS and HUWS. For example, an integrated management mechanism and protection plan have been established. This has to some extent promoted a shift from individual garden protection to integrated city–garden protection. However, even though CGS and HUWS are concurrently managed, they still suffer from a conventional "isolated management" pattern, and their symbiotic relationship remains fractured. With the climate crisis, while building on the existing "good practices" of coordinated water management and heritage protection, it is crucial to promote the recovery of the symbiotic relationship between CGS and HUWS. This can be accomplished by active and effective transmission of the resilience value inherent in that relationship, which is also an important criterion for assessing whether the latter has been effectively restored. The water management and heritage protection of CGS and Suzhou's HUWS needs to be made even more synchronized, while continuing to enhance their hydrological connectivity. In the long run, this will enable both to provide multiple ecosystem services such as landscape beautification, climate regulation, biodiversity conservation and flood regulation.

Based on the protective measures mentioned above, to maintain the resilience of the symbiotic relationship between CGS and HUWS, it is necessary to regard CGS and HUWS as an organism and restore their symbiotic relationship holistically. It is also important to ensure the connectivity of gardens, rivers, lakes and wetlands, and to strengthen the ecological material exchange and the functions of risk distribution and reduction between CGS and HUWS. Additionally, efforts should be made to strengthen the restoration and reconstruction

of historic waterways and to continue to reconnect dead-end waterways to improve water system connectivity and restore the ecological systems of gardens and urban water bodies.

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Amsterdam's Quay Walls: Methods for Connecting Past, Present and Future

Carola Hein, Regina Klinger, Christel Voncken, Prapti Gupta & Vincent Baptist

Abstract
The much-needed repair and rebuilding of Amsterdam's historical quay walls and bridges coincides with growing demand for innovation, ranging from improved logistics and energy systems to enhanced biodiversity and climate resilience. These technology-driven transformations are unfolding in the heart of a World Heritage property known for its distinctive architectural and urban character. This article explores the complexities of integrating heritage into transdisciplinary design processes, focusing on the Canal Ring Area inside the Singelgracht. It proposes three axes for planning interventions that draw meaningfully on the past while addressing future needs, including those related to climate change. In particular, the article considers how historical analysis, spatial mapping and narrative-based approaches can strengthen the integration of historic spaces and practices into locally grounded, sustainable, climate-responsive design.

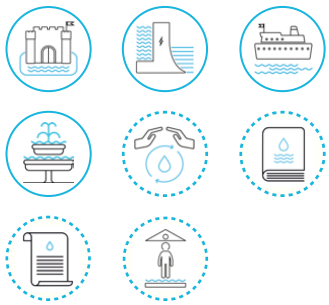
Policy Recommendations

- Reframe heritage as a shared design resource. Designers and decision-makers should promote approaches that treat heritage not as a constraint or afterthought, but as a source of inspiration that supports sustainable, climate-adaptive and circular design.
- Improve access to historical information. Municipal leaders and cultural institutions should make heritage knowledge easier to access and use by investing in digitization, clear organization, visual tools and a glossary that helps non-specialists navigate key terms.
- Use heritage narratives to guide site-specific design. Designers and decision-makers should draw on place-based narratives to contextualize historical knowledge, ensuring that interventions respect local histories, values and trajectories.

KEYWORDS

UNESCO World Heritage
quay walls and bridges
climate change
narratives
sustainable design

WATER ICONS



CLIMATE

A B **C** D E

Cfb: Temperate oceanic climate

< Fig. 1 At the Singelgracht waterway looking towards Marnixkade street, during SAIL 2025 maritime event (Source: Regina Klinger, 2025).

Introduction

Amsterdam, like many historic cities, is a layered urban fabric shaped by successive stages of development. Much of this historic palimpsest lies hidden underground and includes sewage lines, canal foundations and dams, which affect what can be repaired, reused or rebuilt. The collapse of parts of the Grimburgwal, a small canal in the center of the city, in 2020 and construction delays due to the discovery of old sewage lines (Korff, Hemel and Peters 2022) illustrate this continuity. Today, new electrical systems and other infrastructures rest on the foundations of old windmills and industrial buildings along the Singelgracht, the semi-circular canal that borders the city center and was once at the city's outer edge.

In 2021, the NWO KIEM grant project Amsterdam Time Travel laid the groundwork for heritage-based analysis. Insights from this research, which focused on the analysis and inventory of historical datasets and included a case study of Amsterdam's underground infrastructure, were published by Kremer, Scheffers and Geven (2023). The project also provided the foundation for the World Heritage Work Package of the Multi-Functional Quay Walls (MFQW) project (2024–2028) funded by the Dutch National Growth Fund of RVO.[1] The MFQW project aims to deliver innovative designs for the renewal and renovation of quay walls, tested in a living lab (AMS 2025), while taking into account the UNESCO World Heritage status of Amsterdam's inner city.

