



# Blu Shift – Water in the 21<sup>st</sup> century

Strategies, Technologies, and Governance Models for Water  
Resilience in an Era of Systemic Change

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## EXECUTIVE SUMMARY – BLU SHIFT: WATER IN THE 21<sup>ST</sup> CENTURY

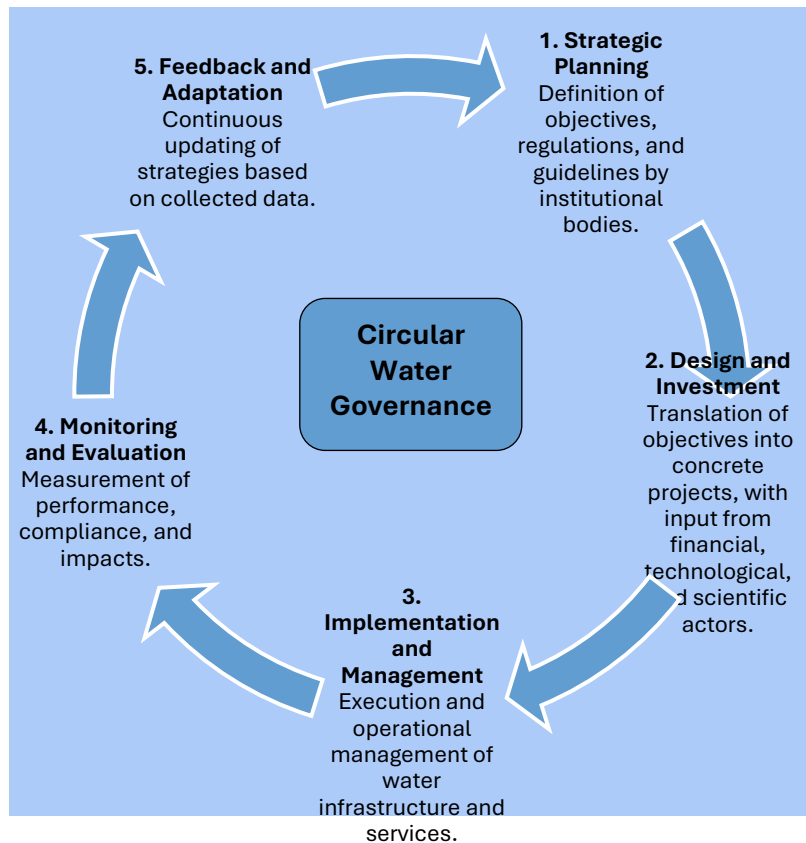
Water is no longer a given resource. It is today a systemic risk threatening food security, urban stability and industrial competitiveness. More than 2 billion people already live in areas under water stress, and that number is growing.

This report offers a transformative vision: water as an “invisible infrastructure” and regenerative natural capital, the foundation of social cohesion and climate resilience.

### THE 5 KEY CRITICAL ISSUES

No.	Critical Issue	Primary Impact
1	Structural water stress – WEI <sup>+</sup> > 20 % over one-third of European territory; peaks > 40 % in the Mediterranean.	Supply security, production discontinuities
2	Network losses and inefficiencies – up to 35–50 % in urban systems; process inefficiencies > 45 % in many industrial sectors.	High operating costs, resource waste
3	Under-utilized water reuse – < 4 % of treated effluent reused globally, despite 56 % being potentially suitable.	Pressure on conventional sources, missed circular-economy opportunities
4	Regulatory and financial barriers – slow authorization processes, uneven standards, estimated €28 billion/year investment gap (EU).	Plant delays, high capital costs
5	Social acceptance and fragmented governance – low trust in potable/industrial reuse, cross-sector conflicts, poor participation.	Project risk, inequity and water exclusion

### CIRCULAR WATER GOVERNANCE



## **THE 5 SYSTEMIC SOLUTIONS**

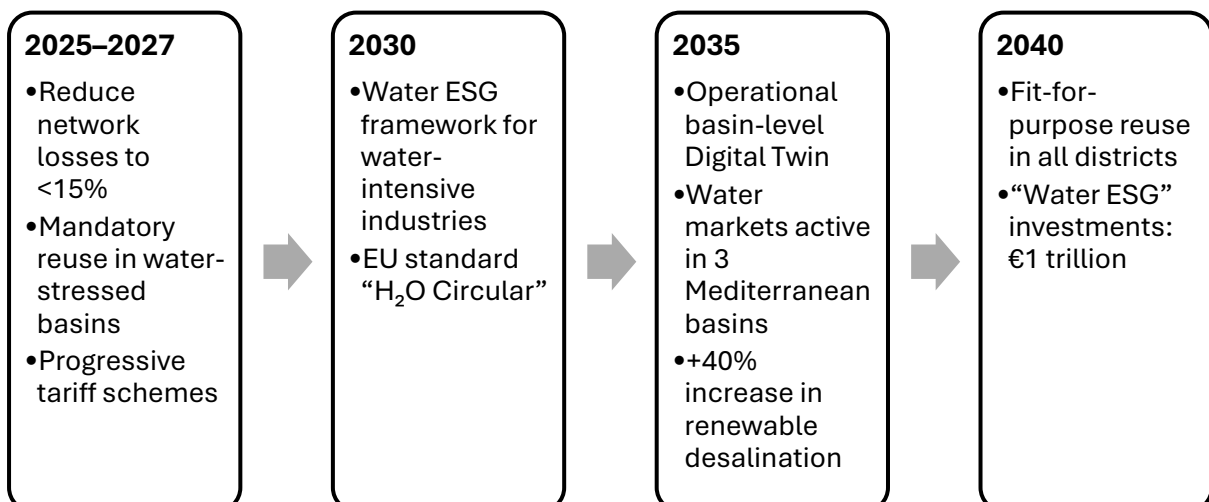
1. Circular water economy: fit-for-purpose reuse; recovery of energy and nutrients from effluent; industrial symbiosis.
2. Digital Water & smart networks: smart metering, IoT, Digital Twin models to cut losses by 30–50 % and optimize OPEX.
3. Resilient finance & blended finance: progressive tariffs, green/blue bonds, performance-based PPPs, EU taxonomy and SEEA Water for bankability.
4. Adaptive multistakeholder governance: scenario planning (Adaptive Pathways), regulated water markets, inclusive basin platforms.
5. Nature-based & decentralized solutions: constructed wetlands, rainwater harvesting, managed aquifer recharge (MAR); containerized MBR modules for peri-urban communities.

## **THE 10 PRIORITY ACTIONS (2025-2030)**

1. Reduce network losses to < 15 % by 2030 via 100 % smart metering and predictive maintenance.
2. Mandate  $\geq 25$  % reuse of effluent in agriculture in basins with WEI<sup>+</sup> > 20 % (transposition of EU Reg. 741/2020).
3. Implement progressive tariff schemes + social support funds: recover €0.20/m<sup>3</sup> to finance circular CAPEX.
4. “Water ESG” investment plans for manufacturing (> €250 billion in water-intensive turnover), targeting  $\geq 60$  % internal recycling/reuse.
5. Deploy basin-scale Digital Twin platforms in all EU critical water districts by 2028.
6. Establish a single quality standard “H<sub>2</sub>O Circular” for reuse in industrial processes and cooling towers.
7. Launch urban MAR/NBS programs in 50 vulnerable European cities: retention ponds, green roofs, and wetlands.
8. Pilot water markets in three Mediterranean basins, modelled on the Murray–Darling Basin, for flexible rights allocation.
9. Increase renewable-powered desalination capacity by + 40 % using solar RO where WEI<sup>+</sup> > 40 % and solar potential > 1 400 kWh/m<sup>2</sup>/year.
10. Training & behavioural-change campaigns (“Water-Smart Citizens”) to cut domestic consumption to 100 L per capita/day.

*Targets to be calibrated to local network specifics.*

## **STRATEGIC ROADMAP FOR WATER RESILIENCE (2025 – 2040)**



**SUMMARY ESTIMATE OF COSTS/BENEFITS (10-YEAR HORIZON, EU-27)**

Macro Intervention	CAPEX (public + private)*	Expected Annual Benefits**	Payback	Key Notes
<b>Network loss reduction</b>	€ 45 billion	€ 9–13 billion (water & energy saved)	4–6 years	Includes digitalization + pipe replacement
<b>Agricultural &amp; industrial reuse</b>	€ 32 billion	€ 11–15 billion (water, fertilizer, CO <sub>2</sub> avoided)	3–5 years	Covers 7 % of EU irrigation needs
<b>Urban NBS &amp; MAR</b>	€ 18 billion	€ 4–6 billion (flood & heat-island reduction)	6–8 years	Ecosystem services value included
<b>Circular effluent plants (energy &amp; nutrients)</b>	€ 25 billion	€ 7–9 billion (biogas, struvite, less landfill)	4–5 years	Energy self-sufficiency of 70–80 %
<b>PV-powered desalination</b>	€ 12 billion	€ 2–3 billion (additional potable water)	6–7 years	Only in high-stress coastal areas
<b>Total</b>	≈ € 132 billion	≈ € 33–46 billion/year	< 5 years avg.	<i>Blended finance: 45 % public / 55 % private</i>

\*CAPEX = initial investment cost. \*\*Annual benefits include avoided water/energy costs, fertilizer value, ecosystem services (EU ENV valuation), and CO<sub>2</sub> avoided at € 95/t (ETS 2025).

**CONCLUSION**

Water efficiency is not only an environmental issue but a strategic lever for industrial competitiveness, food security and urban resilience. Technologies are available, but scaling them requires integrated policies, flexible governance models and targeted investments. The transition to a circular water economy is a systemic opportunity capable of delivering long-term economic, environmental and social benefits.

Every euro invested in water resilience yields € 2.5–3.5 of economic, social and environmental benefits within ten years. Today's circular and digital solutions can reduce water stress, decarbonize production cycles and generate systemic value. Acting decisively between 2025 and 2030 is critical to avoid inaction costs estimated at over 6 % of GDP in the most vulnerable regions by 2050.



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## ABSTRACT

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In the 21st century, water is no longer an unlimited resource but a strategic pillar for global stability. This report delves into the complex dynamics of water efficiency and resilience, exploring the challenges and opportunities emerging across key sectors: agriculture, industry, urban systems, and wastewater treatment. Operating within a context of increasing water stress, climate instability, and an urgent ecological transition, our analysis begins with an in-depth assessment of sectoral vulnerabilities and the cutting-edge technological solutions currently available.

We then propose an integrated framework for measuring water efficiency, grounded in robust quantitative indicators, advanced reporting tools, and environmental accounting methodologies, fully aligned with the Sustainable Development Goals (SDGs).

Chapter 5 marks a turning point, introducing a paradigm shift that elevates water resilience to a strategic asset for macroeconomic stability and industrial competitiveness. We examine the economic returns of water reuse, highlighting the effectiveness of sustainable finance instruments such as blended finance, green bonds, and Public-Private Partnerships (PPPs) (World Bank, 2023). Furthermore, we explore models of adaptive governance—such as the System of Environmental-Economic Accounting for Water (SEEA), the application of Key Performance Indicators (KPIs), and scenario-based planning—as vital tools for managing hydrological uncertainty.

A comparative assessment reveals significant variations in water's added value across sectors—from €1–3/m<sup>3</sup> in agriculture to over €500/m<sup>3</sup> in high-tech industries—providing critical insights for more informed strategic and resource allocation decisions.

In the last chapter, we outline concrete operational recommendations for businesses, regulators, and policymakers, supported by international case studies and emerging best practices. This white paper offers a bold vision of a resilient and circular industrial strategy—one that redefines water not merely as a cost or a constraint, but as an invisible infrastructure and a regenerable natural capital.

It is this vision that forms the essential foundation for social cohesion, productive sovereignty, and Europe's sustainable transition.

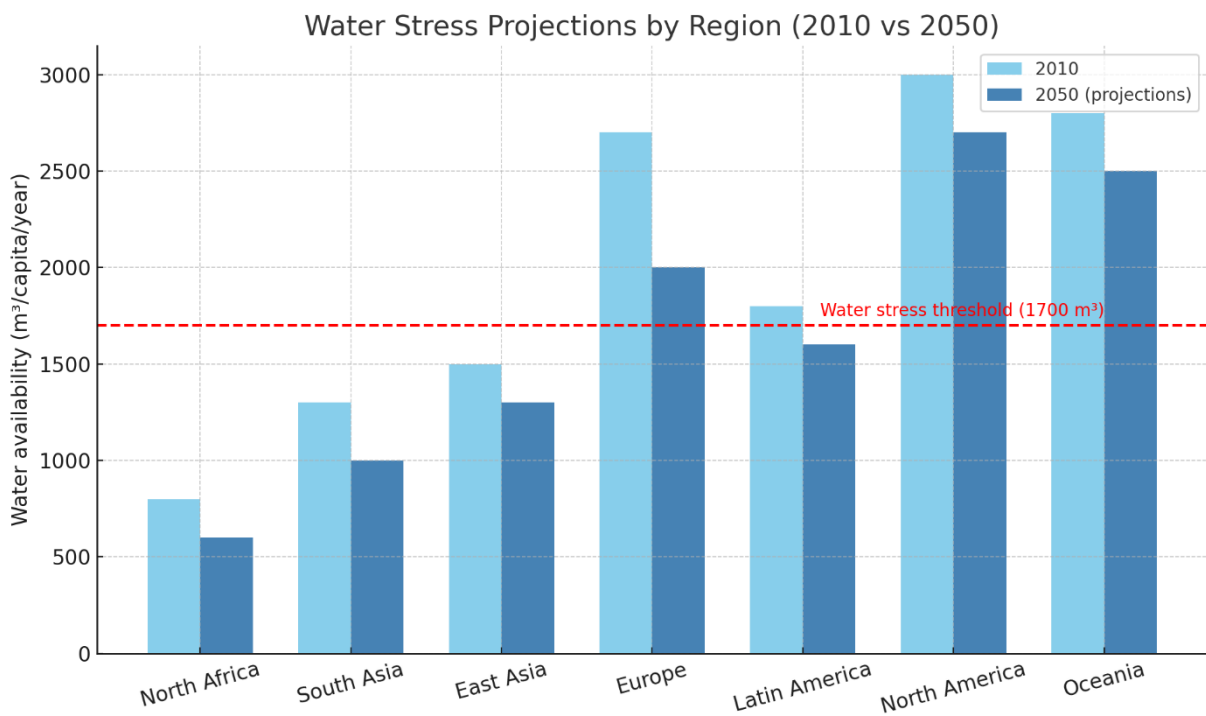
# 1 INTRODUCTION

## 1.1 WATER SCARCITY AS AN EMERGING GLOBAL CHALLENGE

Water—the lifeblood of our planet—is at the heart of today’s most pressing environmental, economic, and social challenges. In an era defined by intensifying climate change, rapid urbanization, and unprecedented pressure on both natural and artificial ecosystems, the availability of water resources is becoming increasingly uncertain and irregular (Scanlon et al., 2023).

More than two billion people currently live in regions affected by high water stress, and future projections indicate a significant increase in this trend, extending even into industrialized countries (UNESCO & UN-Water, 2020; Liu et al., 2022). Water scarcity transcends the environmental dimension—it constitutes a systemic risk that threatens food security, business continuity, urban stability, and territorial resilience. The linear paradigm of “withdraw, use, and discharge” has exhausted its inherent sustainability (Lindner & Stamm, 2025). A radical rethinking of water management is imperative, shifting toward a circular, regenerative, and cross-sectoral perspective (Delgado et al., 2024).

Figure 1 Estimated annual per capita water availability in selected global macro-regions, comparing the situation in 2010 with projections for 2050. The red line indicates the critical threshold of  $1,700 \text{ m}^3/\text{year}$ , below which water stress is considered to occur (adapted from FAO, UNESCO, Liu et al., 2022).



As illustrated in Figure 1, per capita water availability is expected to decline significantly in many macro-regions, falling below the critical threshold in much of sub-Saharan Africa and South Asia.

## 1.2 CROSS-SECTORAL IMPACTS ON FOOD SECURITY, INDUSTRY, AND URBAN SYSTEMS

The impacts of water scarcity vary greatly across key economic sectors but have a transversal effect on food security, economic stability, and urban resilience. Each sector experiences specific vulnerabilities which, if not addressed with appropriate tools, may escalate into systemic crises (Leijnse et al., 2024).



In the agri-food sector, for instance, the increasing frequency and severity of extreme weather events—combined with broader climate instability—is already compromising agricultural productivity across large areas of the globe. This directly affects the availability and accessibility of food globally and locally (Toromade et al., 2024). Irrigation—central to primary food production—is under significant pressure, making precision technologies and advanced systems essential to reduce consumption and optimize efficiency (Hrozencik & Aillery, 2021).

Manufacturing and chemical industries are also highly exposed. Water scarcity leads to growing operational risks, process interruptions, rising procurement costs, and increasingly stringent environmental constraints. In this context, efficient water resource management is no longer optional—it is a strategic operational asset to ensure production continuity, environmental sustainability, and economic competitiveness. Companies are increasingly investing in reuse, treatment, and recycling technologies for wastewater, reducing both environmental impact and operating costs (Karki & Rao, 2023).

In urban systems, vulnerability is exacerbated by high population density and the rigidity of existing water infrastructure (Jones et al., 2024). The water crisis in Cape Town is a telling example of how cities can rapidly descend into emergency conditions if lacking resilient tools. To address these challenges, it is crucial to adopt innovative solutions—such as green infrastructure and decentralized systems—that can enhance the flexibility and sustainability of urban water management (Delgado et al., 2024; Mbavarira & Grimm, 2021).

At the social and economic level, water scarcity intensifies territorial inequalities and inequities in access to the resource. The most vulnerable populations are often the most affected, with repercussions on social cohesion and political stability (Jones et al., 2024).

### **1.3 OBJECTIVES AND STRUCTURE OF THE REPORT**

This report aims to provide an integrated, evidence-based perspective on the opportunities linked to water efficiency, with a particular focus on industrial and urban sectors. The analysis will cover several critical areas:

- the exploration of advanced technologies for closing the water loop, including membrane solutions, advanced oxidation processes (AOPs), and digital system optimization.
- the examination of sector-specific strategies for the agri-food and manufacturing sectors, as well as for wastewater treatment.
- the presentation of robust measurement tools, such as the water footprint and indicators aligned with the Sustainable Development Goals (SDGs).
- and finally, the analysis of innovative models for governance, financing, and policy designed to support and accelerate this water transition.

