

BLUE GOLD: BIODIVERSITY AND TECHNOLOGICAL INNOVATION IN WATER MANAGEMENT

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Abstract

Water is a strategic resource increasingly threatened by climate change, overexploitation, and demographic pressure. Acquedotto Pugliese, one of Europe's largest water and sanitation utilities, manages more than 33,000 km of pipes and serves over four million people in Southern Italy. AQP's operations are essential for maintaining a reliable water supply and for protecting ecosystems and biodiversity. This paper examines a range of innovative strategies, including advanced wastewater treatment, water reuse, desalination projects, and digital innovations in leak detection and network monitoring. Case studies, such as the Melendugno constructed wetland system, demonstrate that nature-based solutions may enhance biodiversity and support sustainable water management. The findings indicate that technological innovation and environmental restoration can jointly safeguard water resources for future generations.

Keywords

Water management, biodiversity, constructed wetland, desalination, Smart Water Management

1. Introduction

The International Day for Biodiversity highlights the importance of integrating technological innovation with ecological preservation, underscoring the interdependence between natural ecosystems and human infrastructure. Water, often referred to as “Blue Gold”, is central to this challenge. As a limited and vulnerable resource, water supports agriculture, energy production, and domestic needs, while shaping landscapes and habitats.

In the Mediterranean Basin, a recognised climate change hotspot (Giorgi & Lionello, 2008), water systems face heightened stress due to increased drought frequency, agricultural demand, and ageing infrastructure (Makropoulos & Savić, 2019). These factors collectively intensify risks for both human populations and ecosystems. Recent reviews summarise how climate change affects life in Mediterranean cities (Nastos & Saaroni, 2024), and confirm that climate-driven warming and salinity increases are altering the delicate balance of coastal ecosystems (De Padova et al., 2024). These findings highlight the need to couple restoration and reuse initiatives with continuous environmental monitoring to ensure adaptive responses to evolving marine conditions.

The Commission Staff Working Document Impact Assessment Report points out that “16% of the present Mediterranean climate zone (an area half the size of Italy) could become arid by the end of the century” (European Commission, 2021).

In Italy, the Apulia region exemplifies the challenges of water scarcity in arid environments with very limited local freshwater resources.

To address these constraints, Apulia has developed extensive aqueduct systems that convey water from remote sources to city centres. Over the past century, Acquedotto Pugliese (otherwise known as AQP), a publicly owned utility recently designated by the Italian government as company of strategic relevance to the national interest, has constructed one of the world's most complex and interconnected systems of large-diameter transmission pipes.

The case studies depicted here demonstrate that integrating innovative water management with ecological objectives enhances both system resilience and biodiversity protection, leading to sustainable outcomes.

Recent global assessments reinforce this perspective. According to more than 900 experts worldwide, the four risks estimated as most severe over a 10-year period all fall in the *Environmental* category. They are 1) Extreme weather events

(e.g., floods, heatwaves), 2) Biodiversity loss and ecosystem collapse (e.g., species extinction or reduction), 3) Critical change to Earth systems (e.g., sea level rise, thawing permafrost), and 4) Natural resource shortage (e.g., food, water) (World Economic Forum, 2025).

AQP faces these concerns by demonstrating how biodiversity protection and water security can be addressed jointly.

2. *The Acquedotto Pugliese System*

AQP is among the largest water and sanitation utilities in Europe. Its network comprises more than 33,000 km of pipelines, including 5,000 km of long-distance transmission mains, 15,000 km of water distribution pipes, and 13,000 km of sewer pipes, along with hundreds of pumping stations and treatment facilities. The utility reaches about four million people across 260 municipalities in Apulia and part of Campania.

The system is highly interconnected, allowing water transfers among basins to balance spatial and seasonal variations of demand and supply. Its water sources are diverse—approximately 58% from reservoirs, 28% from springs, and 14% from groundwater wells—which provide flexibility but also require constant monitoring to prevent the overexploitation of aquifers and to ensure ecological balance.