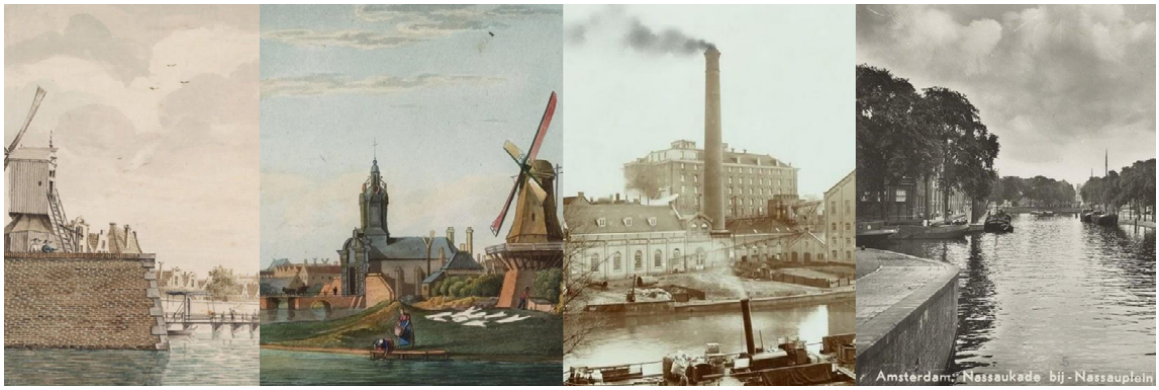
The Work Package argues that sustainable design innovation requires long-term, multi-scalar and multi-stakeholder analysis. It combines: (1) archival and field-based study of historical and local conditions; (2) integration of heritage within social, economic and policy frameworks, aligned with UNESCO and municipal guidance; and (3) development of shared terminologies and narratives linking past, present and future. Together, these approaches form the foundation for sustainable design practices, which are tested in a living lab through iterative prototyping and evaluation with interdisciplinary teams.

This article outlines the approach of the MFQW's World Heritage Work Package in the context of Amsterdam's historic canal belt. It explores the main challenges and opportunities for the first living lab case of the Marnixkade, a quay wall strip along the Singelgracht in western Amsterdam.

Bringing Historic Quay Walls into the Future

The City of Amsterdam faces urgent challenges in water management, alongside the pressures of the energy transition, climate change, tourism and broader societal change. The repair or replacement of the city's quay walls is becoming increasingly pressing as their load-bearing capacity is tested by heavier electric vehicles, intensified logistics and growing urban activity. Contemporary requirements for traffic loads, new urban infrastructures such as data cables, and climate adaptation add further complexity to the renewal of Amsterdam's water edges. In addition, the growing call for biodiversity introduces new ecological considerations for how these spaces are rebuilt and managed. Yet, large-scale interventions affecting the form and function of the quay walls risk undermining both Amsterdam's livability and its World Heritage status. Acknowledging Amsterdam's historic engineering ingenuity and UNESCO

1. RVO (Rijksdienst voor Ondernemend Nederland) is the Netherlands' Enterprise Agency, which aims to boost business growth.



^ Fig. 2 Transformation of the Singelgracht (Sources, left to right: Verrijk 1786; De Kruyff, Lutz, and Buffa & Sons 1825; Amstel Suikerraffinaderij gezien over de Singelgracht 1905; Nassaukade tussen Nassauplein en Eerste Nassaustraat en links Marnixkade 2-5, Afb ANWU01721000004 1925).

World Heritage status calls for equally innovative, context-aware interventions.

The "Seventeenth-Century Canal Ring Area of Amsterdam inside the Singelgracht" obtained World Heritage status in 2011, notably for its outstanding engineering, architecture and urban form. The Outstanding Universal Value of the property is described as "exemplary hydraulic and urban planning on a large scale through the entirely artificial creation of a large-scale port city. In the 17th and 18th centuries, Amsterdam was seen as the realization of the ideal city that was used as a reference urban model for numerous projects for new cities around the world" (World Heritage Centre 2014).

The MFQW's World Heritage Work Package proposes heritage-led design practices that use the city's historical and cultural context as a foundation for innovation. These are guided by cultural and historical insight rather than by purely technological or economic drivers. In line with Amsterdam's goals to promote circular processes (AMS 2022; Municipality of Amsterdam 2024a), we argue that circular building practices require knowledge of historical materials, technologies and practices, as well as the continuous documentation of interventions. This includes the reuse of historical data to inform planning for the future.