The ultimate objective of this work is to promote water management that inherently integrates economic competitiveness with environmental sustainability and long-term resilience.

### **1.4 METHODOLOGY, SOURCES AND TOOLS**

The methodology used to draft this report is structured in several phases.

First, a review of the scientific literature was conducted, prioritizing peer-reviewed articles and institutional reports from key organizations such as FAO, UNESCO, WRI, EEA, and the World Bank.

The research was carried out using Google Scholar and Lens.org.



Second, the selection of quantitative data prioritized official sources where available, resorting to sectoral averages or consolidated estimates in their absence, in order to maintain the reliability of the information. It is important to note that some of the charts and tables presented are based on reprocessed disaggregated data—a process that has been indicated to ensure transparency and replicability.

Finally, selected case studies were included based on their geographical representativeness, the technical replicability of the solutions adopted, and the availability of verifiable data, offering concrete examples of success and lessons learned.

The entire methodological approach was guided by a strong alignment with the United Nations Sustainable Development Goals (SDGs), in particular targets 6.4 (water-use efficiency), 9.4 (industrial modernization), 12.2 (efficient use of natural resources), and 13.1 (resilience to climate-related disasters), strengthening the global relevance and impact of this report's conclusions.

The digital and analytical tools used include Microsoft Excel for data organization and management, while Microsoft Word served as the main platform for drafting the text. Certain phases of quantitative analysis and data processing were conducted using Python scripts.

For editorial and review activities, the use of generative artificial intelligence models (OpenAI, versions GPT-4o and GPT-4.5) was also integrated. These tools were employed exclusively for linguistic refinement of the first draft, cohesive cross-checking of internal references, preliminary verification of source consistency, and editorial support.

The adoption of AI served an auxiliary, non-substitutive function: all analyses, interpretations, and conclusions presented were manually validated.

## 2 SECTORAL FOCUS: STRATEGIES AND CRITICAL ISSUES

Water resource management is emerging as a cross-cutting challenge that affects all economic sectors. However, its significance increases exponentially in water-intensive contexts such as agri-food, manufacturing and chemical industries, and wastewater and sludge management. This section explores each of these sectors, highlighting their main critical issues and the emerging strategic responses to address increasing water stress.

### 2.1 AGRI-FOOD INDUSTRY

#### 2.1.1 A Critical Dependence: Agriculture's Water Fragility

Agriculture is the largest global consumer of water resources, accounting for about 70% of freshwater withdrawals worldwide (FAO, 2021). However, this dependence varies significantly across continents. In Asia and Africa, over 80% of freshwater is used for irrigation, while in Europe, this share is around 33%, due to higher rainfall and the adoption of less water-intensive farming practices (FAO, 2021; UNESCO, 2020).

Table 1: Agricultural Sector Water Dependency by Continent

Continent	Irrigation Share of Total Withdrawals (%)	Irrigated Land Share of UAA (%)
Asia	81	37
Africa	82	6
Europe	33	10
Latin America	71	12
North America	41	14
Oceania	56	5

As shown in Table 1, the percentage of irrigated land relative to the Utilized Agricultural Area (UAA) is highly uneven. In Asia, where production systems heavily depend on irrigation, 37% of UAA is irrigated, compared to a modest 6% in Africa. This highlights that agriculture's vulnerability to water scarcity is not solely a climatic issue but is closely tied to infrastructure and technological availability.

This fragility intensifies in semi-arid and arid areas where irrigation dependency is highest. Even minor water availability variations in these regions can significantly reduce crop yields, jeopardizing food security and local economic stability (Liu et al., 2022). Projections suggest that by 2050, over 40% of arable land will experience water scarcity for at least part of the year, with especially severe impacts in subtropical and low-income regions (Liu et al., 2022; Vanham et al., 2021). The absence of stable water reserves and modern irrigation systems makes many regions vulnerable to seasonal fluctuations and extreme events like prolonged droughts or irregular rainfall. Enhancing agri-food sector resilience requires integrated interventions involving advanced infrastructure, digitalization, and multilevel governance.

However, water scarcity in agriculture cannot be viewed in isolation from global trade dynamics. Recent studies show that while international trade in agricultural products can mitigate overall water scarcity through the transfer of "virtual water," it may also lead to regressive equity effects. Gu et al. (2024) found that the impacts of agricultural trade on water scarcity and equity are deeply asymmetric: in developing countries, low-income groups are most affected by worsening water scarcity and inequality, while in developed countries, disadvantaged groups benefit more

from the synergies between reduced scarcity and better distribution. Over 35% of people in developing countries experience both increased water scarcity and inequality, with an average per capita income 16% lower than the national average. These findings underscore the urgent need to consider the redistributive dimension of water policies in agriculture, integrating tools to address territorial and social disparities stemming from international agri-food trade (Gu et al., 2024).

### 2.1.2 Irrigation Efficiency Technologies and Climate Resilience

Global agriculture is now undergoing a profound process of technological renewal. The objective is twofold: to increase productivity to meet the ever-growing demand for food, while simultaneously reducing the water footprint of agricultural processes. At the heart of this transition is irrigation efficiency—defined as the ability to maximize yield per unit of water used, while reducing losses due to evaporation, runoff, and deep percolation. The technologies available to achieve this efficiency vary in terms of both water savings and implementation costs, as shown in Table 2 (Ray & Majumder, 2024).

Table 2 - Irrigation Technologies: Average Efficiency vs Initial Cost

Technology	Average Efficiency (%)	Estimated Initial Cost (€/ha)
Surface Irrigation	40	300
Sprinkler Irrigation	70	900
Drip Irrigation	90	1500

Beyond efficiency percentages, it's crucial to evaluate the actual impact of different technologies in terms of annual water consumption per hectare. Table 3 outlines potential savings compared to surface systems, based on standard operational scenarios from Zhang et al. (2022).

Table 3 - Average Annual Water Consumption and Relative Savings by Irrigation Technology

Irrigation Technology	Average Consumption (m <sup>3</sup> /ha/year)	Savings Compared to Surface (%)
Surface	12,000	–
Sprinkler	8,000	33%
Drip	5,000	58%
Subsurface	4,000	67%

Analyzing these technologies:

- Surface: Still widely used in traditional contexts, but marked by major losses and very low efficiency, with usage up to 12,000 m<sup>3</sup>/ha/year.
- Sprinkler: An intermediate solution improving distribution and reducing consumption to ~8,000 m<sup>3</sup>/ha/year (–33%).
- Drip: A high-efficiency method delivering water directly to the root zone; consumes ~5,000 m<sup>3</sup>/ha/year (–58%), ideal for horticulture and vineyards.
- Subsurface: Advanced system delivering water below the soil surface via capillarity; despite higher upfront costs, mainly feasible for high-value crops, consumes just ~4,000 m<sup>3</sup>/ha/year (–67%).

Precision irrigation, supported by sensors, SCADA systems, AI, and telemetry, enables dynamic and adaptive water management. Real-time monitoring of soil moisture, microclimatic conditions, and crop-specific needs allows for calibrated water distribution, reducing waste and improving agricultural resilience (Rastogi et al., 2024). In semi-arid contexts, strategies such as controlled deficit irrigation, drought-tolerant crop varieties, and dry farming are proving effective (Hrozencik & Aillery, 2021).

Despite proven advantages, precision irrigation faces several structural barriers: high initial costs (800–2,000 €/ha), digital skill gaps, poor rural network coverage, and local skepticism of unfamiliar technologies (Rastogi et al., 2024; IJSRA, 2024).

Yet, the benefits are significant: water savings of 20–50%, yield increases of up to 15% for water-intensive crops, and labor savings of 30–40%. Automation boosts management efficiency, and initial investments may break even within 3–5 years due to input and resource savings (Yasin et al., 2021; Udo et al., 2024). Public policy plays a key role: tax incentives, affordable credit access, and training programs are vital to accelerate the transition (UNESCO & UN-Water, 2020).

Finally, agricultural digitalization—powered by big data, machine learning, and agro-climatic forecasting models—offers proactive water optimization. Integrating sensors, cloud platforms, AI-driven decision systems, and predictive tools enables farmers to make informed decisions, reduce water waste, and enhance crop resilience. This digital transformation is a cornerstone of sustainable, adaptive agriculture (Vahdanjoo, Sørensen, & Nørreremark, 2025). A recent review (Lakhari et al., 2024) highlights the central role of smart irrigation systems in increasing water efficiency, reducing fertilizer use, and enhancing climate resilience. The combined use of soil sensors, predictive algorithms, and IoT platforms enables targeted irrigation management based on real-time data. Field studies report water consumption reductions ranging from 25% to 45%, yield increases of up to 20%, and economic returns within less than 5 years, depending on the crop type and system implemented.

### **2.1.3 Reuse of Treated Wastewater in Agriculture**

The reuse of treated wastewater is emerging as a key strategy to relieve pressure on conventional water resources. Despite its vast potential, recent estimates reveal that global wastewater reuse remains largely underexploited. While around 56% of global domestic wastewater flows were safely treated in 2020, only a small fraction—estimated globally at under 4%—was reused (WHO & UN-Habitat, 2021; UNESCO & UN-Water, 2020). Despite proven environmental and economic benefits, direct reuse often remains confined to pilot projects or localized urban and industrial contexts (World Bank, 2021).

Treated wastewater can be used to irrigate non-food crops, forage, and industrial crops and, where regulations allow and quality is ensured, even food crops. In arid and semi-arid areas such as Israel, California, and Tunisia, water recovery has already reached significant levels, playing a crucial role in ensuring production continuity and food security (Delgado et al., 2024).

From a technological standpoint, wastewater treatment—through advanced processes such as membrane filtration, ozone or UV disinfection, and reverse osmosis—yields a safe effluent that meets international health standards (Sharma et al., 2024). Reuse also contributes to closing nutrient cycles, as agricultural wastewater often contains nitrogen and phosphorus in bioavailable forms, reducing reliance on synthetic fertilizers.

The experience of the Axarquía region in Spain demonstrates the effectiveness of integrated strategies based on resilient crops, agricultural water reuse, and desalination plants powered by renewable energy. These approaches have helped reduce agricultural water deficits while also limiting climate-altering emissions by replacing groundwater withdrawals with regenerated water (Tocados-Franco et al., 2024).

However, it is important to note that recent estimates suggest the potential of treated water reuse has often been overestimated. Expósito et al. (2024) point out that in contexts like Spain, where reuse is widespread, earlier studies frequently overlooked critical factors such as the role of return flows, the availability of cheaper conventional sources, and the actual willingness to pay among agricultural users.



Moreover, water reuse actively contributes to closing nutrient cycles, as agricultural wastewater may contain nitrogen and phosphorus in bioavailable forms—reducing dependence on synthetic fertilizers.

Nevertheless, in many countries, the lack of a clear regulatory framework hampers systematic adoption. Additional challenges include perceived risks and public acceptance—especially concerning food crops (Mbavarira & Grimm, 2021). To overcome these barriers, coordinated actions are necessary:

- ✦ Establishing clear, risk-based water quality standards aligned with WHO or EU guidelines.
- ✦ Implementing targeted public awareness and education campaigns.
- ✦ Adopting participatory governance models that actively involve farmers and local communities.

## 2.2 MANUFACTURING AND CHEMICAL INDUSTRIES

### 2.2.1 Water Use in Industrial Processes and Operational Risks

Manufacturing and chemical industries are among the largest consumers of water throughout their production cycles, using water mainly for cooling, washing, material transport, chemical reactions, and steam generation. Globally, industrial water uses account for about 19% of total withdrawals, but in many advanced economies, this percentage exceeds 40%, with significant peaks in the energy, chemical, steel, and paper production sectors (UNESCO & UN-Water, 2020). For instance, producing one ton of steel can require up to 200 m<sup>3</sup> of water, while refining a barrel of oil requires between 2 and 5 m<sup>3</sup>, depending on the technologies used.

This intrinsic water dependency exposes companies to several interconnected risks:

- ✦ **Physical risks:** Water scarcity can severely limit raw water availability, leading to production reductions or even operational shutdowns.
- ✦ **Regulatory risks:** Increasing restrictions on withdrawals and discharges require companies to comply with stricter environmental standards, necessitating investments in sustainable technologies and processes.
- ✦ **Reputational risks:** Excessive or polluting water use can cause conflict with local communities and damage corporate image and reputation, impacting market performance and stakeholder relations (Mbavarira & Grimm, 2021).

A study on the U.S. manufacturing sector shows that up to 60% of industrial water withdrawals can be reduced through the implementation of already available and often economically viable technologies. These include process water reuse, thermal recovery, and improved cooling systems (Karki & Rao, 2023). Integrated industrial water management is not just an environmental necessity but a strategic competitive driver.

### 2.2.2 Strategies for Reducing, Recycling, and Reusing Process Water

Growing regulatory pressure, concrete risks linked to water scarcity, and the need to reduce costs are pushing many industries to radically reconsider their relationship with water. This has led to the emergence of multi-level strategies.

#### **REDUCING CONSUMPTION**

Reduction strategies focus on optimizing and increasing process and plant efficiency. These interventions include:



- Replacing water-intensive machinery with low-energy and low-water consumption models.
- Implementing automatic valves and real-time monitoring systems to prevent waste.
- Adopting predictive maintenance to avoid leaks and failures. In many cases, adopting 'water smart' solutions has achieved 20% to 50% reductions in medium-term consumption, with positive economic returns (Karki & Rao, 2023).

### **INTERNAL RECYCLING OF PROCESSED WATER**

- Recycling involves treating and reintroducing water into the same production cycle, drastically reducing discharge volumes and dependence on external supplies. Key enabling technologies include:
  - Membrane filtration systems (Ultrafiltration - UF, Nanofiltration - NF, Reverse Osmosis - RO).
  - Integrated biological treatments (such as membrane bioreactors - MBR).
  - Distillation systems and ion exchange. According to Sharma et al. (2024), closed-loop systems are particularly effective in high water-use industries, such as chemical production and metalworking, where they can recover up to 90% of process water, significantly lowering net water demand.

### **REUSE FOR ALTERNATIVE PURPOSES**

External reuse—using treated water for purposes other than its original use—is another strategic direction. Possible destinations include:

- Irrigation of industrial green areas.
- Cooling tower supply.
- Civil and municipal uses (where permitted by local regulations). Industrial reuse is particularly relevant in water-stressed areas, where environmental laws authorize—and sometimes encourage—treated water reuse, provided it meets specific quality standards.

### **BENEFITS AND BARRIERS**

Implementing reduction, recycling, and reuse strategies synergistically delivers tangible benefits:

- **Significant savings** on water sourcing and treatment costs.
- **Reduced indirect greenhouse gas emissions** related to water pumping and treatment.
- **Improved environmental compliance** and strengthened corporate reputation. However, large-scale adoption is still hindered by high upfront costs, regulatory uncertainty, and a shortage of technical skills, especially among Small and Medium-sized Enterprises (SMEs) (Mbavarira & Grimm, 2021).

#### **2.2.3 Regulatory Barriers, Transition Costs, and Economic Incentives**

Despite growing interest in sustainable water management strategies, industries face several regulatory, economic, and institutional barriers that require an integrated approach to overcome.

#### **REGULATORY BARRIERS**

Many jurisdictions still lack a coherent and updated regulatory framework specifically governing industrial water reuse. Key issues include:

- Uncertainty about quality standards for reuse, particularly for non-agricultural applications.
- Lack of clear technical guidelines on required treatments for specific end-uses.

- Delays in permitting processes are often due to fragmented responsibilities among local, environmental, and health authorities. In Europe, for example, while Regulation EU 2020/741 established harmonized standards for agricultural reuse, no binding EU-wide guidelines yet exist for industrial reuse (Mbavarira & Grimm, 2021), limiting project scalability in the manufacturing sector.

### **TRANSITION COSTS**

- Adopting water efficiency technologies requires significant investments, particularly for:
- Installing advanced treatment systems (e.g., membranes, AOP).
- Reconfiguring plants for internal recycling.
- Adapting production processes and monitoring systems. According to Karki and Rao (2023), the Levelized Cost of Conserved Water ranges from -4000 to +85 €/1000 m<sup>3</sup>, with negative values indicating economically advantageous solutions. However, when returns are only achieved in the medium-long term, many firms hesitate to adopt structural measures, especially without strict regulatory mandates. SMEs are particularly disadvantaged due to limited access to credit and lack of in-house technical skills.

### **ECONOMIC INCENTIVES AND SUPPORT MECHANISMS**

To overcome these barriers, many countries have introduced financial tools to support industrial water transition. The main mechanisms include:

- Tax credits for investments in 'water-efficient' technologies.
- Water tariff reductions for users who reduce pollution loads or close the water cycle.
- Soft financing programs (e.g., Horizon Europe, EIB Green Loans).
- Voluntary environmental certifications (e.g., ISO 14046, AWS Standard) that reward virtuous companies reputationally and competitively.

According to Mbavarira and Grimm (2021), combining economic incentives, procedural simplifications, and public-private partnerships is the most effective strategy to accelerate industrial water transition, especially in decentralized and high-intensity contexts.

#### **2.2.4 Manufacturing and Chemical Industries – Quantitative Analysis**

This section presents a comparative analysis of water consumption, reduction potential, and payback times for investments in water technologies across key manufacturing and chemical industry sectors. The data—covering average water consumption, reduction potential, and return on investment by sector—are based on figures from Karki & Rao (2023), integrated with North American statistics (USGS, Statistics Canada) and modelling using the Levelized Cost of Conserved Water. It's important to note that these values are indicative sector averages and may vary significantly depending on the technologies adopted and specific application contexts.

