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

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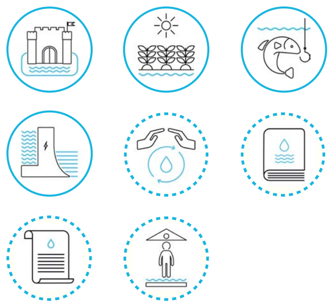
Abstract
Watermills are not remnants of obsolete technologies but dynamic socio-ecological systems in which hydrology, craftsmanship, landscape processes and community knowledge have co-evolved for centuries. Although mills appear in many UNESCO World Heritage and Intangible Heritage inscriptions, their 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

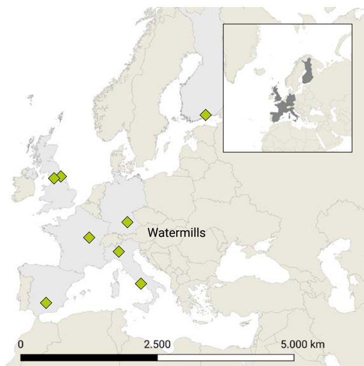
WATER ICONS

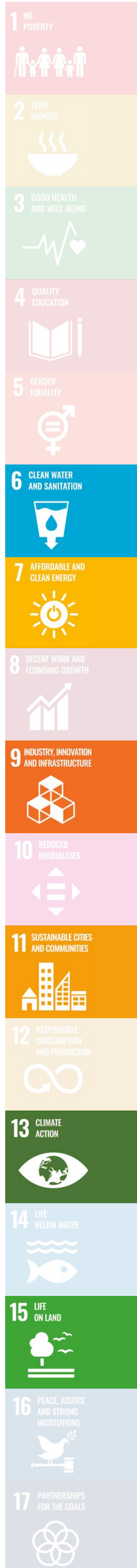


CLIMATE

A B C D E

Cfb + Csa: Temperate oceanic and Mediterranean (hot-summer) climate





< 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 (Jackson 2024) (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

^ 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).

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 Histor-

^ 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).

ic 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, 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

^ 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).

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. 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 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).

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, 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 emerg-

^ 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).

es: 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 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,

^ 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).

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 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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