

Entry

Shaping Water Infrastructure Futures in the European Union Context

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Definition

This entry explores how foresight approaches can guide the future of water infrastructures. It highlights key long-term disruptive drivers of change—such as climate change, digital transformation, and geopolitical tensions—that infrastructures must withstand and adapt to. It also emphasizes the role of collective choices and innovation alliances, including Water-Oriented Living Labs, in shaping resilient and sustainable water systems. The focus is on transforming today's infrastructures into adaptive systems that ensure water security and ecosystem integrity for future generations. Although many of the drivers of change are global, this entry emphasizes the European context, where policy frameworks and innovation agendas are currently shaping infrastructure transitions.

Keywords: water infrastructure; resilience; transition management; water quality management; Water-Oriented Living Labs (WOLLS)

1. The Nature of Water Infrastructures

Water infrastructures are long-lived systems that evolve over time through successive interventions and partial renewals. Individual assets are indeed designed for specific service lives depending on their type and context; however, as integrated systems, these infrastructures endure far beyond the lifespan of their components. This systemic piecemeal renewal approach [1], guided by capital maintenance strategies, allows infrastructures to adapt to new requirements while preserving the value embedded in existing assets. Because water infrastructures comprise numerous interdependent assets with different lifespans, their long duration and high cost reinforce the need for system-based approaches that maintain overall service continuity while guiding the renewal of individual assets through lifecycle management principles. Such adaptive approaches are essential in high-uncertainty environments where linear planning assumptions are no longer sufficient. Large components such as dams, maritime structures, treatment plants, pipelines, and reservoirs represent significant public investments that cannot simply be discarded. Instead, their ongoing management must focus on extending functionality, upgrading performance, and ensuring resilience. In this sense, the challenge is not only to operate and maintain current systems, but also to manage their transition toward the infrastructures we aspire to have in the future.

This perspective reframes infrastructure as a living system—one that must continuously adapt to shifting societal expectations, technological innovations, and environmental pressures. The central task, therefore, is to guide the evolution of water infrastructures in ways that preserve existing value while steering them toward long-term sustainability and resilience.



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This applies to water infrastructures for water resources management, water services (urban, agricultural, and industrial), maritime systems (coasts, ports, and harbors), and inland navigation, encompassing grey, blue, and green infrastructures such as Nature-based Solutions (NbS). The focus of this entry, however, is on water resources, urban water services, and maritime systems, without addressing the specificities of inland navigation.

2. Disrupting Factors and Opportunities

Water infrastructures face a range of emerging pressures that demand foresight and proactive planning. Key disruptors include climate change, geopolitical tensions, supply chain vulnerabilities, shifts in societal values, energy disruptions, biodiversity loss, and the interconnected digital world [2]. These pressures manifest in more frequent and intense extreme events—such as floods, droughts, and wildfires—as well as in increasing risks to safety and security.

At the same time, opportunities arise from novel sensors, materials, construction technologies (including advanced methods for buried assets), and from advanced process approaches. Expanding knowledge on waterborne human and environmental health hazards, artificial intelligence (AI) and machine learning (ML), together with growing societal calls for climate action, further broaden these opportunities. Emerging trends such as renewable energy integration (e.g., hydropower–solar hybrids), remote sensing and data acquisition, and cloud seeding for drought mitigation also influence water futures. Recognizing these disruptive factors—while also addressing the structural challenge of aging infrastructures—is essential to design infrastructures that are resilient, adaptive, and aligned with evolving societal and environmental needs [3].

3. Water Infrastructures

3.1. Water-Resources-Related Infrastructure

Increasing water scarcity requires sound, integrated management of all candidate water sources—surface water, groundwater, treated wastewater, desalinated water, and rainwater—through a context-specific and seasonally adaptive mix that ensures sustainable use.

Dams and associated waterworks, such as spillways and intakes, play an essential role in managing surface water resources, maximizing their value for the economy and society. However, the disruptors mentioned above are creating new risks and opportunities, leading to emerging paradigms. Once considered a “golden solution” for decades, many existing dams are now aging, raising concerns about structural safety and their ability to meet modern objectives, such as ecological requirements. Meanwhile, proposals for new dams remain highly contentious.

Rethinking these infrastructures may involve structural rehabilitation, capacity reinforcement, the implementation of both hard and soft risk management measures, the installation or upgrading of fish passages, and the development of new ecosystem services. Increasingly, dams are managed as interconnected networks rather than isolated assets. For example, the Alqueva reservoir system in Portugal—the largest in Europe—is increasingly managed as part of an interconnected network of smaller reservoirs, enhancing both hydropower and water supply through the water–energy nexus [4]. The development of new infrastructures now requires multidisciplinary approaches that balance needs, available resources, and potential impacts.