*Table 4 – Water Consumption and Reduction Potential in Industrial Sectors*

<b>Industrial Sector</b>	<b>Average Consumption (m<sup>3</sup>/ton)</b>	<b>Reduction Potential (%)</b>	<b>Payback Time (years)</b>
<b>Chemical</b>	250	55	3.2
<b>Metallurgical</b>	400	60	2.8
<b>Food</b>	120	50	4.5
<b>Paper</b>	300	45	3.7
<b>Pharmaceutical</b>	180	58	3.1

Figure 1 Average water consumption in m<sup>3</sup> per ton of product

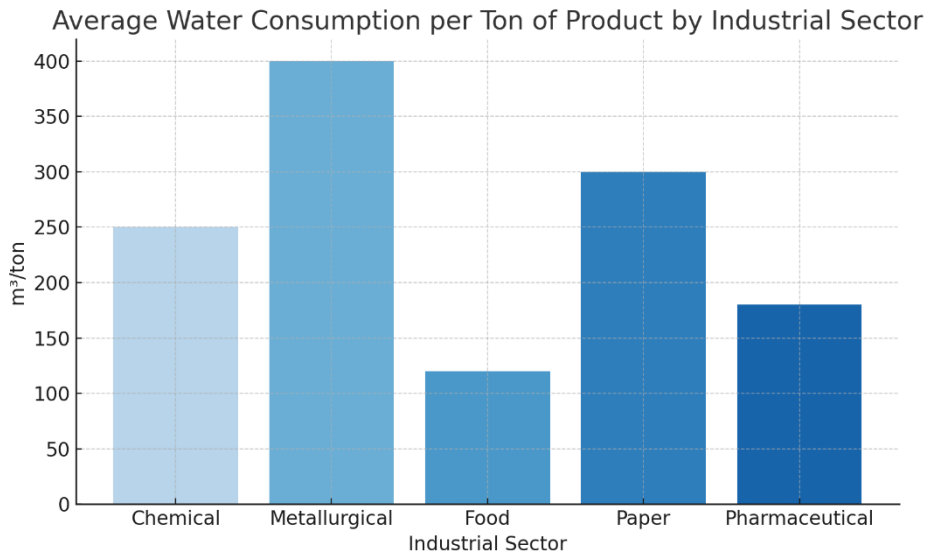


Figure 2 provides a visual comparison of average water consumption per ton of product across five industrial sectors:

- The **Metallurgical sector** is the largest consumer at 400 m<sup>3</sup>/ton, due to intensive water use for cooling and metal processing.
- The **Paper sector** follows, with 300 m<sup>3</sup>/ton, reflecting the large water input required for paper production.
- The **Chemical sector**, at 250 m<sup>3</sup>/ton, includes a range of operations from reactions and dilutions to intensive washing.
- **Pharmaceutical** and **Food** sectors, despite strict water purity requirements, show lower consumption levels at 180 and 120 m<sup>3</sup>/ton respectively.

These figures highlight which sectors should be prioritized for water efficiency interventions—especially water-intensive sectors like metallurgy and paper.

Figure 2 Water Consumption Reduction Potential by Industrial Sector

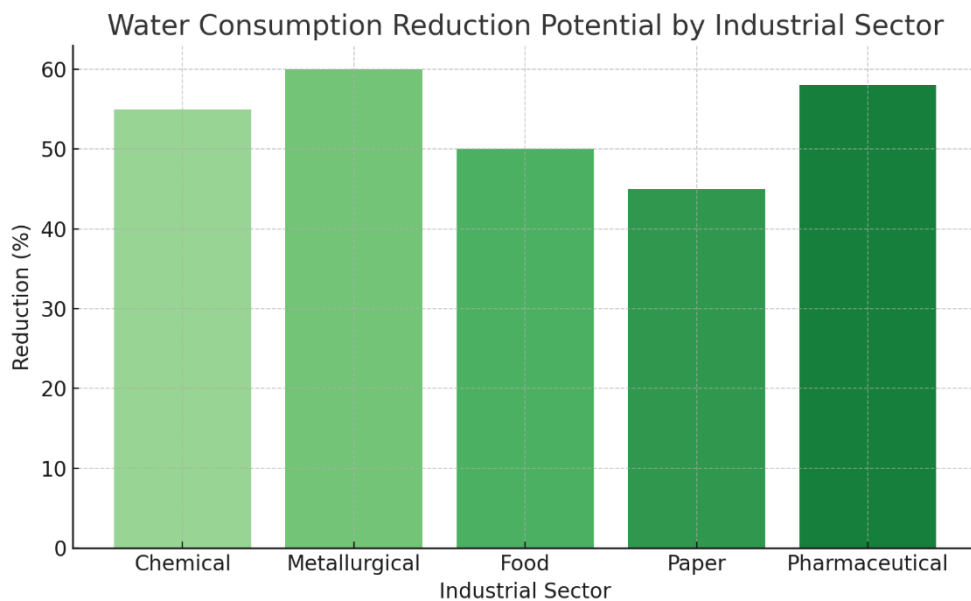


Figure 3 illustrates the potential for efficiency improvement in each sector:

- All sectors show a **reduction potential above 45%**.
- The **Metallurgical and Pharmaceutical** sectors exceed **58–60%**, thanks to measures such as closed-loop systems, dry cooling, and advanced wash water reuse.
- The **Food sector**, with a 50% potential, can also significantly reduce its water footprint through low-consumption technologies and water reuse.

These results demonstrate that even the most water-intensive industries have technically and economically viable margins to optimize their water use—transforming the challenge of scarcity into an efficiency opportunity.

Figure 3 Payback Time for Investments in Water Efficiency Technologies

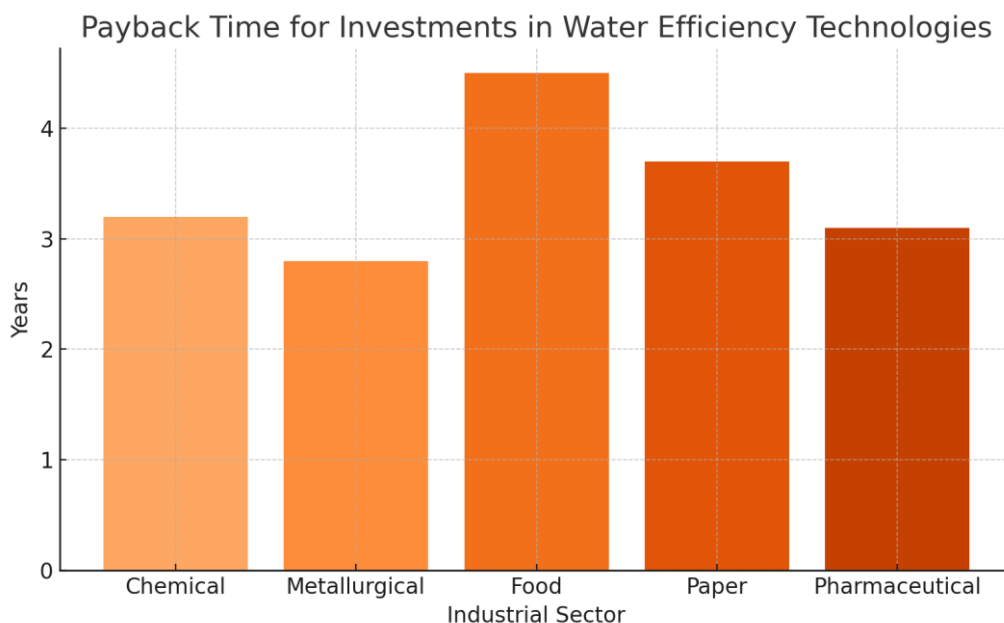


Figure 4 shows the **average time (in years) to recoup investment** in water efficiency technologies:

- A promising finding is that **all sectors report payback times below five years**.
- **Metallurgical and Chemical** sectors show the shortest periods (~3 years), due to high savings from water recovery.
- The **Food sector**, though slightly longer at **4.5 years**, remains well within economically sustainable thresholds.

This data supports the argument that investing in water technologies is not only environmentally sound but also financially beneficial within a timeframe compatible with industrial planning—especially when supported by targeted policy incentives. This fully justifies implementing political strategies to promote the widespread adoption of efficient solutions.

### 2.2.5 Water Stress in High-Tech Sectors

In addition to the water pressure from traditional industrial sectors, a growing challenge is emerging: the rapid expansion of high-tech industries. These include semiconductor manufacturing, data centres, the biopharmaceutical industry, and green hydrogen production.



Despite their differences, these sectors share a strong dependency on ultrapure water (UPW), strict quality requirements, and a high sensitivity to water supply disruptions.

For example, semiconductor production requires on average between 2,000 and 7,000 litres of ultrapure water per chip, depending on process and technology generation (ESIA, 2023; Intel, 2022). A notable case is Taiwan Semiconductor Manufacturing Company (TSMC), the global industry leader, which consumes about 150,000 m<sup>3</sup>/day—the same as a city of 600,000 people.

Similarly, modern data centres use between 2 and 5 million litres of water daily for cooling, depending on the technology (evaporative, adiabatic, or hybrid) and local climate (Uptime Institute, 2022).

In the energy sector, producing green hydrogen via electrolysis requires 9–12 litres of deionized water per kg of hydrogen. Achieving the ambitious Green Hydrogen EU Roadmap targets would imply a total water demand exceeding 21 billion m<sup>3</sup>/year by 2050 (Hydrogen Europe, 2023; IEA, 2022).

Even advanced pharmaceutical manufacturing imposes extremely high-quality water demands (e.g., WFI – Water for Injection), with cleaning and production cycles accounting for up to 20–25% of total plant energy consumption (EFPIA, 2022).

While these sectors may consume less water by volume than metallurgy or papermaking, they exert significant qualitative and operational pressure, often in densely populated and seasonally water-stressed areas. Their vulnerability to water risk directly translates into reputational, operational, and financial risk, with measurable impacts on production downtime, value loss, ESG ratings, and credit access (CDP, 2023).

According to Water Europe (2024), high-water-intensity technologies now represent one of the main challenges in aligning industrial policies, climate adaptation plans, and water governance strategies. To manage this critical issue, it's essential to shift from static allocation logic to prioritization models based on marginal value, systemic risk, and operational resilience.

An analysis conducted in the Netherlands revealed that the location of industries is strongly correlated with proximity to water sources, but also influenced by factors such as extraction rights, competition for water use, and the quality of available resources. The study highlighted that some highly industrialized regions (e.g., Noord-Brabant) are experiencing growing vulnerabilities related to water stress, with direct implications for production continuity and spatial planning. The assessment of the economic impact of water consumption by sector underscores the urgency of risk management strategies based on territorial indicators (Teo et al., 2025).

## **2.3 WASTEWATER AND SLUDGE TREATMENT**

### **2.3.1 Circular economy in wastewater treatment**

Wastewater treatment has traditionally been perceived as a "downstream" process, primarily aimed at environmental protection through discharge purification. However, with the intensification of global water scarcity and growing environmental pressures, a new paradigm based on the circular economy is emerging. In this innovative vision, water is no longer just a resource to be purified, but becomes a valuable vehicle for value recovery, through the reuse of treated effluent, energy production, and recovery of essential nutrients.

#### **FROM LINEAR MODEL TO CLOSED LOOP**

While the linear model involves simple withdrawal, use, and discharge of water, the circular approach aims to “close the loop” through various interconnected strategies:



- The direct reuse of treated effluent for multiple purposes.
- The valorisation of sewage sludge through biogas production or transformation into fertilizers.
- The recovery of critical resources such as phosphorus, nitrogen, metals, and high-quality regenerated water. According to the World Bank (2021), the integration of Circular Economy principles into water treatment systems can significantly reduce environmental footprint and generate new revenue for water operators (Delgado et al., 2024).

### **INTEGRATION OF ENABLING TECHNOLOGIES**

To implement a circular treatment plant, integration of advanced technologies is required, including:

- ✦ **Membrane Bioreactors (MBR)**, guarantee very high-quality effluents.
- ✦ **Anaerobic digestion** for biogas generation from sludge.
- ✦ **Phosphorus recovery** via precipitation in the form of struvite ( $MgNH_4PO_4$ ).
- ✦ **Advanced separation systems** such as nanofiltration and reverse osmosis, to obtain water with high purity standards. In pioneering countries like the Netherlands and Germany, these approaches are already implemented in plants operating as actual “water biorefineries,” capable of simultaneously producing energy, reusing water, and secondary raw materials (Taron et al., 2023).

### **ENVIRONMENTAL, ECONOMIC AND SYSTEMIC BENEFITS**

The advantages of adopting a circular approach are manifold and span various dimensions:

- ✦ **Reduction of dependence on primary resources** such as synthetic fertilizers.
- ✦ **Reduction of sludge disposal costs**, transforming them from waste into a resource.
- ✦ **Greater resilience of urban water systems**, making them less vulnerable to water shocks.
- ✦ **Opportunities for integration with related sectors** (energy, agriculture, industry), creating virtuous synergies. A study conducted by the International Water Management Institute (IWMI) highlighted that business models based on sludge recovery and reuse can be economically sustainable even in Global South contexts, provided they are supported by favourable regulatory frameworks and adequate strategic planning (Taron et al., 2023).

### **BARRIERS AND ENABLING FACTORS**

Despite significant technological progress, the transition to circular treatment plants is still hindered by various barriers: outdated regulations, low social acceptance of water and sludge reuse, and the lack of targeted financial incentives for operators. To overcome these obstacles, it is essential to integrate reuse and recovery into environmental regulations, promote public-private collaborations, and incentivize decentralized solutions and models of urban circular economy.

#### **2.3.2 Resource Recovery: Water, Energy, Nutrients**

Modern wastewater treatment technologies not only enable purification but also pave the way for the valorisation of regenerated water, the production of renewable energy, and the extraction



of nutrients useful for agriculture and industry. Recent estimates further reinforce the strategic role of treated water valorisation as a key asset to close the gap between water availability and demand. According to Kahn et al. (2025), the full reuse of globally available wastewater could reduce the global water gap by 9.1% under current climate conditions, with only slightly lower effectiveness even in warming scenarios up to +3°C. The potential impact is particularly relevant in highly stressed metropolitan contexts: in the city of Delhi, for example, total wastewater reuse could reduce the urban water deficit by 29.6%, while the reuse of already treated water alone would still lead to a reduction of 16.6%. These data highlight the urgent need to invest in infrastructure for advanced treatment and reuse, not only for environmental reasons but also as an effective adaptive response to increasing climate variability and demographic pressure (Kahn et al., 2025).

To enable effective valorisation of wastewater in industrial settings, it is also necessary to address the regulatory, economic, and social barriers that often hinder reuse. According to Capodaglio et al. (2023), “fit-for-purpose” reuse strategies, based on multibarrier approaches (technological and managerial), decentralized plants, and transparent communication paths with stakeholders, can overcome the main obstacles to widespread adoption. Social acceptance, in particular, proves to be a critical factor for the scalability of reuse systems and requires the integration of participatory practices, environmental education, and transparency in performance quality.

### **REGENERATED WATER RECOVERY**

Treated water can have various uses, helping to reduce dependence on primary sources:

- ♣ **Agricultural irrigation**, both for food (with adequate standards) and non-food crops.
- ♣ **Industrial uses**, such as cooling and process washing.
- ♣ **Non-potable urban uses**, such as street cleaning or supplying fountains.
- ♣ In selected cases and after advanced filtration (RO, UV, ozone), it can also be used as an **indirect potable resource**. Technologies such as membrane bioreactors (MBR), nanofiltration (NF), and reverse osmosis (RO) make it possible to obtain high-quality water. For example, in Singapore, Israel, and California, regenerated water plays a crucial role in meeting urban and industrial demand (Delgado et al., 2024).

### **ENERGY RECOVERY**

Sludge produced from biological wastewater treatment is rich in organic matter and represents an excellent source of energy production. The main energy recovery technologies include:

- ♣ **Anaerobic digestion** for the production of biogas (methane), which can be used to generate electricity or heat.
- ♣ **Pyrolysis and gasification** for the production of syngas and biochar.
- ♣ **Co-incineration** with heat recovery. According to Taron et al. (2023), anaerobic digestion can reduce sludge volume by up to 50% and produce up to 0.8 m<sup>3</sup> of biogas per kg of destroyed volatile solids, making the most advanced plants energetically self-sufficient.

### **NUTRIENT RECOVERY**

Sewage sludge and treated effluents contain key macronutrients for agriculture: nitrogen (N), phosphorus (P), and potassium (K). Recovering these nutrients reduces dependence on synthetic fertilizers, whose production cycle is energy-intensive and often geopolitically vulnerable. Emerging technologies allow:



- ♣ The precipitation of phosphorus as struvite ( $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ ).
- ♣ The recovery of nitrogen as ammonia or nitrates.
- ♣ The agronomic valorization of digestate. In Germany, new regulations (AbfKlärV) require the mandatory recovery of phosphorus from plants with a capacity over 50,000 Population Equivalent (PE) starting from 2029, encouraging the spread of these technologies (Taron et al., 2023).

### **THE ECONOMIC AND ENVIRONMENTAL VALUE OF INTEGRATED RECOVERY**

Simultaneous recovery of water, energy, and nutrients offers several benefits:

- ♣ Reduction in sludge disposal costs.
- ♣ Reduction of greenhouse gas emissions.
- ♣ Generation of reusable and marketable products.
- ♣ Contribution to SDG goals (especially 6, 7, 12, and 13).

A study conducted by IWMI estimates that integrated recovery and reuse models can reduce overall operating costs by more than 25%, while also generating new revenue for water service operators (Taron et al., 2023).

#### **2.3.3 Innovative Business Models and Scalability of Solutions**

The large-scale implementation of circular economy practices in wastewater and sludge treatment cannot be separated from the adoption of new business models capable of harmoniously integrating environmental sustainability, economic efficiency, and social value. These innovative models aim to overcome the traditional “utility-centric” approach, paving the way for public-private partnerships, performance-based investments, and market logic for resource recovery, transforming treatment plants into true water bio-refineries.

**"Resource-as-a-Service" Models:** One of the most promising emerging models is that of “resource-as-a-service,” where water service managers no longer limit themselves to selling “treatment,” but actively offer recovered resources: regenerated water, fertilizers, energy, and biomaterials. Plants thus become hubs of circular production, generating multiple revenue streams:

- ♣ **The sale of reclaimed water** to public entities or local industries for non-potable uses.
- ♣ The **commercialization of fertilizers** derived from struvite or sludge compost.
- ♣ The **generation of energy** for self-consumption or grid sale (e.g., biogas or syngas). This model is already in operation in advanced plants in Belgium, the Netherlands, Germany, and Sweden, where operators have developed dynamic local markets for treatment by-products (Mbavarira & Grimm, 2021; Taron et al., 2023).

**Public-Private Hybrid Models (PPP):** The intrinsic risk management of technological complexity and large-scale investment makes PPP hybrid models strategic, where private actors bring specialized expertise and capital in exchange for shared benefits. This has led to the spread of:

- ♣ **DBOO contracts** (Design-Build-Own-Operate), entrust the private party with design, construction, ownership, and plant operation.
- ♣ **Joint ventures** for the management of digestion and valorisation plants.