We put these principles into practice in the MFQW Project, in which engineers and landscape architects are developing modular design solutions based on a generalized canalscape. This synthetic representation of the spatial, technical and cultural elements that define Amsterdam's canal environment allows for optimized interventions. These designs need to be adapted to specific sites and contextualized within the city. In the project's first design phase, designs will be implemented through a living lab at the Marnixkade. Our work package therefore started with an analysis of the history and heritage of this area.

This outer canal of Amsterdam's nineteenth-century ring exhibits distinctive pattern of transformation. Unlike the iconic inner canals, the Singelgracht has been continually reshaped over time, adapting its form to the changing needs of Amsterdam's residents and urban environments. These changes include the introduction of floating vegetable markets and changes in quay wall construction materials and

shipping-related elements along the water (figs. 2–4). Working at this site has highlighted the challenges of integrating heritage knowledge with sustainable, future-oriented design.

Challenges of Linking Heritage Knowledge to Sustainable Design

Amsterdam's quay walls are not only in need of repair but also serve as high-potential test sites for technological innovation, involving, for example, prefab concrete elements, climate-adaptive systems with heat exchangers, digital service cables, waste facilities, parking spaces and biodiversity measures. These interventions often compete with heritage values; In test designs, alignment with World Heritage features is not always a central concern. Over the course of the project so far, we have identified four key challenges.

First, engagement with technically oriented colleagues reveals the dominance of sectoral thinking and the absence of a shared value system that includes heritage as a foundation for sustainable innovation. A heritage walk and subsequent survey during the starting phase of the MFQW project demonstrated that many participants perceive heritage as static and obstructive, closely associated with "preservation." As a result, heritage is often considered an obstacle or afterthought in the design process, addressed only at the end to comply with basic regulations. Such an approach risks marginalizing historical values in new designs.

Second, one of the underlying reasons for this limited engagement with heritage is a lack of standardized methods, vocabulary and clear guidance on how to design for heritage. In response, design and engineering colleagues in search of such instructions seem to implicitly "reverse-engineer" UNESCO's OUV, beginning with the formal criteria that define a site's heritage value. They then work backward to interpret which cultural, social or material attributes need to be preserved and how these relate to the broader canal system. While UNESCO's OUV and Historic Urban Landscape (HUL) frameworks emphasize the distinctiveness and protection of heritage sites, they offer limited practical direction concerning how to integrate modern infrastructural requirements into these settings.

Third, the absence of analysis and visualization of historic features and future challenges further complicates collaboration. Yet, the value of such visualization is evident from the MFQW project practitioners' widely acknowledging the usefulness of the Beeldkwaliteitsplan (Municipality of Amsterdam 2024b), which successfully communicates spatial heritage features. Such guidance can be further improved and implemented through interactive and digital mapping, as in the UNESCO Urban Heritage Atlas (UNESCO 2023), which visualizes the complex architectural, urban and landscape features of UNESCO designated properties and highlights climate-related challenges, while also visually illustrating the UNESCO HUL approach.

Finally, the lack of integration between archival sources and contemporary design tools makes it difficult to implement digital and circular practices. Historical materials remain fragmented across municipal, institutional and private archives, many of them undigitized or incompatible with modern design software. Organized according to past systems or terminology, these records risk being overlooked as outdated or restrictive. Improved digitization and interoperability can help link historical data to contemporary decision-making and translate lessons from the past into sustainable, future-proof design.

^ Fig. 3 Appeltjesmarkt Singelgracht (Stadsarchief Amsterdam, n.d.).

Delivering Heritage-Based Solutions for Design Professionals

Building on the challenges identified in the MFQW project, we propose three axes of intervention for integrating heritage knowledge into design practice. These axes – historical analysis, narrative creation and spatial mapping – provide complementary approaches for connecting spatial and material practices of the past with future-oriented, climate-adaptive design. Together, they establish a framework for engaging historical knowledge as an active component of sustainable urban transformation.

1. Historical Analysis: Developing Methods and Vocabulary for Data Circularity

The first axis concerns the analytical use of historical materials to inform contemporary design decisions. Current canal models in the MFQW project categorize waterways by technical parameters such as width and structural type, which limits recognition of the cultural and ecological diversity embedded in each site.

By enriching these datasets with canal-specific historical evidence, linking archival sources to past material practices, uses and maintenance cycles, heritage can be operationalized as an active form of knowledge. Establishing a shared vocabulary and metadata structure across disciplines enables this information to circulate within design processes, creating feedback loops between historical precedents and contemporary innovation.

Historical analysis thus becomes a mechanism of data circularity, transforming archival research from static documentation into a dynamic tool for sustainable, climate-resilient design. It demonstrates that understanding the life cycle of materials, infrastructure and practices provides insights for both technical and social dimensions of urban adaptation.