As for groundwater resources, aquifers are natural infrastructures that have been, and will continue to be, increasingly affected by the disruptors and opportunities outlined in Section 2. Adequate management requires improvements in monitoring, forecasting and early warning systems and in recharge management for quantity and water quality

control. Aquifers are a key water supply source for human activities, often the most relevant in terms of water availability. Managed aquifer recharge may contribute, for instance using treated wastewater and flood water as input. In this case, the infrastructures (e.g., infiltration basins and trends) that provide managed recharge of aquifers may be considered nature-based solutions (NbS) working with and enhancing nature-inspired processes, e.g., using controlled layers of soil to provide a complementary treatment of the water during infiltration [5].

3.2. Urban Water Services Infrastructure

Traditionally, urban water infrastructure has included drinking water supply systems and wastewater drainage and treatment systems, the latter encompassing both urban wastewater and stormwater. Historically, wastewater services primarily aimed at removing water from its point of production and safely discharging it, with treatment focused on minimizing environmental impacts. These services have generally been regarded as natural monopolies, each with well-defined missions and operational boundaries.

In regions where universal access to basic sanitation has been achieved, the focus is now shifting towards managing used water and rainwater as valuable resources. This approach emphasizes fit-for-purpose water supply, integrated wastewater management, and rainwater management. Wastewater is increasingly viewed not simply as a waste to be disposed of, but as a source of water, nutrients (phosphorus and nitrogen), and energy.

Transitioning existing networks, storage facilities, pumping stations, and treatment plants to meet these new objectives is essential. Traditional governance and business models are often insufficient, requiring significant adaptation. Wastewater treatment operators are evolving into managers of resource recovery facilities and diversified water supply systems. When multiple water qualities are supplied, networks may need to be duplicated. The increased use of reclaimed or non-potable water can reduce drinking water demand and network flows, while local water reuse—such as greywater at the building or neighborhood level—reduces flows in drainage sewers. Recent concepts such as sponge cities and nature-based solutions (NbS) illustrate the shift from grey to hybrid blue-green infrastructures, integrating ecological processes into urban water management [6], with implications on the existing grey infrastructure.

Risk management is critical to ensuring safety and public trust in alternative water sources, such as treated wastewater. NbS are increasingly being adopted (see Section 8). Water quality management is becoming more demanding due to emerging contaminants, including microorganisms exhibiting antimicrobial resistance (AMR), pharmaceutical residues, PFAS, and microplastics. These challenges drive the need for innovation in monitoring, source control, and treatment technologies.

Urban water service infrastructures are aging, with many assets exceeding their technical lifetimes and often in poor condition. Renovation provides an opportunity to rethink and transition to new paradigms, rather than simply replace assets like-for-like. Constructed assets are costly and long-lived, making premature decommissioning inefficient. At the same time, the pace of technological and societal change, along with the uncertainties associated with new water management objectives, requires operational flexibility. Such flexibility can be achieved through smart sensing for early warning, advanced control systems (e.g., AI-supported), and innovative approaches to network layout and management.

Moreover, the recast Drinking Water Directive (Directive (EU) 2020/2184) [7] and the recast Urban Wastewater Treatment Directive (Directive (EU) 2024/3019) [8] will significantly shape the future of urban water infrastructures in Europe and may influence beyond. The former [7] strengthens requirements on risk assessment, monitoring, and transparency,

pushing utilities toward smarter sensing and improved governance. Reducing non-revenue water losses remains a key operational concern, supported by advances in detection and diagnostic methods. The latter [8], effective from January 2025, extends obligations to smaller agglomerations, mandates advanced treatment for nutrients and micropollutants, and introduces provisions for energy neutrality, resource recovery, and health-related monitoring. While both directives present substantial technical and financial challenges, they also create strong incentives to optimize existing facilities, deploy smarter monitoring, and strategically complement treatment plants with modular or nature-based solutions.

3.3. Maritime Natural and Built Infrastructures

Coastal protection and maritime infrastructures—both natural and constructed—play a critical role in safeguarding and enhancing the value of coastal areas, ports, and harbors. Their primary functions are to protect communities and economic activities from marine forces while enabling navigation, trade, fisheries, tourism, and the broader blue economy.