- ✦ **Multi-service concessions** with extended responsibilities for treatment and resource recovery. These configurations prove particularly effective in urban or industrial high-density contexts, where scale allows significant economies of scale and learning (Delgado et al., 2024).

**Performance-Based Schemes:** New financial tools tied to environmental sustainability, such as green bonds and environmental performance contracts, are incentivizing the development of plants oriented towards the concept of “zero waste.” In these schemes, the economic return for the investor or operator is directly tied to the quantity and quality of recovered resources, rather than just the amount of water treated.

This approach reduces long-term costs for society and contributes to improving the overall resilience of the water system.

**Decentralized Micro plants:** The scalability of circular solutions depends on a combination of factors, including:

- ✦ The **size of the plants**, with greater recovery potential in those exceeding 100,000 Population Equivalent (PE).
- ✦ **Local demand for secondary resources**, for example from nearby peri-urban agriculture or industrial districts.
- ✦ The **presence of favourable policies**, such as incentivizing tariffs, specific recovery obligations, and clear environmental standards.
- ✦ In the Global South, IWMI (2023) has documented success stories in which decentralized micro-plant models, managed by local cooperatives or social startups, have produced fertilizers and water for urban agriculture in a financially sustainable way. These successes were made possible by a combination of low-tech innovation, access to microcredits, and strong integration with local urban policies.

Business models for the valorisation of wastewater and sludge are moving toward multi-product, multi-actor, and multi-sector approaches. Their scalability will depend on the ability to create local ecosystems that connect the supply and demand of regenerated resources.

## 2.4 INTERSECTORAL INTERCONNECTIONS AND SYNERGIES IN THE WATER CYCLE

Water is a resource that cuts across all sectors; therefore, to understand its use, it cannot be analysed in a compartmentalized manner.

Agriculture, industry, the urban sector, and advanced technologies not only compete for water resources, but also cooperate in their use.

A sustainable and resilient governance must therefore consider the systemic interconnections between sectors, going beyond the simple analysis of direct consumption.

### 2.4.1 Competition for the Resource

In contexts characterized by high water stress (indicated by a WEI+ > 20%), access to water generates significant competitive dynamics between economic sectors and civil use, especially during summer months or periods of prolonged drought.

The main areas of tension occur between:

- ✦ **Agricultural irrigation and urban supply**, as seen in regions such as Southern Italy or Eastern Spain, where the water needs of agriculture may conflict with civil demands.

- ✦ **Energy-intensive industrial sectors and digital technologies**, with examples like cooling for data centres or electrolysis for green hydrogen production, which require large volumes of water.
- ✦ **Environmental protection and ecosystem conservation versus economic uses**, regarding the need to ensure minimum ecological flows for the health of aquatic ecosystems (Vanham et al., 2021).

These competitions involve opportunity costs, making transparent allocation tools and intersectoral compensation mechanisms necessary for a fairer and more efficient management of the resource (OECD, 2022).

#### 2.4.2 Synergies through Reuse and Symbiosis

Alongside competitive dynamics, numerous technically feasible synergies can reduce systemic pressure on the water resource and improve the overall efficiency of the cycle:

- ✦ **Urban effluent for agricultural irrigation**: The reuse of treated wastewater for irrigation purposes, including through constructed wetlands, is a virtuous example of symbiosis between the urban and agricultural sectors.
- ✦ **Treated industrial water for non-potable urban uses**: Adequately treated industrial waters can be reintroduced into the urban cycle for uses such as street washing or public green irrigation.
- ✦ **Sludge and agro-industrial waste for biogas/struvite production**: The valorisation of treatment sludge and agro-industrial waste for the recovery of nutrients (such as phosphorus in the form of struvite) and the production of energy (biogas) creates a virtuous loop.
- ✦ **Cooling water from data centres for district heating networks**: Waste heat water from data centres can be used to supply district heating networks, as already happens in Amsterdam and Singapore, turning a “waste” into an energy resource.

These industrial-water symbiosis models can be systematically integrated into high infrastructure density contexts through the development of **Water-Oriented Living Labs** (Water Europe, 2024), which serve as real experimental environments for innovative solutions.

#### 2.4.3 Towards Integrated Planning

To promote smart and sustainable intersectoral water use, it is essential to adopt integrated water planning tools, including:

- ✦ **Multisectoral water balances**: The use of frameworks such as the **UN SEEA-Water** (System of Environmental-Economic Accounting for Water) allows for a holistic view of water flows.
- ✦ **Environmental accounting with cross-sector flows**: To track and evaluate the interchange of resources between different sectors.
- ✦ **Indicators of intersectoral co-benefits**: To measure not only the direct benefits but also the indirect and synergistic ones (e.g., avoided greenhouse gas emissions, fertilizing value from nutrient recovery, improved urban water security).

Moreover, it is essential to strengthen coordination mechanisms among key actors (agriculture, utilities, industry, and local authorities) through the development of stable, multilevel platforms. Only a collaborative and integrated approach can ensure the long-term sustainability of the water resource in the face of growing environmental and demographic challenges.

## 2.5 TABLES AND COMPARISONS

### 2.5.1 table comparing recovery technologies from wastewater and sludge

Type	Technology	Resource Recovered	Estimated Efficiency (%)	Maturity Level
Regenerated Water	Reverse Osmosis (RO)	Water for potable/industrial reuse	95	Advanced
Regenerated Water	Membrane Bioreactor (MBR)	Water for agricultural/urban use	85	Advanced
Energy	Anaerobic Digestion	Biogas	60	Widespread
Energy	Pyrolysis/Gasification	Syngas, biochar	40	Emerging
Nutrients	Struvite Precipitation	Phosphorus (P)	70	Widespread
Nutrients	Ammonia Separation	Nitrogen (N)	50	Emerging

### 2.5.2 Summary Table of Key Strategies and Main Critical Issues

Sector	Key Strategies	Main Critical Issues
<b>Agrifood</b>	Precision irrigation, reuse of treated effluents, digital monitoring	High climate vulnerability, losses, regulatory limits on reuse
<b>Manufacturing</b>	Internal recycling, process optimization, plant digitalization	High initial investment costs, localized water scarcity, regulation constraints
<b>Wastewater Treatment</b>	MBR, AOP, anaerobic digestion, nutrient recovery and water reuse	Fragmented regulation, operational costs, social acceptance issues

### 2.5.3 Table of Business Models for Wastewater and Sludge Treatment

Model	Description	Application Examples	Main Advantages
<b>Resource-as-a-Service (RaaS)</b>	Sale of resources recovered from treatment processes	Regenerated water, fertilizers, energy	Revenue diversification, circular economy
<b>Public-Private Partnerships (PPP)</b>	Collaboration between public and private entities in plant management	DBOO contracts, joint ventures	Risk sharing, access to expertise and capital
<b>Performance-Based Schemes</b>	Financial models tied to achieved results	Green bonds, performance contracts	Efficiency incentives, reduced operating costs
<b>Decentralized Microplants</b>	Small plants managed locally	Containerized plants for agriculture	Flexibility, adaptability, reduced distribution costs

## 2.6 KEY POINTS

### **The agri-food sector is the largest water consumer.**

With around 70% of global withdrawals, agriculture is intrinsically dependent on water resources and particularly vulnerable to the impacts of climate change. The critical intervention point is irrigation, through the adoption of precision technologies and the safe reuse of water (Liu et al., 2022; Rastogi et al., 2024).

### **Manufacturing industries face increasing operational risks.**

Water scarcity can compromise production continuity, raise costs, and affect regulatory compliance. Water efficiency and internal water recycling are becoming key factors for industrial competitiveness and resilience (Karki & Rao, 2023).

### **Wastewater treatment is shifting from cost to resource.**

The adoption of advanced technologies such as Membrane Bioreactors (MBR), Advanced Oxidation Processes (AOP), and nutrient recovery is enabling treatment plants to become true circular hubs. These plants can produce regenerated water, energy (biogas), and green fertilizers, reaching a potential of up to 80% energy self-sufficiency (Taron et al., 2023).

### **Effective sectoral solutions exist, but scalability remains a challenge.**

Technologies for water efficiency and resource recovery are ready and available. However, their large-scale adoption is still hindered by widespread barriers, including the lack of clear standards, high initial costs, and regulatory and cultural resistance. To replicate success stories, effective coordination, targeted incentives, and the development of public-private partnerships are essential.

### **A differentiated yet integrated approach is necessary.**

Each sector presents specific needs and constraints regarding water management. However, the key to a sustainable transition lies in systems integration (e.g., agricultural use of industrially treated wastewater or the creation of shared water districts) and in building circular and cooperative ecosystems among the different stakeholders.

### 3 MEASURING WATER EFFICIENCY

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As observed by Lord William Thomson Kelvin: "If you cannot measure it, you cannot improve it."

This maxim is particularly apt when discussing water efficiency, which represents one of the key indicators for evaluating the sustainability of productive, urban, and natural systems. Consistently and comparably measuring the ratio between water use and results obtained is essential for planning effective interventions, monitoring progress, and identifying priority areas for action.

#### 3.1 QUANTITATIVE INDICATORS: WATER FOOTPRINT, WATER STRESS, SECTORAL PERFORMANCE

Quantitative indicators offer valuable tools for assessing the intensity of water use, the level of water stress a system is subjected to, and sectoral performance compared to regional or international benchmarks.

##### WATER FOOTPRINT (WF)

The concept of the Water Footprint (WF), developed by Hoekstra et al. (2011), is an indicator that measures the total volume of freshwater used to produce a good or service. This concept is divided into three main components:

- ♣ **Blue Water:** Refers to water withdrawn from surface or groundwater sources, such as rivers, lakes, and aquifers.
- ♣ **Green Water:** Indicates soil moisture originating directly from rainfall and stored in the root zone, used by vegetation for growth.
- ♣ **Grey Water:** Represents the volume of freshwater needed to dilute pollutants released during production to acceptable quality standards.

To provide a concrete reference for the average water footprint associated with major consumer goods, here are some examples: for beef, the value is around 15,000 litres per kilogram; for rice, the average water footprint is estimated at approximately 2,500 litres per kilogram; while for cotton, the water requirement is around 10,000 litres per kilogram. Such estimates highlight the high intensity of water use in production processes and emphasize the need for mitigation strategies aimed at efficient and sustainable water use (Hoekstra & Chapagain, 2007; Mekonnen & Hoekstra, 2011).

This indicator proves extremely useful for comparing the water footprint of different products, regions, and production strategies. The WF concept is also integrated into numerous voluntary standards, such as ISO 14046.

##### WATER STRESS

Water stress is defined as the ratio of total annual freshwater withdrawals to total renewable freshwater resources, according to the UN SDG indicator 6.4.2. A situation is considered to be under severe stress when this ratio exceeds 40% (UN-Water, 2020). However, more advanced analyses suggest that this measure is incomplete if it does not also consider the quality of available water (van Vliet et al., 2021).

The most up-to-date data shows an alarming picture:

- ♣ In 2022, approximately 2.4 billion people lived in countries affected by water stress, an increase from previous years (UNESCO & UN-Water, 2024).



- 25% of the global population is exposed to "extremely high" water stress, meaning they use over 80% of their annually available freshwater resources (WRI, 2023).
- Globally, the SDG 6.4.2 indicator reached 18.6% in 2021, an increase of 2.8% compared to 2015 (FAO & UN-Water, 2024).
- By 2050, approximately 60% of the world's population could be affected by water stress for at least one month per year (WRI, 2023).
- In Europe, in 2022, water scarcity affected 34% of the EU territory during at least one season; approximately 30% of the European population lives in areas with permanent water stress, while 70% experience seasonal summer stress (EEA, 2025).

Van Vliet et al. (2021) propose an integrated approach that also includes surface water quality (salinity, organic pollutants, nutrients, temperature) as a key determinant of water stress. This approach reveals that the proportion of the global population affected by severe water scarcity increases from 30% (based only on quantity) to 40% if quality is included. Conditions are particularly critical in Eastern China, India, the Middle East, Mexico, and the Mediterranean basin, where pollution from agricultural, urban, and industrial wastewater amplifies quantity-related limitations.

The analysis also highlights the potential contribution of "clean" water technologies, such as desalination and treated wastewater reuse, in reducing water stress. An expansion of desalination (from 2.9 to 13.6 billion m<sup>3</sup>/month) and wastewater reuse (from 1.6 to 4.0 billion m<sup>3</sup>/month) could reduce the global population exposed to severe stress from 40% to 14% (van Vliet et al., 2021). However, these solutions require careful evaluation of energy costs, emissions, residue management (e.g., brine), and social acceptability.

Finally, Water Stewardship tools, such as the AWS (Alliance for Water Stewardship) protocol, allow for the application of stress indicators also at the basin level, promoting coordinated actions among different users and sectors (AWS, 2019).

### **SECTORAL PERFORMANCE**

To evaluate sectoral water efficiency, specific indicators are used, such as:

- m<sup>3</sup> of water per ton of product (industry, agriculture).
- litres per kWh (thermoelectric energy).
- litres per inhabitant per day (urban water cycle).
- economic productivity of water (Water Productivity) expressed in €/m<sup>3</sup> or \$/m<sup>3</sup>.

Water consumption varies significantly depending on the sector of use and the geographical context. For example, steel production requires an average of 120 to 200 cubic meters of water for every ton of steel produced, depending on the technology employed and the efficiency of the plants (Karki & Rao, 2023). In agriculture, rice irrigation is one of the most water-intensive practices, with consumption generally ranging between 3,000 and 5,000 cubic meters per hectare, depending on the irrigation system adopted and local agro-climatic conditions (Uhlenbrook et al., 2022). Even in urban areas, water consumption shows wide variations: per capita use is estimated between 100 and 250 litres per inhabitant per day, with marked differences due to socioeconomic, infrastructural, and cultural factors (Millington & Scheba, 2020; Vanham et al., 2021).

Benchmarking this data against sectoral standards and best practices allows for:



- ✦ Identifying areas for improvement.
- ✦ Evaluating the return on investment in efficiency.
- ✦ Integrating reduction targets into ESG reports and environmental statements.

When these indicators become part of regulations, industry standards, or corporate environmental statements, they become valuable allies for conscious and transparent water management.

#### **Operational Note: Water Productivity – The Limits of the Economic Indicator**

The indicator of "economic water productivity" (expressed in €/m<sup>3</sup> or \$/m<sup>3</sup>) is widely used to compare water efficiency across sectors and regions. However, if used alone, it can create an illusion of efficiency, as it reflects neither water scarcity nor environmental impacts. Ozcelik et al. (2024) show that the growth in economic output associated with a reduction in withdrawal does not necessarily imply an improvement in sustainability: it may be a spurious decoupling, linked to price increases or macroeconomic variations, rather than real water optimization.

It is therefore recommended to integrate it with biophysical metrics (e.g., Physical Water Productivity in kg/m<sup>3</sup>) and with contextual indicators such as the Water Stress Index and the degree of pressure on natural water capital. This approach helps avoid overestimating efficiency and improves the ecological readability of corporate and territorial strategies.

#### **3.1.1 Physical and Qualitative Limits to Real Water Availability**

Water efficiency cannot be evaluated solely in volumetric terms. The real availability of water resources is, in fact, strongly conditioned by a series of physical limits (accessibility, seasonality, climatic stress) and qualitative limits (chemical contaminants, organic loads, pathogens) that determine its suitability for agricultural, industrial, and civil uses (Jones et al., 2024; Biswas et al., 2025).

##### **PHYSICAL LIMITS TO ABSTRACTION AND WITHDRAWAL**

- ✦ **Topographic accessibility:** Water basins and groundwater aquifers may be inaccessible due to altimetric barriers (e.g., mountainous reliefs) or unfavourable geological conditions that hinder abstraction techniques (Biswas et al., 2025).
- ✦ **Unstable seasonal regime:** In many river basins, particularly Mediterranean ones, the marked intra-annual variability of precipitation makes reliable withdrawal possible only in limited periods of the year, aggravating the problem of intermittent useful flows (Jones et al., 2024).
- ✦ **Climatic stress:** Extreme climatic events, such as persistent droughts and torrential rains, profoundly alter the natural recharge of surface and groundwater reserves. This seriously compromises forecasts of future availability (Biswas et al., 2025; Zhang et al., 2022).

##### **QUALITATIVE LIMITS TO USABILITY**

Water, even when available in abundance, may be unsuitable for many uses due to exceeding critical regulatory thresholds established by international regulations (WHO, 2020; EU Reg. 741/2020). Table 5 summarizes the main limiting parameters of water.

Table 5 Limits to water usability. Source: WHO (2020), ISO 16075, EU Reg. 741/2020, Legislative Decree 152/06.

Parameter	Typical Critical Limit (EU/WHO)	Impact on Reuse
Salinity (EC)	1.5–3.0 mS/cm	Phytotoxicity, damage to irrigation systems
Nitrates	50 mg/L	Health risk, eutrophication
COD/BOD	125/25 mg/L	Incompatibility with industrial uses
Pathogens (E. coli)	0 CFU/100 ml (for potable use)	Excludes direct urban reuse
Heavy metals (e.g. Pb)	<0.01 mg/L	Bioaccumulation in the food chain

The quality of water conditions the real efficiency of the resource more than the theoretical quantity available. Reuse strategies must therefore be based on a joint analysis of water flows and their qualitative composition (Jones et al., 2024). For example:

- Urban wastewater can only be used for irrigation if it meets stringent microbiological limits (e.g., <1000 CFU/L for E. coli; EU Reg. 741/2020).
- Coastal groundwater can undergo salinization due to marine intrusion, making it unsuitable for agricultural irrigation (Jones et al., 2024; Zhang et al., 2022).

Various territorial contexts emblematically highlight the criticalities related to water resource management and reuse.

In India, the Delhi metropolitan area represents a case of inefficiency in wastewater treatment: only 15% of urban wastewater undergoes adequate treatment, while most of it presents high levels of heavy metal contamination and organic loads, making any form of safe reuse impractical (Kahn, 2025).

In the Mekong Delta, the exacerbation of groundwater and soil salinization – due to concomitant factors such as sea-level rise, anthropogenic subsidence, and aquifer overexploitation – has transformed the area into a regional water hotspot. According to Lindner and Stamm (2025), such pressures have severely compromised local water security. Leijnse et al. (2024) estimate that approximately 36% of the delta's surface shows water degradation conditions that constitute high vulnerability, with significant impacts on the agricultural and peri-urban sectors.

Even in European contexts with apparent water availability, such as the Emilia-Romagna region in Italy, significant limitations are found. In particular, the quality of surface waters intended for reuse in irrigation is compromised by the widespread presence of nitrates and pesticides, with restrictive effects on the use of non-conventional water resources in agricultural districts (ISPRA, 2023).