Notably, the 244-km Caposele aqueduct canal (Fig. 1), known as “Canale Principale”, represents a landmark in sustainable engineering, as it exploits, after more than a century from its construction, the natural gravitational flow of spring water to carry water from Caposele in Campania to Apulia, without pumping, crossing the Apennines by tens of galleries and canal-bridge.



Fig. 1: Caposele aqueduct canal transporting water from Campania to Apulia

This challenging hydraulic infrastructure anticipated today's sustainability principles by minimising energy use.

3. *Innovations*

3.1 *Wastewater and Reuse*

Wastewater treatment and reuse are central to reducing pollution, lowering the ecological footprint of urban settlements, and supporting agricultural demand in water-scarce regions. Acquedotto Pugliese has invested heavily in this field, operating 185 wastewater treatment plants and 21 advanced tertiary treatment facilities that not only reduce pollution loads but also recover resources and reintroduce refined water into natural cycles. In 2023, these plants delivered 1.16 Mm³ of refined water for reuse, the majority of which was used in agriculture, a sector critically dependent on stable water availability. Projections for 2028 indicate a significant increase in treatment capacity, with expected reuse volumes of 57–63 Mm³ per year across Apulia.

The relevance of these efforts extends beyond technical operations. EU Regulation 2020/741 establishes harmonised minimum requirements for water reuse in agriculture, setting strict safety, monitoring, and risk-management standards across Member States (Regulation (EU) 2020/741, 2020).

The regulation also requires the approval of a Water Reuse Risk Management Plan for each reuse scheme, reflecting the multi-barrier approach to health protection (Ho et al., 2024)

Within Italy's National Recovery and Resilience Plan (PNRR), investment goals explicitly include the reuse of treated wastewater for irrigation and industrial purposes (Italian Government, 2021).

Despite these initiatives, water reuse in the EU remains in its infancy relative to its potential; less than 3% of treated urban wastewater is currently reused across the EU.

In Italy, the theoretical reuse potential is 8.5 billion m³ per year, yet only 5% is currently exploited (Malinauskaite et al., 2024).

This review highlights that wastewater reuse in Europe remains largely untapped in relation to its potential, due to various barriers and bottlenecks. Key challenges include a historical legislative gap (until 2020) with non-uniform standards across regions, resulting in fragmented regulations, high treatment and monitoring costs,

public health concerns, and a lack of dedicated infrastructure.

The new EU Water Reuse Regulation (effective 2023) aims to mitigate some of these issues by providing clear, harmonized criteria for safe reuse (focused initially on agriculture) and prompting Member States to update their national rules accordingly. However, further investments—for example, in distribution networks to convey reclaimed water to end-users—and broader public acceptance will be required to fully realise water reuse as a pillar of water resource management (Malinauskaite et al., 2024).

Significant differences in reuse advancement may be observed among EU countries: smaller states like Cyprus and Malta already reuse over 60% and 90% of their wastewater, respectively, while in larger countries such as Italy, Spain, and Greece, the reuse rate is only about 5–12% (Malinauskaite et al., 2024). Since the late 1980s, Spanish golf courses have been required to use reclaimed water where possible, making reuse a common practice for green areas (Rodríguez-Villanueva & Sauri, 2021). In Barcelona, an indirect potable reuse programme was piloted during drought, with extensive monitoring to ensure safety (Munné et al., 2023).

3.2 Constructed wetland in Melendugno

The constructed wetland system in Melendugno (Fig. 2) serves as a prominent example of circular water use, demonstrating that these nature-based solutions can fulfill both technical and ecological goals.



Fig. 2: Constructed wetland as part of the wastewater treatment in Melendugno, Apulia, Italy

The system utilizes wetland plant species, including common reed (*Phragmites australis*), cattail (*Typha latifolia*), soft rush (*Juncus effusus*),

and white water lily (*Nymphaea alba*), to naturally treat effluents, thereby reducing nutrient loads and enhancing water quality prior to reuse (Fig. 3).



Fig. 3: *Phragmites australis*, *Typha latifolia*, *Juncus effusus*, and *Nymphaea alba* (from left to right and top to bottom)

Simultaneously, it creates habitats for amphibians, reptiles, and insects, strengthening regional biodiversity.