Climate change is profoundly increasing the pressure on these infrastructures. Rising sea levels, more frequent and intense storm surges, coastal erosion, and saline intrusion pose escalating risks. While floods from the sea are not new, their frequency, severity, and impacts are increasing, making coastal flooding an escalating threat for many European cities. Traditional hard protection measures, such as breakwaters, dikes, and seawalls, will require reinforcement, adaptation, or redesign. In parallel, nature-based approaches—such as dune restoration and wetland protection—as well as hybrid and multi-purpose solutions offer opportunities to combine risk reduction with ecological and social co-benefits. One example is the integration of port-protection maritime structures with wave power generation or recreational functions.

Despite their importance, maritime and coastal infrastructures often remain at the margins of water policy. European initiatives tend to focus either on inland waters (through directives such as the Water Framework Directive and the Floods Directive) or on marine and ocean issues (through the Marine Strategy Framework Directive and blue economy policies). This omission is particularly visible at the land–sea boundary, where the interplay between inland waters and marine systems demands more integrated governance.

3.4. Land-Sea Interface

The interface between freshwater and the sea—estuaries, coastal aquifers, deltas, and coastal systems—is frequently overlooked in policy and governance frameworks, creating a gap. Yet this transition zone is precisely where many pressing challenges converge: freshwater salinization, ecosystem degradation, conflicts between land use and marine pressures, and the vulnerability of coastal cities and infrastructures.

Oceans frameworks too often treat rivers and freshwater flows merely as boundary conditions that bring pollution, restrict sediment delivery, and disrupt ecological connectivity. Conversely, inland water management frequently views the sea as a source of problems: erosion, saltwater intrusion, flooding, and the “loss” of freshwater that is allowed to flow into the ocean despite scarcity on land. These siloed perspectives obscure the reality that the land–sea continuum is a single, interconnected system where pressures and opportunities converge.

Future resilience strategies should, therefore, explicitly embrace this interface, fostering governance, research, and investment frameworks that recognize freshwater and coastal infrastructures as interdependent components of a coherent whole. Recognizing coastal infrastructures as integral to water resilience would help close this policy blind spot. Better linking blue economy strategies with freshwater management, and embedding coastal infrastructures into European water resilience frameworks, is essential. Research

programmes, partnerships, and future European missions should address this interface directly, ensuring that natural and built infrastructures at the land–sea boundary are not treated as “no one’s land,” but rather as central components of resilient water and climate strategies.

4. Centralized and Distributed Water Systems

Section 3 highlighted the need to rethink hydraulic works, moving from isolated structures to more interconnected systems, from purely centralized solutions to integrated networks. A similar trend started to occur and must now accelerate significantly in the water services sector.

For more than a century, water services have been largely organized around centralized infrastructures. These large-scale systems take advantage of economies of scale, provide operational efficiency, and enable the use of advanced technologies that require specialized expertise. Centralization has, therefore, been seen as the most reliable approach to ensure safe water supply and effective wastewater management in urban environments.

However, emerging pressures are reshaping this paradigm. The need for resilience in the face of climate extremes, the growing importance of circular-economy principles, and the demand for locally adapted solutions point toward hybrid or semi-distributed systems [9]. These configurations combine centralized backbones with localized treatment, reuse, and recovery units, reducing systemic vulnerabilities while enabling more flexible, low-impact, multi-purpose infrastructures. Even when some components are decentralized, managing them in an integrated manner alongside centralized assets enhances both operational efficiency and system resilience.

The viability of distributed approaches is further strengthened by digitalization and AI, which allow for more precise monitoring and safer operation of decentralized infrastructures. Yet governance of partially distributed and NbS is inherently more complex, requiring coordination across multiple actors, scales, and technologies. Balancing efficiency, accountability, and resilience in this fragmented landscape is a central challenge in shaping water futures that reflect the diverse needs and growth patterns of different economic sectors.

5. Water Quality: Health and Environmental Drivers

Water quality management has advanced considerably in recent decades, driven by scientific progress and technological innovation. Nevertheless, new and complex challenges are emerging, underscoring the need for stronger source control strategies, a better understanding of the effects on ecosystems and human health, and more effective water treatment. Climate change, wildfires, and other extreme events are intensifying erosion processes and increasing sediment and pollutant loads in surface and groundwater bodies. At the same time, industrial development introduces novel contaminants of emerging concern (CECs), while demographic shifts, such as aging populations, contribute to rising levels of pharmaceutical residues and antimicrobial-resistant microorganisms in wastewater.

Although treatment processes can remove most conventional contaminants, their effectiveness for CECs varies widely and remains insufficiently documented for many compounds [10–13]. This is the case with the elimination of certain microbial species. The concentrated discharge of these microorganisms into receiving waters, or even the reuse of this water under insufficient treatment conditions, may inadvertently foster the spread of resistant or invasive strains—an issue of growing concern that demands further research and innovation.