### **CASE STUDY – INDIA: SUSTAINABILITY VS. APPARENT EFFICIENCY**

Apparent efficiency in irrigation use can mask structural criticalities if the physical limits of the water system, particularly the sustainability of aquifers, are not considered. An emblematic case of structural imbalance between efficiency and physical limits is illustrated in the study by Rajput et al. (2024), where it was shown how excessive groundwater withdrawal for rice cultivation is causing an annual deficit of 10–15% in the districts of Kaithal and Karnal. The approach based on Water Accounting+ made it possible to quantify the gap between withdrawal, natural recharge, and irrigation needs, highlighting how some agricultural practices are not compatible with resource regeneration. The model suggests that delaying rice transplantation by 15–20 days could significantly reduce overdrafts, aligning demand with the monsoon window.



Such results underscore the importance of integrating efficiency indicators with basin-scale water balances and real hydro-climatic scenarios to avoid "efficient but unsustainable" policies.

### 3.2 MONITORING AND REPORTING TOOLS FOR INDUSTRIAL MANAGEMENT

Monitoring and reporting water consumption are essential tools for evaluating the efficiency of industrial operations, supporting data-driven decisions, and ensuring regulatory and environmental compliance. However, effective monitoring cannot be limited to quantitative aspects; it's increasingly crucial to also include water quality parameters. Recent studies show that pollution from salts, organic compounds, and pathogens severely compromises the actual availability of the resource for industrial and civil uses. According to Jones, Bierkens, and van Vliet (2024), 55% of the world's population is already exposed to clean water scarcity for at least one month per year, a percentage projected to increase to 66% by 2100. This highlights how the quality of surface waters directly influences the ability of water systems to meet demand, even when theoretically adequate water volumes are present. Integrating qualitative parameters into monitoring systems is therefore essential to ensure truly sustainable and resilient water resource management.

#### **REAL-TIME MONITORING SYSTEMS**

Digital technologies are revolutionizing the monitoring of water flows within industrial plants. Key tools include:

- ✦ **IoT (Internet of Things) Sensors:** For continuous measurement of flow rates, pressures, leaks, and water quality parameters.
- ✦ **Smart Metering:** For precise monitoring of consumption per individual production line.
- ✦ **SCADA (Supervisory Control and Data Acquisition):** For centralized and automated plant management, enabling remote control and process optimization.
- ✦ **Cloud-based Platforms:** For predictive data analysis and benchmarking performance across different production sites.

Integrating these tools allows for the creation of **normalized water consumption models** (e.g.,  $\text{m}^3/\text{unit of product}$ ), which are essential for identifying inefficiencies, intervening promptly, and optimizing resource use, shifting from reactive to proactive management. Further details are in Chapter 4.

#### **KEY WATER PERFORMANCE INDICATORS (KPIs)**

Adopting **KPIs** enables companies to measure water performance in a comparable and standardized way. Among the main ones are:

- ✦ **Water Intensity** ( $\text{m}^3/\text{unit of product}$ ).
- ✦ **Recirculation Rate** (percentage of recycled water relative to total consumption).
- ✦ **Discharge Quality Index** (compliance with environmental standards).
- ✦ **Internal Reuse Capacity** (% of treated water reused in the process).

These indicators are integrated into environmental management systems (e.g., ISO 14001) and ESG reporting.



## **VOLUNTARY REPORTING AND INTERNATIONAL FRAMEWORKS**

Many companies report their water impact within globally recognized frameworks. Keys among them are:

### **🔩 CDP Water Security**

- The Carbon Disclosure Project invites companies to report water risks and strategies. The "Water" questionnaire allows for a detailed assessment of governance, metrics, and resilience (CDP, 2023).

### **🔩 GRI 303: Water and Effluents (2018)**

- The Global Reporting Initiative (GRI) requires details on withdrawals, discharges, impacts, and strategies to improve water management in sustainability reports.

### **🔩 ISO 14046 – Water Footprint**

- Provides guidelines for quantifying the water footprint of processes, products, and organizations, also considering associated environmental impacts.

### **🔩 AWS Standard (Alliance for Water Stewardship)**

- A multi-stakeholder standard that guides companies in responsible water management at the basin scale, valuing stakeholder engagement.

## **INTEGRATION INTO DECISION-MAKING PROCESSES**

Monitoring and reporting tools are most effective when integrated into an organization's operational, financial, and environmental management systems. Leading companies use interactive dashboards that offer real-time insights into water performance, link water metrics to overall economic performance, and establish specific, measurable reduction targets.

A key example of this integration is the increasing use of Artificial Intelligence (AI) for predictive optimization, especially in water-intensive sectors like food & beverage. Companies like Coca-Cola HBC, for instance, use IoT sensors and SCADA systems to monitor water consumption in real-time. AI algorithms analyse this data to identify anomalies, predict water demand, and optimize water use (for example, for cooling or cleaning). This not only leads to a reduction in actual consumption and operational costs but also contributes to improving profit margins. Aggregated data, including financial impacts, are presented in management dashboards to guide the setting of new targets and strategic decisions.

### **Geospatial benchmarking and executive dashboard**

The introduction of dynamic benchmarks based on geospatial data and smart dashboards for industrial management allows for continuous control of critical parameters. These solutions combine geospatial analysis and business intelligence systems capable of integrating environmental, operational, and management data in real-time. The use of geo-referenced dashboards enables interactive visualization of water performance at urban, industrial, or territorial scales, supporting dynamic comparisons between regions, plants, and periods. According to Dasallas et al. (2024), the KPI framework developed in European urban contexts allows for a comparative evaluation between cities and water districts, guiding decisions towards intelligent and resilient practices.

### 3.3 INTEGRATED ASSESSMENTS: WATER ACCOUNTING, COST-BENEFIT ANALYSIS, AND SDG 6.4

Beyond using technical indicators to assess water efficiency, it's crucial to adopt integrated approaches that encompass environmental, economic, and social dimensions. Tools like water accounting, cost-benefit analysis (CBA), and alignment with the Sustainable Development Goals (SDG), particularly Target 6.4, are fundamental assets for guiding strategic decisions, promoting sustainable investments, and monitoring progress.

In addition to these tools, there is growing interest in applying multidimensional metrics to evaluate the sustainability of decentralized and integrated wastewater treatment and reuse systems (IRSSs). These metrics include indicators of water efficiency, treated effluent quality, climate resilience (e.g., ability to respond to extreme events), and the level of regulatory and institutional integration. According to Panepinto et al. (2023), an approach based on these parameters allows for a more complete evaluation of the technical and environmental adequacy of interventions, facilitating the comparison between solutions, transparency in decisions, and their alignment with circular economy principles.

#### **WATER ACCOUNTING**

**Water accounting** is an analytical tool that systematically tracks water flows—inflow, outflow, use, recycling, and losses—within a physical or economic system (UNESCO, 2020). It's used to:

- ♣ Quantify water availability, demand, and actual uses.
- ♣ Identify inefficiencies and waste within water systems.
- ♣ Support the development of more effective allocation and pricing policies.

There are two main approaches:

- ♣ **Physical water accounting:** Measures the real volumes of water withdrawn, used, returned, or lost (in m<sup>3</sup>).
- ♣ **Economic water accounting:** Evaluates the economic value of different water uses and available resources, following methodologies similar to environmental accounting (SEEA-Water, System of Environmental-Economic Accounting for Water).

The combined use of both approaches is recommended to integrate water management plans with comprehensive sustainability and efficiency objectives.

A recent and promising evolution in water accounting is the integration of indicators inspired by circular economy principles:

- ♣ **Water Circular Economy Index (WCEI):** Measures the degree of circularity of water used in a territorial or productive system, integrating indicators of withdrawal, reuse, losses, environmental reintegration, and water self-sufficiency (Pot, 2023).
- ♣ **Net Water Value (NWW):** Evaluates the net economic value generated by each cubic meter of water withdrawn, considering direct and indirect benefits as well as the environmental, social, and regulatory costs associated with resource use (Vardon, Obst, & La Notte, 2025).



## **COST-BENEFIT ANALYSIS (CBA) APPLIED TO WATER EFFICIENCY**

**Cost-benefit analysis (CBA)** is a well-established methodology for evaluating the economic profitability and the social and environmental impact of water efficiency interventions. Key elements analysed include:

- ♣ **Costs:** Investment, operating, and maintenance costs of interventions.
- ♣ **Direct benefits:** Water and energy savings, reduced emissions, lower tariffs.
- ♣ **Indirect benefits:** Improved corporate reputation, reduced regulatory risk, valorization of by-products.

According to ISPRA (2022), in many industrial and agricultural contexts, CBA shows a benefit/cost ratio greater than 2, especially with public financial support and a water value exceeding €0.5/m<sup>3</sup>. The analysis is often integrated with multi-criteria methods (MCA) to include qualitative aspects (such as equity, social acceptability, and territorial impacts) and to support decisions under hydrological and climatic uncertainty (La Rosa, 2019).

## **KPIs AND NATURE-BASED SOLUTIONS: TOWARDS AN INTEGRATED ASSESSMENT OF EFFICIENCY AND RESILIENCE**

In the context of increasing attention to environmental sustainability, Key Performance Indicators (KPIs) for water are essential tools for transparently and comparably evaluating the performance of organizations and companies. However, the excessive or unselective use of these indicators can generate redundancies and distortions in ESG reporting. As demonstrated by Benuzzi, Şahin, and Paterlini (2025), only 20% to 25% of commonly used KPIs truly explain the variance in ESG scores, suggesting the urgent need to rationalize metrics and focus more on informational quality.

Water efficiency assessments are limited if they don't also consider the ecosystem co-benefits and indirect impacts of adopted solutions. In this sense, Nature-Based Solutions (NBS)—such as vegetated buffer strips, artificial wetlands, and managed aquifer recharge (MAR)—can offer comparable or superior results to conventional technologies, with advantages in terms of biodiversity, carbon sequestration, and hydrogeological risk mitigation.

Marijuan et al. (2024) propose a multidimensional Key Performance Indicator (KPI) matrix to evaluate the efficiency of NbS in the context of water security.

The framework includes:

- ♣ Volume of water treated or saved (m<sup>3</sup>/ha/year).
- ♣ Reduction of risk from extreme events (flood/drought buffer).
- ♣ Increase in socio-ecological system resilience (qualitative and quantitative indicators).
- ♣ Alignment with the global IUCN standard for NBS.

The systematic inclusion of such KPIs in integrated assessments allows for an analytical leap in scale: from process efficiency to systemic effectiveness. Therefore, the use of these frameworks in water balances and corporate and territorial sustainability assessments is recommended.

## **CIRCULARITY INDICATORS FOR WATER PROCESSES**

To more accurately assess the degree of water circularity in industrial processes, it is useful to adopt analytical tools such as the Process Circularity Index (ProCI), recently proposed by



Pilipenets et al. (2025). This framework integrates flows of materials, energy, water, and emissions, enabling a more detailed and comparable evaluation of circularity across sectors.

In the water component, ProCI specifically evaluates the share of water that is reused, recycled, or recovered relative to the total consumed. It includes indicators related to the type of treatment (e.g., MBR, RO), the quality level (fit-for-purpose), and the presence of lost or evaporated flows. In addition, it accounts for the energy required per cubic meter treated and the associated emissions, thus offering an integrated efficiency measure that combines environmental sustainability, operational performance, and ecological footprint reduction.

The adoption of indices like ProCI can strengthen ESG metrics and support reporting aligned with the EU taxonomy.

**Data Quality and Statistical Relevance of Water Indicators**

The validity of water efficiency assessments heavily depends on the quality, completeness, and reliability of the data used.

Incomplete, noisy, or systematically biased datasets can undermine the robustness of indicators, leading to misleading conclusions.

Uddin et al. (2024) show that applying data cleaning and outlier detection techniques — such as Isolation Forest (IF) and Kernel Density Estimation (KDE) — can significantly enhance the reliability of composite indicators like the Integrated Environmental Water Quality Index (IEWQI), increasing the coefficient of determination from  $R^2 = 0.92$  to  $R^2 = 0.95$ .

The following table summarizes some key techniques:

Method	Water-related Application	Main Advantages
Isolation Forest	Detection of physicochemical outliers (pH, TDS)	Unsupervised, noise-robust
KDE	Seasonal anomaly patterns	Flexible, adaptive interpolation
IQR / Z-score	Preliminary data cleaning	Simple implementation

Integrating these methods into monitoring systems enables more effective handling of measurement errors, supporting more reliable and comparable indicators across sectors and over time.

**SUSTAINABLE DEVELOPMENT GOAL 6.4: EFFICIENCY AND AVAILABILITY**

Target SDG 6.4 of the 2030 Agenda aims to:

*"Substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity."*

Two key indicators are associated with this objective:



- **6.4.1:** Measures the change in water-use efficiency over time (expressed in USD/m<sup>3</sup>).
- **6.4.2:** Assess the level of water stress by renewable freshwater withdrawal (expressed as a %).

The adoption of harmonized methodologies for the calculation and reporting of these indicators is strongly encouraged by both UNEP and Eurostat, in order to promote multi-level, transparent, and consistent governance of water resources.



### 3.4 TABLES AND COMPARISONS

#### 3.4.1 Comparative Table of Water Efficiency Indicators

Indicator	Simplified Description	Unit of Measure	SDG Link
<b>Water Footprint (WF)</b>	Total amount of water used, including "hidden" water in production	m <sup>3</sup> , m <sup>3</sup> /kg, m <sup>3</sup> /\$	SDG 6.4.1
<b>Water Use Efficiency (WUE)</b>	Output obtained per cubic meter of water used	\$/m <sup>3</sup> , kg/m <sup>3</sup>	SDG 6.4.1
<b>Water Stress Index (WSI)</b>	Extent to which water use exceeds the effective availability in an area	%	SDG 6.4.2
<b>Reuse Ratio</b>	Percentage of treated water that is reused instead of discharged	%	SDG 6.3.1
<b>Leakage Rate</b>	Amount of water lost in distribution networks	%	SDG 6.4.1
<b>Specific Water Consumption</b>	Volume of water used per unit produced (e.g. per kg, liter, ton)	m <sup>3</sup> /unit	SDG 6.4.1

- ♣ SDG 6.3.1 – Improve water quality and reduce untreated discharges
- ♣ SDG 6.4.1 – Increase water-use efficiency across all sectors
- ♣ SDG 6.4.2 – Reduce the level of water stress

#### 3.4.2 Standards and Monitoring Table

Tool/Standard	Purpose	Scope of Application
<b>CDP Water Security</b>	Voluntary reporting for investors and stakeholders	Corporate, multi-sectoral
<b>GRI 303: Water and Effluents</b>	Comprehensive reporting on withdrawals, discharges, and strategies	Corporate and industrial
<b>ISO 14046: Water Footprint</b>	Assessment of water footprint of products/processes	Products, processes, organizations
<b>AWS Standard</b>	Sustainable water management at the watershed level	Production sites, water districts
<b>Smart Metering / IoT</b>	Real-time monitoring of consumption and leakage	Industrial plants and urban networks
<b>SCADA + Cloud Platforms</b>	Centralized control and predictive analysis of water data	Industry, utilities, agriculture

### 3.4.3 Comparison Between Traditional and Systemic Indicators for Assessing Water Efficiency in Industrial Processes

Dimension	Traditional Indicators	Systemic Indicators
<b>Saved Volume</b>	m <sup>3</sup> /year of water saved compared to the baseline scenario	% of water reused out of total treated (reuse rate), weighted by quality metrics and final use
<b>Operational Efficiency</b>	m <sup>3</sup> of water consumed per unit of output (e.g., €/m <sup>3</sup> or kg product/m <sup>3</sup> )	Integrated relationship between water inputs, recovery, and useful outputs, including losses, evaporation, and waste
<b>Associated Energy</b>	Generally absent or marginal	kWh/m <sup>3</sup> treated or % of renewable energy used for water treatment
<b>Process Emissions</b>	Not considered	kg CO <sub>2</sub> eq/m <sup>3</sup> of water treated or recovered, including the impact of advanced reuse technologies
<b>Treated Water Quality</b>	Compliant or non-compliant with regulatory standards	"Fit-for-purpose" quality based on adaptation to end use (e.g., cooling towers vs. agricultural reuse)
<b>Reuse and Recycling</b>	% of reuse at plant level (qualitative or declarative)	Quantitative and weighted indices of closed-loop water cycles: reuse, recycle, recovery (water + nutrients)
<b>Life Cycle Approach</b>	Absent or limited to environmental parameters	Integrated water LCA: includes energy, materials, environmental impacts, and long-term economic costs and benefits
<b>ESG Interoperability</b>	Not aligned with ESG criteria or the EU green taxonomy	Metrics compatible with ESG reporting, SEEA-Water, SDG 6.4, and bankability criteria for sustainable finance

- ♣ **Traditional indicators:** conventional methods often focused solely on volumetric water savings.
- ♣ **Systemic indicators:** advanced methods integrating multiple environmental and economic dimensions.



### 3.5 KEY POINTS

#### **Measuring is Governing: Indicators are Fundamental.**

To effectively improve and communicate water performance, it is essential to have clear, comparable indicators aligned with international objectives. Without accurate measurement, a process of continuous improvement is impossible to implement.

#### **There are different types of indicators, with complementary purposes:**

- ✦ Quantitative, such as the Water Footprint, Water Stress, or Water Use Efficiency, are all linked to SDG 6.4 (Sustainable Development Goal 6.4).
- ✦ Operational, for example, the leakage rate or the reuse ratio of wastewater.
- ✦ Process-specific, such as water consumption per unit of product (e.g., m<sup>3</sup>/ton of product, m<sup>3</sup>/dollar of product value).

#### **SDGs 6.3 and 6.4 provide a normative and strategic framework.**

These United Nations 2030 Agenda goals guide action for sustainable water management:

- ✦ SDG 6.4.1 aims to increase water-use efficiency across all sectors.
- ✦ SDG 6.4.2 aims to reduce water stress in territories.
- ✦ SDG 6.3.1 focuses on increasing the safe treatment and reuse of wastewater.

#### **Monitoring and reporting tools are expanding.**

Internationally recognized standards such as GRI 303, ISO 14046, CDP Water, and AWS (Alliance for Water Stewardship), along with advanced technologies like SCADA and IoT, allow for the collection of reliable and comparable data. This data is crucial for ESG (Environmental, Social, and Governance) reporting.