Constructed wetlands are increasingly recognized as cost-effective and biodiversity-supportive alternatives to conventional systems, enabling the safe reuse of water and providing additional ecosystem services (Malinauskaite et al., 2024).

Constructed wetlands are now also being explored for the treatment of reverse osmosis concentrate, offering a low-energy and multi-benefit polishing solution (Scholes et al., 2021).

The Melendugno case aligns with a wider European emphasis on nature-based solutions, which the EU Green Deal and Biodiversity Strategy promote as a means to support biodiversity and climate adaptation concurrently.

3.3 Environmental Restoration

Beyond wastewater treatment, AQP is also committed to environmental restoration via drainage trenches. In Apulia, especially in the province of Lecce, several treatment plants (e.g., San Cesario, Lizzanello, Galatina) discharge tertiary-treated effluent into these infiltration systems (Fig. 4, Fig. 5), which allow treated wastewater to percolate gradually into the subsoil rather than being released directly into the sea or surface water bodies.



Fig. 4: Newly built drainage trenches in San Cesario, Apulia



Fig. 5: Wastewater treatment plant with drainage trenches in Galatina, Apulia, Italy

This process supports Managed Aquifer Recharge (MAR), helping to replenish depleted groundwater reserves, and contributes to a more balanced local water cycle (Dillon et al., 2019).

This provides dual benefits: on the one hand, it improves environmental quality by restoring soil moisture and groundwater levels; on the other hand, it helps prevent saline intrusion into coastal aquifers, a risk that is becoming increasingly acute due to the pressures of climate change, in a region with over 800 km of coastline.

In other areas, such as Gioia del Colle and Casamassima, the use of nature-based drainage trenches and effluent disposal fields has gone beyond groundwater recharge, favouring the formation of wetlands that have effectively become oases.

These transformed sites also serve as habitats for resident and migratory bird species of high naturalistic value, proving that technical interventions can evolve into biodiversity hotspots (Fig. 6).



Fig. 6: Migratory bird species

This approach is consistent with global trends in MAR, which has seen significant growth over the past decades as a sustainable water management tool. For over a century, MAR has played a central role in European water supply, contributing substantially to drinking-water production (Sprenger et al., 2017). Since the 1960s, MAR has expanded at a rate of about 5% annually (Dillon et al., 2019). In coastal Mediterranean zones, MAR is expected to become even more important to counteract salinisation and growing demand (Sprenger et al., 2017).

The EU Groundwater Directive (Directive 2006/118/EC, 2006) and the Water Framework Directive (Directive 2000/60/EC, 2000) provide the legal framework under which MAR projects should be implemented, ensuring that infiltration practices do not compromise groundwater quality. In this sense, AQP's infiltration trenches are aligned with both European and global practice, where MAR is increasingly used not only for quantitative recharge but also as a buffer against saline intrusion in coastal aquifers (Dillon et al., 2019).

3.4 New Water Sources: Desalination Projects

Reuse and environmental restoration constitute essential elements of integrated water management. However, these practices alone may not solve structural water deficits in regions with persistent scarcity. In this context, desalination is recognized as a strategic solution that provides a climate-independent and reliable supply of high-quality water.

However, challenges persist, particularly regarding brine disposal and energy consumption.

To reduce greenhouse gas emissions, coupling desalination plants with renewable energy sources has been highlighted as a promising approach (Elimelech & Phillip, 2011); another environmental challenge of seawater desalination remains the impingement and entrainment of marine organisms at intakes, together with the discharge of hypersaline brine.

AQP has launched three major desalination projects to strengthen resilience against recurrent droughts.

The first plant will be located in Taranto (Fig.7), treating brackish water of the river Tara with a capacity of 630 L/s. Plant commissioning is planned for 2026, and it will serve approximately 385,000 inhabitants.



Fig. 7: Desalination plant in Taranto, Apulia, Italy

The second, located on the Tremiti Islands, is a small plant with a capacity of 12 L/s, designed to serve only the archipelago's 5,000 inhabitants. Funded under the PNRR "Green Islands" initiative, it is conceived as both a solution for local needs and a pilot model for other minor islands or isolated coastal communities.