This issue has been consistently underappreciated internationally, and particularly in Europe, highlighting the need for enhanced monitoring, source control, and treatment

strategies. The Urban Wastewater Treatment Directive (Directive (EU) 2024/3019) [8] offers a lever in this regard.

Expanding safe water reuse remains an important strategy to address increasing water scarcity, while safeguarding the environment and public health. Risk management in this context focuses on ensuring that water for reuse is treated to appropriate standards and safely integrated into the system [14].

Importantly, current practices of uncontrolled indirect water reuse, such as drinking-water abstractions located downstream of wastewater discharges, whether treated or untreated, pose unacceptable risks. Yet, these practices often go unnoticed by both the public and decision-makers, leading to their underestimation.

While the development of novel treatment technologies will be necessary, significant opportunities also exist to optimize the performance of existing facilities and to integrate complementary processes to address emerging threats.

Meeting these challenges calls for resilient, adaptive, and scientifically grounded water infrastructures, supported by long-term strategic foresight.

6. Digitalization and Artificial Intelligence in Water Infrastructures

Digitalization is profoundly reshaping the management and operation of water infrastructures, offering large gains in situational awareness, efficiency and adaptive capacity while introducing novel governance and security challenges [15]. The International Water Association's Digital Water programme and the IWA Digital Water Book provide practical frameworks and case studies showing how utilities can move from isolated sensors and pilots to integrated, utility-wide digital strategies [16].

One immediate benefit lies in automation and optimization of routine decisions: real-time telemetry combined with analytics and machine learning can reduce energy use, detect anomalies (e.g., leaks or process upsets), and support automated control loops—freeing human capacity for higher-level oversight. The JRC/Water 2023 assessment quantifies many such benefits for the European context (notably in leakage reduction, CSO reduction and hydropower optimisation), while stressing that benefits depend on institutional readiness and data quality [17]. A second contribution of digitalization lies in decision support and forecasting. Digital twins—dynamically updated virtual representations of physical assets and systems—are emerging as a unifying paradigm that combines sensor networks, physics-based and data-driven models, and user interfaces to support operational decision-making, scenario exploration, and resilience assessment [18]. Digital twins have been applied across distribution networks, treatment plants and river basins to explore demand patterns, optimize operations, and test interventions *in silico* before field deployment. Representative reviews and case studies summarizing current practice, architectures and open challenges are now available [19–21].

Nevertheless, digitalization is a double-edged sword. Large volumes of operational and customer data raise urgent questions around data governance, privacy, interoperability and ownership; AI and ML models can generate convincing but erroneous outputs (“hallucinations”) that must be identified through validation and human oversight; and increased connectivity expands the attack surface for cyber-threats to critical control systems. The JRC and IWA sources stress that technical deployment must be accompanied by governance frameworks, clear accountability, and workforce development to interpret digital outputs responsibly [16,17].

Finally, digital transformation is not purely a technical exercise: organisational change, regulation, procurement practices and business models all need to adapt. The literature and practice show that successful digital adoption follows a staged approach—from pilot projects with clear use cases, to institutionalisation, to scaling—and benefits hugely from

collaborative living-lab environments and cross-sectoral partnerships. In short, digital technologies (including digital twins and AI) can be decisive enablers of resilient, efficient and circular water infrastructures—but only if embedded in appropriate governance, skills development and data stewardship frameworks [16].

Table 1 summarizes opportunities and risks of digitalization in water infrastructures. This table is an original synthesis by the author, drawing on themes discussed in the text to summarize potential benefits and challenges of digital transformation.

Table 1. Opportunities and risks of digitalization in water infrastructures.

Opportunity	Implications for Water Infrastructures
Routine operational decisions automated	Increases efficiency, consistency, and responsiveness; frees human capacity for higher-level analysis.
Support for administrative, customer service, procurement, and legal tasks	Enhances service quality, reduces costs, and transfers proven solutions from other sectors.
Remote operation of facilities	Enables safe and effective management of semi-distributed systems, reducing geographic constraints.
Forecasting and early warning	Improves flood, drought, demand, and water quality predictions by uncovering new data relationships.
Data abundance and AI analytics	Allows real-time insights and scenario exploration; complements human decision-making.
Data governance and privacy	Clear rules on ownership, ethical use, and sharing of utility-generated data are required.
Skills development	Workforce training and capacity-building are critical to responsibly interpret digital outputs.
Risk	Implications for Water Infrastructures
AI hallucination	Risk of false or misleading outputs undermining trust and leading to poor decisions.
Loss of critical spirit/de-responsibilization	Operators and decision-makers may become over-reliant on AI, reducing accountability.
Cybersecurity risks	Greater exposure to malicious attacks on connected infrastructure, requiring robust safeguards.