#### **Integrated water accounting is an advanced approach.**

This method combines physical (volumes) and economic (costs/benefits) measurements of water. It proves useful for evaluating trade-offs between different sectors, river basins, or technologies, fostering more transparent and sustainable decisions.

#### **Data transparency strengthens governance.**

Shared and accessible indicators improve stakeholder engagement, facilitate benchmarking between companies or territories, and enable performance-based incentive mechanisms.

## 4 TECHNOLOGIES AND INNOVATION

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### 4.1 TECHNOLOGIES FOR CLOSING THE WATER LOOP

#### 4.1.1 Monitoring Systems and Digitization of Networks

Closing the water loop—which involves minimizing withdrawals and maximizing reuse—requires precise, real-time control of water flows throughout the entire system. The digitization of networks and the implementation of advanced monitoring systems are crucial for ensuring the efficiency, operational timeliness, and sustainability of water infrastructures. Moretti et al. (2024) highlights the advancement of real-time monitoring technologies in wastewater treatment plants, with particular focus on online, inline, and AI-based soft-sensing systems. These solutions, combined with IoT and predictive models, enable not only the anticipation of quality deviations in effluents but also the optimization of energy consumption and chemical usage. The widespread adoption of these tools is significantly reducing operational response times in major European facilities.

#### **SMART INFRASTRUCTURES FOR REACTIVE MANAGEMENT**

The digitization of water networks enables a shift from a reactive to a more predictive and adaptive approach in system management. The main components of these smart infrastructures include:

- ♣ **IoT (Internet of Things) Sensors:** Low-energy devices that continuously measure parameters like flow rate, pressure, and water quality (pH, conductivity, turbidity) and can detect leaks or anomalies in real-time (Zulkifli et al., 2022).
- ♣ **Smart Meters:** Tools that allow for automatic and detailed detection of water consumption at the plant, department, or individual user level (Gupta et al., 2020).
- ♣ **SCADA (Supervisory Control and Data Acquisition):** Supervision and control systems that offer real-time management, with interactive dashboards and automatic alert systems for anomalies (Ortiz et al., 2024).
- ♣ **Cloud Computing and Digital Twin Platforms:** Virtual environments that replicate the real-time status of the physical system. This allows for accurate simulations, predictions of network behaviour, and targeted, timely interventions (Wang et al., 2024).

In urban and agricultural settings, these systems achieve an accuracy of  $\geq 95\%$  compared to traditional laboratory methods, with a significant reduction in sampling costs (up to  $-60\%$ ) and an improvement in decision reaction time (from weeks to a few hours) (Jayaraman et al., 2024).

#### **OPERATIONAL AND ENVIRONMENTAL BENEFITS**

Integrating these digital technologies into water cycle management leads to measurable advantages:

- ♣ **Reduction of water losses** by up to 30-50% thanks to early detection of breaks or malfunctions.
- ♣ **Optimization of energy consumption** in pumping and treatment plants, resulting in decreased operational costs and carbon footprint.
- ♣ **Continuous improvement of distributed water quality**, due to constant monitoring of critical parameters.



- ✦ **Increased transparency and accountability** towards users, regulatory authorities, and ESG stakeholders.

According to the International Energy Agency (IEA), the operational efficiency of water systems can improve by 20-40% through automation and advanced sensor technology (IEA, 2022).

### **OBSTACLES AND OPEN CHALLENGES**

Despite their enormous potential, the adoption of digital technologies in the water sector is still uneven. Key challenges include:

- ✦ **High initial costs** can be a significant barrier, especially for small operators.
- ✦ **Lack of interoperability** between existing systems, complicates the integration of new technologies.
- ✦ **Organizational resistance** and a **shortage of digital skills** among staff.
- ✦ **Cybersecurity risks** related to managing sensitive data and the vulnerability of connected infrastructures.

To overcome these barriers, the following are crucial:

- ✦ **Technical-administrative capacity-building programs** to develop the necessary skills.
- ✦ **Fiscal or regulatory incentives** (e.g., premium tariffs) to stimulate investments.
- ✦ **Shared technical standards** (e.g., ISO/IEC 30141 for IoT architectures) to ensure system compatibility and interoperability.

### **APPLICATION EXAMPLES AND FUTURE PROSPECTS**

Singapore PUB has implemented a vast network of real-time sensors and predictive models to optimize water treatment and distribution, setting a global model (Peydayesh & Mezzenga, 2024).

In Italy, the WATER4.0 project promotes the integration of smart metering and predictive maintenance for more efficient management of urban and industrial water networks (Cavalieri & Gambadoro, 2024).

The adoption of digital twins in the water sector is growing rapidly, with applications ranging from design to simulation and integrated management of complex water cycles (Boogaard et al., 2024).

Even in irrigation, case studies show that adopting IoT technologies, both low-cost and high-digital intensity, can ensure high water efficiency in very diverse contexts. In Sub-Saharan Africa, systems based on inexpensive sensors, microcontrollers, and GSM networks have led to 35% water savings, improving food security. In parallel, in California and Israel, the integration of satellite imagery, AI predictive models, and automated water balances has allowed for a reduction in irrigation consumption by up to 50%, with a significant increase in production efficiency (Udo et al., 2024). Such experiences highlight the importance of a scalable and contextual approach to technological adoption.

#### **4.1.2 Fit-for-Purpose Reuse: Adapting Treatment to End Use**

The fit-for-purpose (FFP) paradigm is based on adapting wastewater treatment to the quality level required for the specific end use, avoiding energy-intensive overtreatment and promoting efficient resource utilization (Capodaglio et al., 2023).

In this approach, wastewater is treated according to its origin and destination:



- ♣ **Greywater** (e.g., from showers, and sinks) can be reused with light treatments for secondary domestic uses (e.g., toilet flushing, garden irrigation).
- ♣ **Blackwater** requires advanced biological processes for agricultural or industrial use, given its higher pollutant load.
- ♣ **Industrial effluents** require tailored treatments, often aimed at specific uses such as washing, cooling, or technical recirculation within the production process (Zhang et al., 2022).

Among the main advantages of FFP are the reduction of the water footprint in high-intensity sectors, greater regulatory flexibility (which adapts to specific needs), and the development of local circular economies. In Israel, over 90% of urban wastewater is returned to agriculture under constant microbiological control (Capodaglio et al., 2023). In Italy, too, in industrial districts and agricultural areas, targeted reuse, when supported by effective governance and adequate infrastructure, is proving capable of improving climate resilience and competitiveness (Kahn et al., 2025).

However, the widespread adoption of FFP reuse is still hindered by regulatory, technical, and cultural barriers. To overcome them, flexible but evidence-based regulatory frameworks (e.g., Reg. (EU) 2020/741), reliable digital monitoring systems, and greater public acceptance, promoted through education and transparency, are necessary.

#### 4.1.3 Advanced Treatments: Membranes, Oxidative Processes, Selective Separation

Closing the water loop in industrial and urban systems requires the use of advanced treatment technologies capable of regenerating water and recovering valuable components, even in the presence of high contaminant concentrations or critical operating conditions. These advanced treatments represent the technological core of this transition and primarily include:

- ♣ **Membrane systems** for advanced filtration.
- ♣ **Advanced Oxidative Processes (AOPs)** for micropollutant removal.
- ♣ **Selective separation techniques** for targeted nutrient and metal recovery.

#### MEMBRANE SYSTEMS

Membrane processes enable the removal of particles, organic substances, salts, and microorganisms with high efficiency. They are used in both industrial and municipal applications, particularly for internal reuse and the production of high-quality water (Kim et al., 2022).

Key technologies include:

- ♣ **Ultrafiltration (UF) and Nanofiltration (NF):** Used for removing colloids, viruses, bacteria, and bivalent salts, providing higher water quality than conventional treatments (Kamal et al., 2024).
- ♣ **Reverse Osmosis (RO):** This is the most advanced technology for desalination, demineralization, and ultra-pure water production, effective in removing nearly all dissolved contaminants (Zubair et al., 2023).
- ♣ **MBR (Membrane Bioreactor):** This innovative technology combines biological purification with membrane filtration in a single stage. MBRs significantly reduce plant footprint and drastically improve effluent quality, often making it suitable for direct reuse (Al-Asheh et al., 2021).



Membrane systems offer numerous advantages. Chief among these is the high quality of the treated effluent, which in many cases can reach levels suitable even for potable uses. Furthermore, these technologies are characterized by strong modularity and compactness, facilitating their integration into limited spaces and decentralized contexts. In the most advanced multi-stage systems, over 95% of treated water can be recovered, significantly contributing to the reduction of withdrawals from natural sources.

However, there are some challenges. Reverse osmosis (RO), for example, involves high energy consumption, which impacts operational costs. Membranes can experience fouling and scaling phenomena, requiring regular cleaning and maintenance. Additionally, periodic replacements are necessary, incurring potentially high costs, especially in large-scale plants or contexts with limited management capabilities.

### **ADVANCED OXIDATIVE PROCESSES (AOPs)**

Advanced Oxidative Processes (AOPs) are a set of highly effective technologies for the degradation of persistent organic contaminants, emerging micropollutants (such as PFAS, pesticides, pharmaceutical residues), and pathogens. These systems are based on the *in situ* generation of reactive oxygen species (ROS), particularly hydroxyl radicals ( $\bullet\text{OH}$ ), which possess extremely high oxidizing power (Dong et al., 2022; Kokkinos, Venieri, & Mantzavinos, 2021).

The most common AOP technologies include:

- ◆ **Ozonation ( $\text{O}_3$ )**, also in combination with hydrogen peroxide ( $\text{O}_3/\text{H}_2\text{O}_2$ ), is effective in removing numerous organic and microbiological contaminants (Li et al., 2023).
- ◆ **Advanced Photocatalysis ( $\text{UV}/\text{TiO}_2$ ,  $\text{UV}/\text{H}_2\text{O}_2$ )**, which uses ultraviolet light to activate oxidative reactions (Iqbal et al., 2024). This is effective in removing organic micropollutants, pharmaceuticals, and chlorinated aromatic compounds, even at low concentrations.
- ◆ **Hydrogen peroxide-based processes in activated environments**, such as in activated sludge treatment (Guan et al., 2018).
- ◆ **Electro-oxidation and Fenton systems** are particularly effective in the presence of high contaminant loads. When integrated with the Fenton process, which uses catalytic iron and  $\text{H}_2\text{O}_2$ , the effectiveness in degrading refractory organic compounds significantly increases. This combination is suitable for complex industrial effluents with high concentrations of COD, heavy metals, or synthetic dyes (Nair, Soni, & Shah, 2023).
- ◆ **Oxidative Plasma**: The use of plasma in advanced oxidative processes is based on the generation of high-energy reactive species (radicals, electrons, ions) capable of breaking complex molecular bonds. This technique is distinguished by its rapid reaction rate, high removal efficiency even with recalcitrant contaminants, and the possibility of operating at ambient temperature (Peng et al., 2021).

These technologies are employed in municipal and industrial settings for the tertiary treatment of wastewater and the targeted treatment of complex effluents, for example, in the chemical and pharmaceutical sectors, where contaminants are often refractory to conventional treatments. A further application area is advanced viral disinfection, demonstrated to be effective even against resistant viruses in reuse systems (Kokkinos et al., 2021).

Numerous experimental and review studies have confirmed the ability of AOPs to completely degrade compounds like phenol (Suzuki, Araki, & Yamamoto, 2015), improve the effectiveness of conventional biological treatments, and facilitate the synergistic removal of micropollutants

in combination with UV disinfection. Moreover, the absence of secondary sludge production represents a significant operational advantage.

However, the widespread adoption of AOPs requires careful economic and energetic evaluation. Some processes, such as ozonation or intensive UV photocatalysis, are associated with high energy consumption and the need for specialized chemical reagents, with implications for safety and operational sustainability. For this reason, an integrated technical-economic analysis based on multi-objective criteria is recommended (Saravanan et al., 2022; Pandis et al., 2022). Furthermore, a deep understanding of the formation, interaction, and decay mechanisms of ROS species is fundamental for designing selective, efficient systems adaptable to different water matrices (Oturán & Aaron, 2014).

### **SELECTIVE SEPARATION TECHNIQUES**

These processes are designed for the targeted recovery of specific substances present in effluents, such as nutrients (nitrogen N, phosphorus P), rare metals, or valuable organic contaminants (Chen et al., 2022).

Key technologies include:

- ♣ **Ion Exchange:** Used for the recovery of ammonium, nitrates, and metals. The effectiveness of this process depends on the design of resins or membranes, which can be optimized to respond selectively and regenerably to various contaminants. Recent developments have led to the production of smart ion-exchange membranes, obtained through electrospinning, which offer high sensitivity and a superior separation capacity even in complex matrices, enhancing metal removal efficiency and facilitating their recovery (Bandehali et al., 2024).
- ♣ **Controlled Precipitation:** Specifically employed for the recovery of phosphorus in the form of struvite ( $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ ), a high-value fertilizer. This technique allows for the transformation of phosphorus loads present in effluents into a marketable product, contributing to both eutrophication reduction and the closure of the nutrient cycle (Cabo et al., 2025).
- ♣ **Adsorption on Functionalized Materials:** An advanced technique that uses modified polymers, nanomaterials, or functional membranes for the selective capture of persistent pollutants such as PFAS, heavy metals, and organic micropollutants. Recent developments have led to the creation of smart membranes and porous adsorbents capable of selectively retaining target contaminants and also integrating them into catalytic processes for their degradation or recovery (Makvandi et al., 2021; Georgouvelas et al., 2021; Song et al., 2022).
- ♣ **Reverse Electrodialysis (RED) and Pervaporation:** Techniques for the concentration and separation of salts, solvents, and volatile compounds. RED, in particular, is distinguished by its ability to specifically remove targeted ions from high-salinity streams, leveraging the principle of an alternating electric field to improve selectivity and prevent concentration polarization (Kaniadakis, van Lier, & Spanjers, 2024). Pervaporation, on the other hand, uses selective membranes and pressure gradients to separate volatile components, proving particularly useful in the treatment of organic solvents or advanced desalination.

These technologies form the basis of so-called valorisation plants, where effluent treatment is no longer just purification but transforms into a production process for resource generation (Saleh, Mustaqeem, & Khaled, 2021).



Advanced treatments allow for overcoming the limitations of conventional processes, enabling water regeneration, the removal of emerging pollutants, and resource recovery. Their integration into modular, automated, and digitized systems is essential to close the water loop and make water infrastructures more circular, resilient, and efficient (Metcalf & Eddy, Inc. McGraw-Hill Education 6th).

#### 4.1.4 Integrated Approach

The effectiveness of technological solutions increases exponentially when they are integrated into a cyclic management system, composed of:

- ◆ Continuous detection and monitoring connected to real-time data.
- ◆ Modular and adaptive treatment based on the required quality for the specific end-use.
- ◆ Valorization of secondary resources: recovery of energy, nutrients, and reusable water.
- ◆ Interconnected and intelligent infrastructures for predictive and resilient operations.

The integrated adoption of these technologies allows for optimizing water resource use, closing the internal balance, and reducing withdrawals from natural sources. Simultaneously, this leads to lower environmental impacts, thanks to reduced discharges and climate-altering emissions, and greater economic returns through the recovery and sale of resources (Narayanamoorthy et al., 2022). Furthermore, it significantly improves compliance with ESG standards and global sustainability goals such as SDG 6.3 (wastewater treatment and reuse) and SDG 6.4 (water-use efficiency and reduction of water stress).

The integration of engineering design, environmental simulations, and decision support systems has become central to advanced water projects. Nwankwo et al. (2024) demonstrate how engineering simulations (e.g., CFD, GPS-X, Aspen Plus) are enhancing treatment and reuse efficiency, enabling optimized management of the entire water cycle. This systemic approach allows for reduced resource consumption, scenario evaluation, and anticipation of climate impacts across agricultural, industrial, and urban contexts.

## 4.2 DECENTRALIZED AND NATURE-BASED SOLUTIONS FOR LOCAL MANAGEMENT

For enhanced resilience and circularity in water management, decentralized solutions and Nature-Based Solutions (NBS) offer adaptive and innovative approaches. These solutions are ideal for local scale and can be effectively integrated into both urban and rural settings.

### 4.2.1 Decentralized and MAD Solutions

Decentralized solutions involve installing water treatment, collection, or reuse facilities directly at the building, neighbourhood, or district level. They don't rely on large, centralized networks but operate autonomously or in small clusters, with local or community management (Maniam et al., 2022). MAD (Modular, Adaptive, and Decentralized) solutions represent an evolution of this paradigm, promoting flexibility, resilience, and local participation as fundamental elements for water security in the era of climate change (Wutich et al., 2023).

Key technologies include:

- ◆ **Containerized mini plants** for treating greywater (e.g., from showers, sinks) and blackwater in specific contexts like condominiums, schools, resorts, construction sites, or temporary settlements. These systems are designed for rapid installation and easy transport, and can include biological, physicochemical treatments, and disinfection systems aimed at local reuse of treated water for irrigation or hygiene purposes (Adeyinka et al., 2021).
- ◆ **Phytoremediation systems**, which utilize natural processes mediated by plants to purify water. This is an ecological and sustainable approach with low operating costs and the



ability to integrate into landscapes, finding wide application in rural, peri-urban, or decentralized contexts. Recent studies confirm its effectiveness even for removing toxic metals from soil and water, highlighting its multidisciplinary nature and potential for adaptation to diverse environments (Bhat et al., 2022).

- ✦ **Compact MBR (Membrane Bioreactor) modules with UV disinfection**, ideal for non-potable water reuse. MBRs ensure superior effluent quality, suitable for multiple applications such as urban irrigation, industrial cooling, or environmental reuse, even in limited spaces or decentralized settings (Huang, Jeffrey, & Pidou, 2024; Lehmann, 2024).
- ✦ **Rainwater harvesting and storage** for irrigation or hygiene purposes, particularly useful in densely populated urban areas or regions subject to water stress. Collection and storage systems reduce reliance on conventional water sources, mitigate urban runoff, and improve the climate resilience of settlements (Wartalska et al., 2024).

Decentralized solutions offer significant flexibility, making them particularly suitable for remote or peri-urban contexts. They help reduce water transport and pumping costs while ensuring operational continuity even in the event of central network failures. Additionally, they facilitate the local reuse of water and nutrients, promoting circularity.