The third and most ambitious plant is currently in the study phase and will be located in Brindisi. It is a seawater desalination plant with a 1,000 l/s capacity—sufficient for up to 600,000 inhabitants—whose completion is scheduled in 2032. All plants adopt reverse osmosis (RO).

The recovery ratio of RO is 42% for seawater and 65% for brackish water, as reported in a detailed global outlook on *the state of desalination and brine production* (Jones et al., 2019); this report also highlights the importance of careful management of hypersaline brine effluent in protecting marine ecosystems.

AQP's projects constitute a significant advancement in resilience and illustrate the broader challenges of balancing technological innovation, energy efficiency, and ecological sustainability in Mediterranean water management.

The incorporation of renewable energy sources and energy recovery turbines in new desalination facilities is essential to minimise carbon emissions and support Italy's decarbonization objectives.

These desalination projects complement traditional water sources and provide essential protection against drought by securing water availability during crises and reinforcing long-term resilience for communities and natural ecosystems. AQP's investment forms part of a broader regional and national strategy to diversify water supply sources.

By 2032, once the Brindisi and Taranto plants are operational, Apulia will have a significant desalinated supply to draw upon during dry spells—a radical change for a region that historically depended almost entirely on external sources of freshwater (distant reservoirs and springs).

These projects demonstrate a proactive approach to water security, albeit one that must be managed carefully to balance the benefits of desalination with its environmental costs (energy use and brine disposal). Such considerations have been integrated into AQP's environmental design criteria, supporting the sustainable operation. De Serio et al., 2025 examined the Taranto desalination plant and compared the dynamics of brine versus brackish outfalls, highlighting how site-specific hydrodynamic conditions strongly influence the spatial extent of impacts. Because the River Tara supplies brackish water to the Taranto desalination plant, its discharge is expected to be less saline, about 7 psu, compared to the ambient 38.5 psu in the receiving marine environment (De Serio et al., 2025).

3.5 Digital Innovation for Water Management

Digitalisation has become a cornerstone of AQP's modernisation strategy, enabling more efficient, transparent, and sustainable water management.

At the heart of this approach is the Centralized Control Room (Fig. 8), which manages data from more than 570,000 interconnections and 11,000 sensors embedded throughout the network.

This real-time data stream allows AQP to develop a comprehensive digital twin of the entire water distribution system.

The digital twin is a dynamic virtual model that mirrors the state of pumps, valves, reservoirs, and pipes in real time, enabling advanced functionalities such as real-time monitoring, predictive modelling, and scenario analysis for network interventions.



Fig. 8: Control room of the AQP in Bari, Apulia, Italy

In practice, operators can simulate control manoeuvres on the digital twin and predict their effects before implementation. Operational decisions (as flow reallocations or pressure adjustments) can be optimised based on live data and forecasts, improving both efficiency and resilience.

A particularly advanced area of innovation is leak detection, since water losses represent both an economic burden and an ecological waste. Across the EU, nearly one-quarter of all distributed drinking water is lost before it reaches consumers (The European House – Ambrosetti, 2025).

To tackle water leakages, AQP has deployed a suite of technologies for pinpointing unreported leaks. Over 20,000 NB-IoT noise loggers with correlation functions have been installed on more than 4,000 km of distribution pipelines. (Fig. 9, *left*). The installation of noise loggers has significantly reduced the time required to repair identified leaks—an outcome that illustrates the tangible benefits of these technologies (Fig. 9, *right*).

Additional methods include SmartBall technology—a 70 mm free-swimming acoustic sphere that travels through pressurised pipelines to detect anomalies—and permanent hydrophone correlators, sensitive instruments installed on large-diameter mains that use multi-point cross-

correlation of acoustic signals to locate unreported leaks.



Fig. 9: *left*, Noise Logger; *right*, Leak detection via noise loggers in a water distribution network

Together, these systems contribute drastically to the reduction of water leakages, optimise maintenance operations, and extend the lifespan of infrastructure.

AQP's effort in reducing water losses aligns also with the Drinking Water Directive (Directive (EU) 2020/2184, 2020) that, starting in 2028, will establish a uniform EU method for the drinking water balance and its indicators, fixing a threshold that member states will be required to meet.