7. Innovation, Experimentation, and Technology

The transition of water infrastructures from the current state to their aimed future requires more than incremental improvements; it calls for new paradigms and systematic experimentation. Key domains of innovation where co-development across multiple stakeholders and disciplines is particularly relevant include:

- *Advanced monitoring* (e.g., digital twins, Internet of Things, remote sensing, proxy parameters);
- *Energy-water-resource recovery* (e.g., sea-wave energy, biogas, heat and nutrient recovery);
- *Hybrid centralized–distributed systems* (e.g., modular decentralized units);
- *Hybrid grey-green infrastructures*;

- *Multi-purpose infrastructure* (e.g., coastal protection structures also designed for recreation or sports).

Despite these opportunities, water infrastructures are typically long-lived and risk-averse, which constrains the uptake of new solutions. A recurrent barrier in translating research into practice is limited engagement of infrastructure owners and operators in early stages of innovation. Effective implementation depends on collaborative environments where researchers, technology developers, utilities, regulators, and other stakeholders jointly define challenges, constraints, and opportunities.

Academic research plays a central role in advancing knowledge; however, its prevailing emphasis on peer-reviewed publication may limit applied impact. Strengthening mechanisms that connect research outputs with practice is, therefore, essential.

Safe piloting environments are critical to the success of innovation and market uptake. Water-Oriented Living Labs (WOLs) exemplify such mechanisms and are gaining increasing recognition. WOLs provide real-world settings where technologies, governance models [22], and service approaches can be tested under operational conditions. They enable evaluation of not only technical feasibility, but also social acceptance, institutional adaptability, and economic viability. Such environments foster learning-by-doing and support iterative development of solutions. Because innovation encompasses governance, business models, and public acceptance in addition to technology, such real-world experimentation is indispensable for systemic change. The concept of WOLs was first advanced within European collaborative innovation programmes—most notably under Water Europe’s Water Vision and EIT Climate-KIC initiatives—and was later institutionalized through the European Partnership Water4All [23,24].

By grounding experimentation in practice, WOLs create pathways for translating foresight into implementation, supporting the development of water systems that are both innovative and viable. Many promising technologies remain confined to pilot projects; WOLs offer a bridge between research and practice.

The Water4All Partnership, recognizing the importance of WOLs in leveraging the implementation and impact of its Strategic Research and Innovation Agenda (SRIA) [25], has established criteria for recognition of demo sites as Water4All WOLs, mapped existing initiatives, published a continuously updated WOL Atlas [26], and is building a network of WOLs. This network facilitates dialogue, exchange of experiences, and capacity building, providing a roadmap for the sustainable implementation and management of WOLs [27]. These initiatives align with broader EU missions on climate adaptation and digital transition, reinforcing WOLs as boundary-spanning instruments for innovation.

Systematic experimentation and innovation are, therefore, essential to creating infrastructures that remain resilient under conditions of deep uncertainty.

8. Governance, Strategic Foresight, and Financial Considerations

Foresight exercises must also consider geopolitical tensions, transboundary water governance, political instability, misinformation, and cyber risks. Strategic planning must integrate these risks while also considering financial and economic governance and investment models. The ISO standards on asset management [28–30] may assist organizations implementing a sound strategic planning of the water infrastructures, while guiding governments on how to create or enhance an enabling environment for such transitions [31]. In addition, global guidance such as the UN Handbook on Infrastructure Asset Management [32] provides comprehensive practical tools and planning methodologies to support resilient, lifecycle-based infrastructure governance at local and national levels.

Much progress remains to be achieved. At present, operational, tactical, and strategic planning, as well as financial management, are frequently conducted in isolation within

organizations, resulting in fragmented and sometimes conflicting outcomes. Brown has consistently argued since 2016 that contemporary conditions are characterized by extreme uncertainty, which renders traditional linear strategic planning over long-term horizons increasingly inadequate [33]. This recognition calls for a paradigm shift toward adaptive planning, emphasizing flexibility and responsiveness to unforeseen developments, while explicitly incorporating resilience, safety and security against emerging threats, circularity, and low-carbon pathways, and ensuring that investment models and governance frameworks are robust under future uncertainties.