However, their widespread adoption is still hindered by often incomplete regulations and a lack of clear standards for reuse. These technologies also require constant maintenance and the development of local technical skills, presenting challenges in terms of control and certification in distributed systems.

A representative example is the rural locality of Bojuritsa, Bulgaria, where an IWRM project based on the combined reuse of greywater and rainwater led to a reduction in potable water consumption of up to 60% and a 58% decrease in operational costs. The intervention included phytoremediation, storage, and decentralized disinfection, with an average investment payback time of under 10 years (Angelova et al., 2024). This demonstrates the technical and economic sustainability of decentralized solutions, even in low-density areas.

In addition to containerized MBR plants, a promising option for urban settings is represented by greywater recovery systems (GRS), which can save up to 43% of domestic water demand. Recent studies show that, in European residential scenarios, these systems yield positive economic returns (NPV > 0) with payback periods under 10 years—especially when supported by incentive-based tariffs and tax deductions (Rajski et al., 2024).

#### 4.2.2 Nature-Based Solutions

Nature-based solutions (NBS) utilize ecological processes and green infrastructures to improve water management, reduce pollution, increase the resilience of water systems, and generate multiple environmental and social co-benefits.

Application examples include:

- ✦ **Natural or constructed wetlands:** Used for secondary or tertiary wastewater treatment, acting as natural filters. They can be designed to adapt to various environmental contexts—urban, agricultural, or industrial—and contribute, in addition to improving water quality, to biodiversity, carbon sequestration, and climate resilience. Scientific evidence confirms the effectiveness of wetlands as sustainable water resource management tools (Ferreira et al., 2023).
- ✦ **Riparian forests and vegetated buffers:** Strips of vegetation along waterways that protect surface and groundwater from agricultural pollution or urban runoff. Beyond their ecological role, riparian buffers are fundamental tools for preserving riverine landscapes

and should be integrated into sustainable land management policies (Graziano, Deguire, & Surasinghe, 2022).

- ♣ **Green roofs and permeable soils:** Urban solutions that reduce surface runoff, promote water infiltration into the ground, and mitigate the urban heat island effect. These systems, when designed in "blue-green" multilayer configurations, act as multifunctional devices capable of effectively managing both rainwater and thermal insulation, improving the urban microclimate and contributing to infrastructure resilience (Cristiano et al., 2022).
- ♣ **Artificial lakes and multifunctional retention basins:** Structures designed for water storage, sediment decantation, and flood management, often with landscape and recreational value. Recent evidence shows how artificial lakes located in forest contexts can strengthen ecological functions and water resilience of landscapes, contributing to aquatic fauna conservation and improving the local microclimate (Starzak et al., 2025).

NBS generate a series of relevant environmental and social benefits. They contribute to mitigating heat waves, promote carbon sequestration, and foster urban biodiversity. They also offer improved aesthetics of public spaces and quality of life, while stimulating environmental education and active participation of local communities.

#### 4.2.3 Integration and Scalability

Recent studies (Delgado et al., 2024; Mbavarira & Grimm, 2021) demonstrate that the integration of decentralized and nature-based solutions allows for:

- ♣ **Closing local water cycles**, minimizing waste.
- ♣ **Increasing territorial water autonomy and security.**
- ♣ **Reducing overall infrastructure costs** compared to centralized solutions.
- ♣ **Better adaptation to climatic and demographic variations**, thanks to their flexibility.

An effective approach involves the "functional mosaic": a dynamic combination of technical micro-infrastructure (such as compact treatment modules, sensors, and mobile systems) and environmental ones (NBS) that are adapted to the specific hydrogeological, social, and economic context. This integrated vision, also promoted by recent literature, values the interconnection between urban resilience, technological innovation, and environmental sustainability (Castellar et al., 2022).

#### CASE STUDIES

International experiences confirm the effectiveness of decentralized and nature-based solutions:

- ♣ In **Mexico**, the adoption of rainwater harvesting systems in informal settlements has led to a 40% reduction in municipal water demand (Mbavarira & Grimm, 2021), improving water access for communities.
- ♣ In **Granollers (Spain)**, a hybrid system for urban wastewater reuse has ensured water quality compliant with standards for non-potable uses (irrigation, street cleaning) and high removal of emerging contaminants. It proved economically sustainable (cost €0.71–0.75/m<sup>3</sup>) also considering environmental and social benefits; moreover, the natural component improved public acceptability and system resilience (Gonzalez-Flo et al., 2023).



- ✦ In the **Netherlands and Belgium**, industrial districts have successfully integrated phytoremediation plants and decentralized MBR modules, demonstrating the technical scalability of these solutions even in complex contexts (Mbavarira & Grimm, 2021).
- ✦ Globally, the **World Bank's WICER program** has provided an operational framework for designing and implementing resilient interventions based on NBS and distributed systems, adaptable to various urban contexts (Delgado et al., 2024).

### 4.3 INTEGRATION WITH OTHER SECTORS: ENERGY, AGRICULTURE, MANUFACTURING

The integrated approach to water resource management is based on systemic awareness: water is not an isolated entity but is intimately interconnected with energy, agri-food, and productive systems. The paradigm of the water-energy-food-industry nexus is evolving towards technological and regulatory convergence that prioritizes overall efficiency, climate resilience, and decarbonization (Yasin et al., 2021; World Economic Forum, 2011; Zarei et al., 2021).

#### **WATER-ENERGY: SYNERGIES FOR DECARBONIZATION**

The energy sector is an intensive water consumer but at the same time a crucial provider of infrastructure and services for the water cycle. The most promising synergies include:

- ✦ **Energy recovery from sludge and wastewater:** Technologies like anaerobic digestion and pyrolysis enable the production of biogas and syngas, useful for cogeneration and grid injection (Taron et al., 2023).
- ✦ **Integration of hydraulic turbines and CHP in treatment plants:** This allows for the recovery of hydromechanical and thermal energy, improving the overall efficiency of the plants (Delgado et al., 2024).
- ✦ **Digitization for energy saving:** IoT sensors, inverters, and SCADA systems can reduce the energy consumption of water plants by up to 40%, contributing to decarbonization (IEA, 2022; Zarei et al., 2021).
- ✦ **Green hydrogen production:** The integration of electrolyzers powered by renewable sources into water cycles allows for the generation of H<sub>2</sub> using treated wastewater (Delgado et al., 2024).

These innovations support the development of "positive energy-water districts," where water and energy networks collaborate synergistically for self-sufficiency and climate neutrality (Ali & Acquaye, 2024).

#### **WATER & AGRICULTURE: REUSE, NUTRIENTS, AND CLIMATE RESILIENCE**

Agriculture accounts for over 70% of global freshwater withdrawals (Zhang et al., 2022; Biswas et al., 2025) and is directly affected by increasing water scarcity (Kahn et al., 2025). The most effective integration strategies include:

- ✦ **Agricultural wastewater reuse:** The use of treated water for irrigating non-food crops can reduce withdrawals from conventional sources, with positive impacts on water security (Kahn et al., 2025; Lalawmpui & Rai, 2023).
- ✦ **Nutrient recovery:** The reuse of phosphorus and nitrogen in the form of organic-mineral fertilizers contributes to closing the nutrient cycle and reduces dependence on chemical inputs (Barman et al., 2025).
- ✦ **Smart irrigation based on IoT:** Automated irrigation systems, based on sensors and predictive models, improve water efficiency and increase yield (Udo et al., 2024).

- Circular agroecology:** The integration of treated wastewater, rainwater, and compost reduces the environmental footprint of agricultural activities (Barman et al., 2025; Ali & Acquaye, 2024).

Irrigation not only has productive effects but can also contribute to mitigating the impacts of climate change at the local level. As demonstrated by Zhang et al. (2022), artificially induced evapotranspiration in irrigated fields modifies the surface energy balance, reducing sensible heat flux (H) and promoting air cooling.

Figure 5 Distribution of energy fluxes produced (Reworked by Zhang et al., 2022).

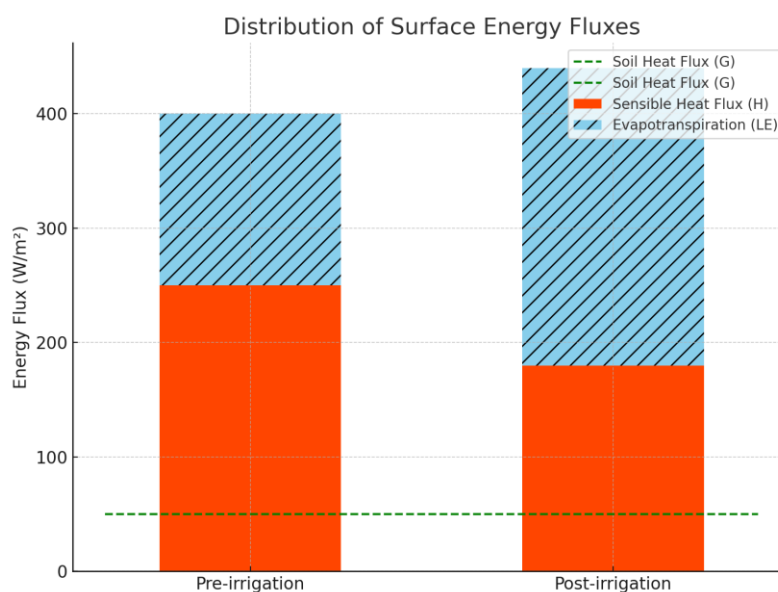


Figure 5 illustrates this redistribution of surface energy fluxes before and after irrigation, with a marked increase in latent heat flux associated with evapotranspiration. This effect has been documented in vast irrigated areas of India, China, and the United States, with thermal reductions of up to 1 °C in summer months. However, this benefit is balanced by an often inefficient use of water resources, especially in contexts with poor distribution infrastructure or high unproductive evaporation. It is, therefore, crucial to promote a transition towards more efficient irrigation systems (e.g., drip, sub-irrigation, predictive sensors), which maximize useful evapotranspiration and reduce unproductive losses, thus integrating climate mitigation and adaptation in a synergistic way. These solutions reduce dependence on conventional sources, improve resilience to climate change, and increase the productivity of systems.

### **WATER-MANUFACTURING: INDUSTRIAL SYMBIOSIS AND CLOSED-LOOP PROCESSES**

In the manufacturing sector, water is used in almost every production phase: from cooling to washing, from chemical reactions to material transport. Integration with other sectors allows for:

- Industrial symbiosis:** The exchange of water and material flows between neighbouring companies (e.g., waste heat, treated water, valorised sludge) creates a more efficient and circular industrial ecosystem (Ali & Acquaye, 2024).
- Closed-loop systems:** Internal recirculation of treated process water (e.g., in steel mills, paper, and textile industries) drastically reduces freshwater withdrawal and discharges (Lalawmpuii & Rai, 2023).
- Decarbonization of production processes:** Through water reuse, energy recovery, and the reduction of pollutant loads, industries can significantly reduce their environmental footprint.



- ◆ **Certifications and integrated reporting (ESG):** Efficient water management is a key parameter for evaluating industrial sustainability, increasingly requested by investors and stakeholders.

Successful examples exist in Italian industrial districts (e.g., Prato textile, Modena agri-food), where consortium plants allow for shared management of wastewater and circular reuse, demonstrating the feasibility of these models.

Integrating water with energy, agriculture, and manufacturing is an enabling condition for the ecological transition and for achieving SDGs 6 (clean water and sanitation), 7 (affordable and clean energy), 12 (responsible consumption and production), and 13 (climate action).

Promoting cross-sectoral policies, shared governance tools, and investments in joint infrastructure maximizes environmental, economic, and social benefits, transforming water flows into strategic resources for territorial resilience.

Furthermore, this is essential for achieving the Sustainable Development Goals, particularly SDGs 6, 7, 12, and 13 (Gu et al., 2024; Jones et al., 2024).

#### **4.4 CASE STUDIES SUPPORTING THE TRANSITION**

The adoption of innovative technologies and management models for closing the water loop is strongly supported by a growing number of real-world experiences. These cases demonstrate the technical feasibility, economic sustainability, and environmental value of such approaches. Numerous case studies offer replicable examples of how a circular water economy can be successfully implemented in urban, industrial, and agricultural contexts.

##### **ITALY: INDUSTRIAL DISTRICTS AND CONSORTIUM REUSE**

In the Prato textile district, a major European fashion hub, wastewater management is entrusted to the GIDA consortium, which annually treats approximately 12 million cubic meters of urban and industrial wastewater. The integration of advanced technologies like membrane bioreactors (MBR) and ozonation allows for the reuse of over 60% of the treated water in local production cycles. This model has significantly reduced groundwater withdrawals and pollutant loads, contributing to strengthening the district's competitiveness.

Another significant example is the Modena agri-food district, where a consortium treatment system enables the reuse of wastewater for irrigation and secondary industrial uses, such as plant washing. Solid fractions are also valorised as fertilizers, effectively closing the nutrient-water loop.

##### **SINGAPORE: NEWATER AND INDIRECT POTABLE REUSE**

Singapore has adopted a systemic approach to water resource management through its "Four National Taps" strategy: local resources, imports from Malaysia, desalination, and indirect potable reuse (NEWater). The NEWater program covers over 40% of national demand and relies on a combination of MBR, reverse osmosis, and UV disinfection. The treated water is reinjected into reservoirs before final purification, ensuring high-quality standards and social acceptability. Public campaigns, progressive tariffs, and extensive use of digital technologies make it one of the most advanced models globally (Delgado et al., 2024).

##### **TURKEY – ANTALYA: RAINWATER HARVESTING FOR PROTECTED AGRICULTURE**

In the context of increasing water scarcity in Mediterranean regions, the province of Antalya has developed a program for rainwater harvesting and reuse aimed at the greenhouse sector, which is a strategic agricultural segment for the local economy. Through the recovery of precipitation



from greenhouse roofs—which cover over 50% of the national greenhouse area—a collection potential exceeding 224 million m<sup>3</sup>/year has been estimated, with significant monthly peaks in winter.

Hydrological simulations have demonstrated the possibility of covering a significant portion of irrigation needs for crops like tomatoes while reducing operational costs and pressure on conventional resources. The model integrates modular storage infrastructures, filtration systems, and direct use in production cycles, making it replicable in other intensive agricultural contexts. This initiative represents a virtuous example of a nature-based and low-cost approach for water resilience in agriculture (Ertop et al., 2023).

### **ISRAEL: MAXIMIZING REUSE AND CIRCULAR AGRICULTURE**

Israel represents the context with the world's highest percentage of treated wastewater reuse, exceeding 85%, thanks to highly technological plants like Shafdan. Most of the treated effluent is used for agricultural irrigation, in synergy with drip irrigation systems, fertigation, and precision agriculture. The national strategy integrates fully reflective pricing, technological innovation, and centralized planning.

Israeli water efficiency is supported by strong intersectoral governance and constant investment in R&D.

### **NETHERLANDS: WATER-ENERGY-RESOURCE INTEGRATION**

The Waternet plant in Amsterdam represents one of the most advanced applications of integration between water, energy, and nutrient cycles. Waste heat from wastewater is recovered to power an urban district heating network serving over 100,000 homes. In parallel, sludge is converted into biogas and struvite, a phosphorus-based fertilizer. The entire plant is controlled by a digital twin system, allowing for real-time simulation and monitoring of flows (Delgado et al., 2024).

### **MEXICO CITY: DECENTRALIZATION FOR URBAN RESILIENCE**

In response to an urban water network with losses exceeding 40%, Mexico City has promoted a decentralized collection and treatment model. Containerized modules for local greywater treatment have been implemented in schools, markets, and peripheral neighbourhoods. In parallel, the municipality has incentivized rainwater harvesting systems and domestic and building reuse of rainwater, improving the resilience of the urban water system (Mbavarira & Grimm, 2021).

### **CHILE – OPTIMIZED AGRICULTURAL IRRIGATION VIA LOW-COST IoT**

In the rural region of Biobío, southern Chile, a research team developed a low-cost IoT prototype for smart irrigation, aimed at the needs of small and medium-sized farmers. The system, implemented at the "Hijuela El Proceso" farm, combines soil moisture sensors, an Arduino board, and a cloud platform for remote irrigation management, optimizing water consumption and reducing dependence on manual interventions.

Designed for plots between 0.5 and 40 hectares, the system allows irrigation to be activated only when humidity drops below a predefined threshold and only during the coolest hours, improving energy and productive efficiency. The prototype demonstrated a 33.8% reduction in seasonal costs over 2 hectares of cultivated blueberries, with a payback period of less than three weeks. In addition to water savings, the system promotes the technological autonomy of local farmers and the transition to more resilient digital agriculture (Saez Rojas et al., 2024).



### **SOUTH AFRICA – DURBAN: INDIRECT POTABLE REUSE IN A FRAGILE URBAN ENVIRONMENT**

The city of Durban has initiated one of the first experiences of indirect potable reuse on the African continent, responding to increasing pressure on conventional water sources and the infrastructural vulnerability of peripheral urban areas. The system is based on advanced treatment consisting of membrane filtration and UV disinfection, with subsequent reintegration of the treated effluent into the potable water supply system.

The intervention was accompanied by an intensive public communication campaign and a strengthening of local governance. The results show a significant improvement in water security, a reduction in the risk of service interruptions, and increasing social acceptance of reuse, even in contexts usually resistant to this type of solution (Water Research Commission South Africa, 2021).

In parallel, Cape Town faced a severe water crisis between 2017 and 2018, known as "Day Zero." The municipal government adopted an emergency strategy of drastic demand reduction (up to 50 litres per person per day), new pricing, regulatory limitations, and source diversification. The case demonstrates the effectiveness of risk communication and adaptive governance in preventing the collapse of the water system (Millington & Scheba, 2020).

### **INDIA – TAMIL NADU: DECENTRALIZED PHYTOREMEDIATION AT RURAL SCALE**

In Tamil Nadu, a densely populated region of southern India, water scarcity and groundwater pollution have prompted numerous rural communities to experiment with decentralized solutions for greywater treatment. With the support of local NGOs and international programs, over 150 subsurface flow phytoremediation plants have been built, and managed directly by the villages.

The treated water is reused to irrigate domestic gardens, contributing to food security and reducing demand for groundwater sources. The approach is distinguished by its low implementation cost, simple management, and high social acceptability (UNEP, 2021).