2. Narrative Creation: Activating Heritage Values for Design Inspiration

The second axis uses heritage narratives to connect cultural memory with contemporary urban challenges. In the MFQW project, narrative-thinking reveals a site's development by highlighting past decisions, embedded cultural stories, and narratives that guide future interventions. The following Singelgracht examples illustrate how heritage can inform climate-adaptive, context-sensitive design.

The Appeltjesmarkt (apple market)

This historic market (1895–1934) exemplifies how waterborne trade (fig. 3) supported short food cycles and localized economies, with farmers delivering produce directly by boat to urban residents (Bakker 2007). It offers a precedent for multifunctional waterways and suggests opportunities to reintegrate water-based logistics and community spaces in contemporary climate-adaptive planning.

The former green belt along the Singelgracht

When Amsterdam's city walls were decommissioned in the nineteenth century, ramparts became green promenades serving recreational and ecological functions. Industrialization eroded this green belt, provoking civic protest and revealing its social and cultural value (AmsterdamHV, n.d.). Today, this narrative can inspire green infrastructure and the strategic revival of lost urban green spaces.

Reuse of ballast stones from maritime trade

Stones transported by Scandinavian and northern German ships were reused to stabilize quay walls (Schelling 1946; De Waard 1947), exemplifying early circularity. The walls themselves preserve a material record, which risks being lost if replaced. Contemporary design can draw on reclaimed materials while maintaining historical continuity.

Together, these narratives show that the Singelgracht evolved through culture-based changes, responding to shifting environmental and social conditions. Embedding such narratives in design processes translates historical data into actionable insights for sustainable, climate-responsive urban development.

3. Spatial Mapping: Visualizing and Sharing Heritage Knowledge

The third axis emphasizes spatial mapping to connect archival sources with contemporary design tools and planning systems. Visualizing material and cultural layers helps designers understand how past structures and practices can inform climate-adaptive interventions.

UNESCO's Urban Heritage Atlas demonstrates not only how heritage can be visualized, but also how contributions from World Heritage properties can be collected, organized and made publicly accessible in visual and biographical form. While this platform enhances understanding and accessibility, it does not provide a foundation for site-specific interventions or repairs. Effective design requires juxtaposing contemporary proposals with the multiple physical and cultural layers present at each location, revealing the palimpsest of historical practices.

Geospatial analysis supports this by linking archival material to city plans and expertise. Large-scale projects such as Time Machine Organization (2019, 2025) show how digitized data and 3D reconstructions create a "Google Earth of the past," enabling designers to navigate urban structures and cultural patterns over time. This approach transforms archival inventories into actionable knowledge for urban development and climate adaptation.

Our curated ArcGIS StoryMap[1] for the Singelgracht links historical photographs, drawings, and records to specific canal locations (fig. 4). Contextualized with metadata and source notes, it produces a spatial index of narratives and material traces. It makes heritage accessible to non-historians, facilitating cross-disciplinary collaboration and grounding interventions in the historical and material realities of the site.

Conclusion

The MFQW project demonstrates that climate-adaptive, heritage-sensitive interventions are achievable when design engages with the layered history of Amsterdam's quay walls. Liv-

1. https://storymaps.arcgis.com/stories/88a7f55927f147c4a723d2e14edb7b0b.

^ Fig. 4 Screenshot of our StoryMap collection. The print of the Prinsengracht in 1773 shows the quay as a multifunctional urban edge: washing and water steps at the canal, mooring and unloading, and foot, cart and coach traffic across the bridge. Our StoryMap uses scenes like this to geolocate small land-water artifacts and to show how they supported everyday practice along specific canal stretches (Source: Carola Hein, Regina Klinger, Christel Voncken, Prapti Gupta and Vincent Baptist).

ing lab testing treats the urban environment as a palimpsest, where past material, social and infrastructural practices continue to shape future solutions.

Analysis of design proposals and interdisciplinary collaboration revealed challenges, including fragmented archival data, a lack of shared vocabulary, and delayed integration of heritage considerations. The obstacles also highlight opportunities to put heritage knowledge to work through three complementary approaches. Historical analysis transforms archival materials into reusable datasets, guiding circular and site-specific interventions. Narrative creation activates cultural memory, providing context-sensitive design inspiration. Spatial mapping visualizes and shares heritage knowledge, facilitating cross-disciplinary collaboration and informed, locally grounded decision-making.

Together, these axes enable interventions that are historically informed and future oriented. The MFQW project provides preliminary insights on how heritage can guide contemporary design, offering a methodological model for historic urban environments that aligns sustainability, cultural continuity and adaptive development. These insights will continue to evolve as they are tested in the Marnixkade living lab and further fine-tuned in a second living lab planned elsewhere within Amsterdam's historic ring.

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