In many regions of the world, particularly where external funding plays a dominant role, infrastructure investments are coordinated through centralized national bodies. This arrangement helps consolidate scarce expertise and facilitates access to international finance. However, it also tends to reinforce a focus on building new infrastructures rather than rethinking, maintaining, or adapting existing ones. Local operators, often under-resourced and with limited revenue streams, are left to manage operations without adequate means for maintenance or rehabilitation. The result is a paradox: despite comparable levels of investment per capita with better-performing regions, service quality remains fragile and uneven. This points to a structural governance gap, where strategic asset management and lifecycle thinking are undervalued. Addressing this imbalance is not about prescribing solutions, but about opening space for dialogue between funders, governments, and local communities on how to align investments with sustainable service delivery over time.

9. EU Water Resilience Strategy

The European Water Resilience Strategy (EWRS), presented by the European Commission in its Communication on a Water Resilience Initiative (leading to the EWRS) [34], provides a new policy framework to strengthen resilience, sustainability, and equity in water management across the EU. It is structured around three overarching goals:

- *Restore and protect the water cycle* (source-to-sea), emphasizing full implementation of EU water directives and wider adoption of NbS (wetlands, floodplains, sponge cities).
- *Build a water-smart economy*, reducing overall consumption through efficiency, leakage reduction, reuse, and digitalization.
- *Ensure equitable access to clean and affordable water*, supported by fair pricing, investment in underserved regions, and inclusive planning.

These goals are supported by cross-cutting enablers (Figure 1) that together create opportunities for upgrading aging systems, diversifying sources, expanding reuse, and embedding risk management into infrastructure planning.

The EWRS offers significant potential to modernize European water infrastructure, but its impact will depend on avoiding fragmented, isolated interventions. Priority should be given not only to new investments but also to rethinking and adapting existing infrastructures, embedding resilience, circularity, and equity into their renewal. Achieving this requires integrated governance, innovative financing, and stronger links between research, practice, and policy. Table 2 summarizes both the direct opportunities of the EWRS and the author's perspective on its broader opportunities. This table combines elements from the European Commission Communication on a Water Resilience Initiative [34] with the author's synthesis and interpretation, highlighting enlarged opportunities for water infrastructure transitions.

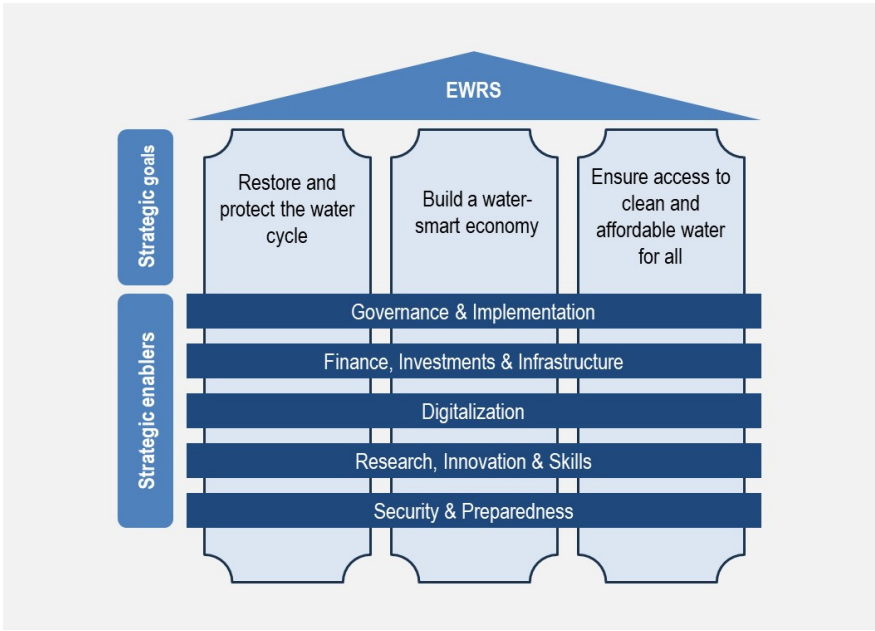


Figure 1. Cross-cutting enablers supporting water resilience goals (schematic based on EWRS [34]).

Table 2. Opportunities under the EU Water Resilience Strategy for transitioning water infrastructures.