The integration of a centralized digital control system with advanced field technologies demonstrates that digitalization and engineering reduce environmental impacts, enhance service reliability, and directly support sustainability objectives.

Digital innovation constitutes both a technical improvement and a cultural transformation, embedding resilience and ecological responsibility into the daily operations of one of Europe's largest water utilities.

4. Conclusions

The experience of Acquedotto Pugliese demonstrates that a water utility may represent a driver of sustainability by integrating engineering, ecological sensitivity, and digital innovation. Biodiversity-oriented initiatives, such as constructed wetlands and drainage trenches, demonstrate that infrastructure can be designed to treat and transport water while also creating habitats, restoring ecological balance, and enhancing biodiversity.

Concurrently, large-scale projects such as desalination plants underscore the necessity of long-term structural investments to address climate change and persistent water scarcity in the Mediterranean Basin.

Digital innovation constitutes another pillar of this transformation, enabling a proactive management model.

The integration of Internet of Things (IoT) devices, digital twins, and advanced leak detection tools demonstrates that technological tools can yield measurable environmental benefits, including substantial reductions in water losses and more efficient resource allocation (Tab. 1).

Digitalisation forms part of a broader socio-ecological strategy that alleviates pressure on natural water sources while enhancing the quality and reliability of services provided to the citizens.

Collectively, these experiences underscore the need to address water management as a socio-ecological system, where natural habitats, technological infrastructure, and human communities are closely interconnected.

In Apulia, a region characterized by water scarcity, climate vulnerability, and historically, agricultural and tourist vocation, this integrated perspective is essential. By treating water as both a vital utility and a foundation for biodiversity, AQP provides a model of resilience applicable beyond the Italian context.

Other Mediterranean and semi-arid regions can adopt Apulia's combination of green and grey solutions, which reinforce historical supply systems with new desalination capacity, supplement centralized treatments with nature-based reuse systems, and integrate analog infrastructure with digital technologies.

This hybrid strategy secures water supplies during periods of uncertainty, protects biodiversity, strengthens ecosystems, and enhances resilience to global environmental change.

AQP's integrated strategy positions the utility as a living laboratory for sustainable water management in semi-arid Europe.

However, several challenges remain, including aligning the energy demands of desalination with clean energy goals, ensuring equitable access to reclaimed water for agricultural and community use, and embedding long-term ecological monitoring into all infrastructure projects.

Tab. 1: Overview of interventions and their effect on the ecosystem

Intervention	Function	Ecosystem co-benefit
Advanced wastewater reuse	Reduce pollution/ Improve irrigation	Reduces nutrient loads and eutrophication risk; stabilises landscapes
Constructed wetlands	Effluent treatment to further improve the quality of wastewater treatment plant effluent	Enhances the diversity of amphibian-, reptile-, and insect habitats
Drainage trenches (MAR)	Prevents saline intrusion	Restores groundwater; improves soil moisture; supports vegetation
Effluent disposal fields	Infiltration and aquifer recharge	Transformation into wetlands and oases; habitats for birds
Desalination projects	Independent water supply	Less freshwater use; potential risk from unmanaged brine
Digital innovations	Enhance processes and services (e.g., reducing water leakage)	Reduced extraction needs, easing pressure on rivers and aquifers

Addressing these issues is essential for transforming Apulia into a model for the water-biodiversity nexus in the Mediterranean.

Water, often described as "blue gold," represents both a technological and ecological frontier and is an essential resource whose stewardship will determine the sustainability of future generations.

From a broader perspective, AQP's experience resonates with ongoing European and global debates on water governance: how to reconcile infrastructure expansion with biodiversity conservation, how to integrate circular economy principles into water management, and how to

ensure social acceptance of reuse and desalination technologies.

Embedding these practices into a long-term adaptive management framework, consistent with the EU Water Framework Directive and SDG 6, will be crucial.

Future research should focus on quantifying ecological and socio-economic benefits of nature-based solutions and on developing energy-neutral desalination systems powered by renewables, ensuring that the path towards water security is also compatible with climate neutrality.

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