Direct Opportunity	Enlarged Opportunity
Infrastructure modernization Significant investments will flow into upgrading aging systems, especially to reduce leakage in water supply systems.	The priority should be to upgrade existing water infrastructure, making it more flexible, resilient, safe, energy-efficient, and easier to maintain and operate, while also responding to current and emerging challenges. Water losses in supply systems are indeed a concern, but they should not be addressed in isolation or treated as the single most important issue. Furthermore, ensuring a skilled and motivated workforce is crucial for the successful implementation of the EWRS. Addressing the growing skills gap and fostering youth engagement in the water sector are essential to maintain and enhance water infrastructure resilience.
Shift toward NbS Traditional grey infrastructure (like dams or desalination) will be used more carefully, while nature-based alternatives—wetlands, river rewilding, floodplain reconnection—will be prioritized.	NbS are generally less intensive, requiring more time and space. Their success and feasibility depend on multipurpose approaches that involve multiple stakeholders. Traditional governance models are often inadequate and tend to fail in the medium term. The EU Water Resilience Strategy (EWRS) should be leveraged to design and implement novel governance models that enable NbS to work effectively and sustainably in practice.

Table 2. Cont.

Direct Opportunity	Enlarged Opportunity
Diversified water supply models Increased water reuse (especially in agriculture and industry) will ease demand pressures, while prioritization of efficiency will reduce reliance on new supply infrastructure.	Water scarcity is increasing in Europe due to climate change and growing demand, including new high-demand sectors such as data centers supporting AI. Effective water management requires matching and integrating demand with supply. The EWRS emphasizes water reuse in agriculture and industry, which remains critical, but urban water reuse represents a significant, underexplored complementary opportunity. Treated wastewater and other alternative sources can be applied across sectors—including agriculture, industry, power production, and urban non-potable uses—supporting circular water systems and enhancing resilience. Overall, the EWRS provides an excellent framework to advance science, technology, governance, financing, and business models in an integrated and multidisciplinary manner, enabling diversified and sustainable water supply strategies across all sectors.
Enhanced risk management and preparedness Investments will support flood and drought early warning systems and integration of water risks into urban planning, reducing reliance on reactive approaches.	With more frequent and more intense extreme weather events, and the increase of uncertainty, it is often no longer feasible to design infrastructure to fail-safe condition. Instead, accepting failures at a certain level, the most important goal is to protect people and goods, minimizing the negative impacts of failures, creating a safe-to-fail-mode. Enhanced risk management and preparedness are therefore key components of strategic and tactical planning of water infrastructures as well as for operational management.
Equity and service access Underserved and vulnerable areas will gain upgraded infrastructure to ensure clean and affordable water, supported by better governance and pricing policies.	In the context of a resilience strategy, equity in access to safe water services for disadvantaged populations is generally not a concern in Europe. However, equity in access to urban water services still needs to be addressed in situations of adverse events, particularly regarding the risk of inundation and water supply interruptions. Semi-distributed systems, for instance, may contribute to equity and continuity of water access. Novel governance and pricing policies to invest in resilience are needed.
Cross-border and local governance Infrastructure planning will account for transboundary river basins and local conditions, encouraging tailored, place-based solutions and coordination—strengthening coherence and equity.	Coherence and equity are supported in fair negotiations and continued collaboration among countries involved. Share of sound and timely information and collaborative <i>fora</i> , such as communities of practice, joint projects, and Water-oriented Living Labs gain relevance in these contexts.

10. Research and Innovation Priorities

To respond to the call for action regarding water infrastructures, problem-oriented research and innovation are very much needed. The Water4All Partnership, through its SRIA [25], provides a shared European vision for water-related research. While infrastructure-specific aspects could be further strengthened and are being worked out

within the partnership for the upcoming revised SRIA, the current version already establishes a valuable foundation for linking water infrastructures with cross-cutting themes such as resilience, digitalization, circular economy, and NbS. This offers an opportunity for the research community to bring infrastructure issues more explicitly into the European innovation agenda, ensuring that the long-lived assets at the core of water services are not overlooked.

Table 3 summarizes research lines that aim at responding to the issues identified in the previous sections. This table is the author's synthesis, developed to summarize challenges and possible research directions identified in the text. It does not reproduce any specific source.

Table 3. Research and innovation priorities for water infrastructures.

Challenge/Issue	Research Line	Expected Innovation Impact
Transitioning aging infrastructures	Develop transition-oriented methodologies that embed resilience, circularity, carbon neutrality, and flexibility into renewal and reinvestment strategies.	Turn rehabilitation and renewal into drivers of systemic transformation rather than like-for-like replacement.
Water scarcity & multiple sources	Integrated management of surface, groundwater, desalinated and reused water; managed aquifer recharge; risk assessment and management for all sources, including water reuse	Secure multi-source systems, enable circular water use; ensure public trust in reuse systems; increase the society's willingness to accept and pay for water safety, security, and resilience.
Climate extremes (droughts, floods, wildfires)	Safe-to-fail design, adaptive capacity, hybrid grey-green solutions.	Increase resilience, reduce human and economic losses.
Digitalization & AI	Trusted AI, digital twins, cybersecurity, data governance and interoperability.	Smarter decision-making, efficiency gains, secure operations.
Emerging contaminants & antimicrobial resistance (AMR)	Smart monitoring, treatment, source control, risk assessment and management.	Protect the environment and biodiversity, protect human health, ensure public trust in reuse systems.
Urban transitions & decentralization	Hybrid centralized-distributed systems, fit-for-purpose reuse, local rain/greywater management.	Flexible, resource-efficient, and equitable water services.
Maritime and coastal infrastructures under climate change	Further develop advanced inspection, monitoring, and forecasting systems combining satellite (e.g., Copernicus), multi-sensor drones, underwater sensors, visual surveys, and integration with numerical and physical models and with AI data analytics; expand the use of digital twins for coastal and maritime structures.	Improve accuracy and timeliness of information, enable systematic inspection and early warning, enhance understanding of coastline evolution, and support adaptive, safe-to-fail design of maritime and coastal protection systems.
Coastal & land-sea integration	Develop governance models, planning tools, and multidisciplinary research approaches that explicitly link freshwater management with coastal and marine systems; integrate data and policies across river basins, deltas, estuaries, and coastal aquifers.	Overcome policy silos, reduce conflicts between inland and marine perspectives, and foster coherent resilience strategies across the land-sea continuum.

Table 3. Cont.

Challenge/Issue	Research Line	Expected Innovation Impact
Governance & financing gaps	Adaptive planning, strategic asset management, innovative financing, and business models.	Ensure long-term sustainability and equity in service delivery.
Intersectoral water management	Develop and promote symbiotic cross-sectoral and cross-border solutions—technical, financial, and governance-based.	Foster innovative cooperation models across agriculture, industry, urban services, and transboundary basins, enabling more efficient water use, reducing competition among users, and mitigating conflicts.

These priorities align with the challenges identified in earlier sections—aging assets, water scarcity, and digital and governance transitions.

11. Concluding Reflections: Shaping Water Infrastructure Futures

Water infrastructures stand at the intersection of permanence and change. They are expected to provide essential services indefinitely, yet they must constantly evolve to meet new challenges, technologies, and societal expectations. This dual nature makes foresight indispensable: without it, infrastructures risk becoming obsolete, fragile, or misaligned with the needs of future generations [3].

A central message of this paper is that managing aging infrastructures cannot be reduced to monitoring conditions and predicting failures. However sophisticated, such approaches remain insufficient if they only lead to like-for-like replacement. Renewal and reinvestment decisions must instead be treated as strategic opportunities to embed new objectives—resilience, circularity, carbon neutrality, flexibility, and equity—into the infrastructures we pass on to the future. In this sense, transition pathways should lie at the heart of infrastructure planning and asset management, turning inevitable cycles of rehabilitation into drivers of systemic transformation. Yet, achieving these transformations may face institutional inertia and short-term political or financial constraints that must be explicitly managed. Future research should, therefore, prioritize ways to overcome financial, political, and social barriers to implementing innovative governance and infrastructure transition frameworks.

The trends explored in this entry—including capital maintenance, hybrid/distributed systems, technological innovation, governance challenges, financial considerations, and environmental pressures—illustrate the complexity and urgency of action. Deliberate shaping of water futures is required, balancing resilience, circularity, digitalization, and NbS.

The research lines outlined in Section 10 directly address the challenges identified throughout this paper, from aging infrastructures to digital and governance transitions. Foresight exercises provide a way to confront uncertainty, explore alternatives, and build shared responsibility among decision-makers, researchers, practitioners, and communities. By doing so, they enable infrastructures not only to withstand the shocks and stresses of the present but also to adapt, regenerate, and safeguard water security and ecosystem integrity for generations to come. By explicitly integrating the land–sea interface into resilience strategies, governance gaps can be overcome and coherent freshwater–marine adaptation pathways ensured.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
AMR	Antimicrobial Resistance
CEC	Contaminants of Emerging Concern
EWRS	European Water Resilience Strategy
ISO	International Organization for Standardization
ML	Machine Learning
NbS	Nature-Based Solutions
SRIA	Strategic Research and Innovation Agenda
UN DESA	United Nations Department of Economic and Social Affairs
UNCDF	United Nations Capital Development Fund
UNOPS	United Nations Office for Project Services
WOLL	Water-Oriented Living Lab

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