### **BURKINA FASO – DECENTRALIZED PHYTOREMEDIATION FOR AGRICULTURAL REUSE IN ARID AREAS**

In the rural village of Nougou, in the central Sahel of Burkina Faso, a horizontal flow phytoremediation system was built for the treatment of domestic greywater (showers, laundry, dishes), to reuse it for irrigating family gardens. The system, built entirely with local materials and without the use of mechanical energy, consists of a collection tank, a gravel pre-treatment, and a vegetated filter with *Chrysopogon zizanioides*. The results show removal efficiencies greater than 90% for organic matter (COD, BOD<sub>5</sub>), a 73% reduction for phosphorus (PO<sub>4</sub><sup>3-</sup>), and 60% for ammonium (NH<sub>4</sub><sup>+</sup>), as well as a reduction in faecal bacteria between 3.4 and 4.2 log<sub>10</sub> units, in line with WHO guidelines for controlled irrigation.

The system has demonstrated not only the technical feasibility and social acceptability of the solution but also significant potential to contribute to food security and climate resilience in water-scarce contexts (Maiga et al., 2024).

### **PERU – LIMA: GREEN INFRASTRUCTURES FOR URBAN CLIMATE RESILIENCE**

Lima, the capital of Peru, faces one of the world's most critical situations in terms of water availability, with an almost total dependence on resources from the Andean mountain range. In response to this condition, the city has developed a system of green infrastructures integrated into a broader climate adaptation plan.

The program includes the creation of filtering parks, rain gardens, retention basins, and multifunctional artificial lagoons, designed to collect and infiltrate rainwater. In addition to the



hydrological benefit, these solutions have contributed to the regeneration of degraded areas, the creation of local jobs, and the promotion of an urban culture more aware of the value of water (World Bank, 2022).

#### 4.4.1 Key Outcomes

The illustrated cases highlight several fundamental outcomes:

On the **technological level**, the versatility of modular and scalable solutions is clear. Technologies like membrane bioreactors (MBRs), reverse osmosis, advanced oxidative treatments (e.g., ozone, UV), and decentralized phytoremediation have proven effective in both urban and rural contexts, adapting to diverse operational and infrastructural conditions.

From an **economic perspective**, consortium models, circular utilities, and public-private partnerships (PPPs) are crucial tools for making projects bankable and sustainable, especially when private initiative is integrated with institutional or community support. Financial flexibility is an essential enabler, even for low-cost solutions in rural areas.

**Socially**, transparency, active community participation, and public communication on the value of reuse are decisive for the success of interventions. The cases of Durban and Tamil Nadu demonstrate this: local involvement not only fosters acceptance of reuse but also ensures its long-term management and maintenance.

At the **institutional level**, the presence of multi-level governance, capable of coordinating public, private, and local actors, accelerates the adoption of circular practices. It is particularly effective when accompanied by clear regulatory instruments and accessible technical guidelines.

Finally, on the **environmental level**, all cases confirm that the circular approach significantly reduces greenhouse gas emissions, limits land use, curbs pollutant loads, and recovers critical resources (water, nutrients, energy), generating systemic benefits and ecosystem co-benefits.

The examined case studies demonstrate that circular water solutions are replicable and adaptable, provided they are supported by effective multi-level governance and an enabling regulatory framework.

## 4.5 TABLES AND COMPARISONS

### 4.5.1 Reuse Classified by Source and End Use

Type of Wastewater	Source	Compatible End Uses	Treatment Requirements
<b>Greywater</b>	Washbasins, showers, laundry	Urban green irrigation, toilet flushing, street cleaning	Light treatment (filtration, UV)
<b>Blackwater</b>	Toilets and combined sewage	Agriculture, non-food industrial uses	Advanced biological treatment
<b>Industrial effluents</b>	Production processes (e.g., textile, chemical)	Equipment cooling, washing, technical recirculation	Tailored treatment, disinfection

### 4.5.2 Overview of Technologies for Closing the Water Cycle

Category	Technology/Tool	Key Function	Strategic Advantages	Main Challenges
<b>Digitalization</b>	IoT Sensors	Monitoring of flow, pressure, and quality	Real-time data, loss reduction	Initial costs, maintenance, cybersecurity
	Smart Metering	Automated measurement per user/process	Consumption optimization, traceability	System interoperability
	SCADA & Digital Twin	Supervision and simulation of systems	Remote control, predictive management	Operational complexity
<b>Membrane Treatments</b>	UF, NF, RO, MBR	Advanced filtration and reclaimed water production	High efficiency, modularity, compact systems	Fouling, energy use, cost
<b>Oxidative Processes</b>	UV, O <sub>3</sub> , AOP (e.g., UV/H <sub>2</sub> O <sub>2</sub> , O <sub>3</sub> /H <sub>2</sub> O <sub>2</sub> )	Micropollutant degradation and disinfection	Complete removal of recalcitrant substances	Energy costs, reagent safety
<b>Resource Recovery</b>	Anaerobic Digestion	Biogas production from sludge	Energy self-sufficiency, volume reduction	Biological process stability
	Precipitation (e.g., struvite)	Phosphorus recovery from sludge/liquids	Green fertilizers, circular economy	Chemical-operational complexity
	Ion Exchange, Selective Adsorption	Recovery of nitrogen and metals	Pollutant load reduction, byproduct valorization	Media regeneration, waste management

For a detailed comparison of the main available technologies, refer to Appendix D – Technology Selection Guide for Water Treatment and Reuse, which presents a summarized multicriteria comparison of applicable solutions.

### 4.5.3 International Case Studies on Closing the Water Cycle

Region	Context Type	Main Strategy	Key Technologies	Social Approach and Governance	Key Results
<b>Italy – Prato</b>	Industrial district	Consortium-based wastewater reuse	Membrane bioreactors (MBR), ozonation	Centralized management by GIDA consortium; supply chain-based consortium model; incentivizing tariffs and cost-sharing	~12 million m <sup>3</sup> /year treated; reduced groundwater withdrawals and pollution loads; strengthened competitiveness of the textile district
<b>Italy – Modena</b>	Agri-food district	Reuse for irrigation and secondary industrial use; sludge valorization	Consortium treatment system, sludge digestion/fertilization	Consortium model; shared infrastructure and costs; integrated nutrient-water cycle	Reuse of wastewater for irrigation and plant cleaning; sludge used as fertilizer; closed nutrient-water cycle
<b>Singapore (NEWater)</b>	National water system	Indirect potable reuse	MBR, reverse osmosis, UV disinfection	Integrated "Four National Taps" strategy; strong public communication; progressive tariffs; centralized governance; digital monitoring	Covers >40% of national water demand; high quality and social acceptance; international benchmark for indirect potable reuse
<b>Turkey – Antalya</b>	Protected agriculture	Rainwater harvesting and reuse from greenhouses	Modular storage systems, filtration, collection networks	Cooperation between farmers and local authorities; technology transfer; low-cost, nature-based approach	Significant coverage of winter irrigation demand; reduced operating costs and pressure on resources; replicable model for other greenhouse systems
<b>Israel – Shafdan</b>	Agricultural irrigation	Maximization of wastewater reuse	Advanced membrane plants; drip irrigation; fertigation	Intersectoral governance; pricing reflects real costs; ongoing R&D investment; centralized planning	Unmatched efficiency; large-scale precision irrigation; maximized water use efficiency



<b>Netherlands – Amsterdam</b>	Water-energy-resource cycle	Integration of water-energy-nutrient cycle	Digital twin; heat recovery from wastewater; biogas; struvite production	Public-private partnerships; real-time monitoring; circular supply chain approach	District heating for 100,000 homes; production of struvite fertilizer and biogas from sludge; optimized flows via digital twin
<b>Mexico City</b>	Fragile urban context	Decentralized greywater treatment and rainwater harvesting	Containerized modules; microfiltration	Municipal incentives for household systems; awareness campaigns; public-private partnerships	>40% network loss reduction; increased resilience in schools, markets, and suburbs; enhanced water autonomy
<b>Chile – Biobío</b>	Rural farm	Low-cost IoT smart irrigation	Soil moisture sensors; Arduino; cloud platform	Involvement of small farmers; training and technical support; open-source model	Seasonal water savings of 33.8% on 2 ha of blueberries; ROI <3 weeks; increased farmers' technological autonomy
<b>South Africa – Durban</b>	Fragile urban context	Indirect potable reuse with reintegration into potable network	Membrane filtration; UV disinfection	Strengthened local governance; intensive public dialogue; engagement of peripheral communities	Improved water security; reduced disruption risk; growing acceptance of reuse in previously hesitant communities
<b>India – Tamil Nadu</b>	Rural areas	Decentralized sub-surface flow constructed wetlands	Constructed wetlands with macrophytes	Direct community management; NGO-village partnerships; international capacity-building programs	Greywater reused for home gardens; low-cost and easy to manage; high social acceptability; contribution to food security and reduced groundwater extraction
<b>Burkina Faso – Nongou</b>	Arid rural areas	Horizontal flow constructed wetlands	Vegetated filter with <i>Chrysopogon zizanioides</i> ; gravel	Community involvement; local materials; no mechanical energy use	>90% COD/BOD <sub>5</sub> removal; 73% PO <sub>4</sub> <sup>3-</sup> , 60% NH <sub>4</sub> <sup>+</sup> reduction;



		using local species			3.4–4.2 log <sub>10</sub> faecal bacteria removal; potential for climate resilience and food security in resource-poor settings
<b>Peru – Lima</b>	Urban context	Green infrastructure for stormwater management	Filtering parks; rain gardens; retention basins; lagoons	Municipal climate adaptation plan; multilateral funding (World Bank); urban participation; local job creation	Improved stormwater infiltration; regeneration of degraded areas; strengthened urban water stewardship culture



## 4.6 KEY POINTS

### **Closing the Water Cycle Is Technically Feasible**

**Mature and scalable technologies** — such as advanced membranes, oxidative processes, and resource recovery systems — now make it possible to treat and reuse water with efficiency levels above 95%, paving the way for a closed-loop internal water cycle.

### **Digitalization as an Enabler of Predictive Management**

Tools like IoT sensors, smart metering, SCADA, and digital twins enable real-time monitoring of flows, pressure, and quality, reducing losses by 30–50% and optimizing costs. The transition toward “smart water networks” (with potential operational improvements of 20–40% – IEA, 2022) is crucial for overall system resilience.

### **Advanced Treatments Expand Reuse Potential**

Cutting-edge technologies such as reverse osmosis, membrane bioreactors (MBR), advanced oxidation processes (AOP), and selective separation enable the production of high-quality effluents, suitable for industrial, agricultural, and even indirect potable uses — turning treatment plants into true bio-refineries.

### **Decentralized and Nature-Based Solutions Increase Flexibility**

Modular and localized systems (e.g., containerized MBRs, rainwater harvesting, constructed wetlands) offer effective solutions in peri-urban, industrial, and rural settings. Nature-based solutions (NBS) such as green roofs and wetlands deliver significant environmental (e.g., carbon sequestration, biodiversity) and social co-benefits.

### **Water Efficiency Is Interconnected with Energy, Agriculture, and Industry**

The water-energy-food-industry nexus highlights the need for an integrated approach. Adopting these technologies not only reduces water consumption but also supports decarbonization, nutrient recovery, and the development of industrial symbiosis, maximizing systemic benefits.

### **Technology and Business Models Must Evolve Together**

Widespread adoption requires sustainable economic models (e.g., PPPs, circular utilities, industrial symbiosis), policy tools (incentives, technical standards, reuse tariffs), and multilevel governance. The technology is ready, and numerous global case studies (e.g., Prato, Singapore, Amsterdam) demonstrate its feasibility — but an enabling environment is essential for global scaling.

## 5 INVESTING IN WATER RESILIENCE: ECONOMIC VALUE, TOOLS, AND SYSTEMIC OPPORTUNITIES

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### 5.1 BEYOND EFFICIENCY: THE TRANSFORMATIVE VALUE OF WATER RESILIENCE

In recent years, the concept of water efficiency has become central to industrial, agricultural, and urban strategies. However, it is now clear that a purely technical-operational approach — focused solely on consumption reduction and process optimization — is no longer sufficient to address the growing complexity of environmental and socio-economic challenges.

Today, water resilience is emerging as a strategic, multidimensional lever. It not only enhances the ability to adapt to climate shocks and anthropogenic pressures but also generates systemic economic value. As highlighted in the WR4ER Framework (Matthews et al., 2024), we must move beyond the conservative paradigm of de-risking and embrace transformative resilience — the ability to absorb shocks, adapt, transform, and enable innovation.

This paradigm shift aligns fully with the priorities of the European Green Deal, the EU Adaptation Strategy, and UN Sustainable Development Goal 6 (SDG 6), which calls for “availability and sustainable management of water for all,” especially in vulnerable contexts (UN-Water, 2023). Resilience, therefore, must be seen as an invisible infrastructure that underpins industrial competitiveness, territorial cohesion, and climate transition.

Water can no longer be treated as a mere production input: it is a critical natural capital, whose real value becomes most evident when its availability is threatened. According to the World Bank (Rodriguez et al., 2024), extreme water events such as droughts or floods can erode up to 6% of GDP in many middle-income countries. In urban settings, even brief water service interruptions cause economic losses of 0.5% to 2.5% of regional GDP, with severe impacts on agriculture, healthcare, manufacturing, and logistics (Pagsuyoin & Santos, 2021).

In Europe, approximately 38% of the population lives in areas under structural water stress, with forecasts predicting the stable exceedance of the WEI+ sustainability threshold (20%) in several regions by 2030 (EEA, 2023). This makes water a limiting production factor, amplifying cross-sectoral tensions and economic vulnerabilities.

From a value creation perspective, a Water Europe (2024) study estimated that integrated investments in water resilience could generate net benefits exceeding €100–120 billion per year by 2030. These include:

- ◆ Environmental savings (eutrophication, GHG emissions, soil degradation),
- ◆ Health benefits,
- ◆ Increased attractiveness for water-intensive sectors (semiconductors, batteries, agri-food, data centres).

At least €30 billion/year can be attributed to efficient demand management and reduction of systemic losses alone. Additional value derives from reduced economic volatility, including lower emergency costs, fewer production disruptions, and minimized infrastructure damage (Matthews et al., 2024; Pot, 2023).

This evidence calls for a revision of traditional economic tools (e.g., NPV, CBA) to incorporate climate uncertainty, indirect benefits, and the value of avoided impacts. Tools such as robust planning and adaptive pathways are already being implemented in several European countries, supporting resilient investment even under uncertain future scenarios (OECD, 2022; Haasnoot et al., 2013).

## 5.2 ECONOMIC INTEGRATION OF WATER REUSE

In a global and regional context of increasing water scarcity, integrating reuse into the water system represents not only an environmental opportunity but also a strategic economic driver capable of generating substantial financial benefits and significantly reducing the risks associated with water resource management (World Bank, 2023).

### 5.2.1 Reducing Water Supply Costs

The reuse of wastewater alleviates pressure on natural water bodies, reducing dependence on conventional sources and mitigating the rising costs of water supply. According to recent FAO assessments (2021), in regions with high water stress—such as the Mediterranean and Middle East—the integrated use of treated wastewater can cover up to 25% of agricultural demand. This significantly lowers pumping and transport costs from distant or deep water sources.

An analysis based on FADN data in Italy estimated an average economic value of irrigation water at €0.29/m<sup>3</sup> for grain maize production, with values ranging from €0.11 to €0.52/m<sup>3</sup> depending on geographic and management factors (Buttinelli et al., 2024). These "shadow prices" reflect the current undervaluation of water in agricultural systems.

In Israel, a global leader in agricultural water reuse, more than 90% of urban wastewater is currently reused, contributing to a substantial reduction in direct supply costs and providing economic stability to the agricultural sector—even under severe drought conditions (Adams et al., 2023).

Similarly, in southern Spain, economic studies in Andalusia have quantified average annual savings of 20% to 30% in total irrigation costs thanks to the reuse of treated water (Lorenzo López & Expósito, 2025).

Further evidence from Portugal supports the economic feasibility of agricultural reuse. The supply cost of treated wastewater ranges from €0.02 to €0.57/m<sup>3</sup>—significantly lower than desalination, which averages €1.66/m<sup>3</sup>. Moreover, the distance between wastewater treatment plants (WWTPs) and irrigated land has been identified as a critical factor for the technical and economic viability of reuse, underscoring the need for integrated spatial planning (Areosa et al., 2024).

### 5.2.2 Nutrient Recovery and Reduced Fertilizer Use

One of the most significant economic benefits of water reuse lies in nutrient recovery, particularly nitrogen (N), phosphorus (P), and potassium (K), which are naturally present in urban and agricultural wastewater. According to a study by the International Water Management Institute (IWMI, 2022), the integrated use of treated wastewater allows for an average reduction of 30–50% in chemical fertilizer use, substantially lowering farmers' input costs while reducing the environmental impacts of over-fertilization.

A detailed economic analysis in Spain by Lorenzo López and Expósito (2025) showed that fertilizer needs in agriculture can be reduced by up to 40% through reuse, generating direct economic savings and associated environmental benefits, including lower emissions of greenhouse gases (N<sub>2</sub>O and CO<sub>2</sub> equivalents) and significantly reduced eutrophication of natural water bodies.

*Example:* The experience of the REUSE project in Egypt confirms that treated wastewater, rich in organic nutrients, can reduce the use of chemical fertilizers by 20%. The system, based on phytoremediation, resulted in overall savings of €6,550/ha/year and reduced energy consumption associated with groundwater extraction. This offers a resilient alternative in arid environments (Wahid et al., 2024).

### 5.2.3 Energy Valorisation from Sludge and Wastewater

Wastewater and resulting sludge also represent an important energy resource. Advanced technologies such as anaerobic digestion, membrane bioreactors (MBR), pyrolysis, and cogeneration now enable the recovery of a significant share of the energy contained in urban and industrial effluents, greatly reducing treatment plants' energy bills and generating additional revenue streams.

Recent studies show that in advanced facilities in the Netherlands and Germany, up to 80% of operational energy demand can be met through biogas generated from anaerobic sludge digestion, delivering economic savings and sharp reductions in climate-altering emissions compared to traditional methods (Water Europe, 2024; OECD, 2022).

Sludge and wastewater valorisation should go beyond just biogas or conventional fertilizers. Advanced anaerobic digestion technologies applied to municipal and agricultural effluents have been shown to yield energy returns above €0.07/kWh, with payback periods under two years, and can replace up to 60% of natural gas and 38% of coal used for energy (Peng et al., 2023). Moreover, integrated valorisation of agricultural sludge in Europe could reduce synthetic fertilizer use across more than 1.8 million hectares of farmland.

### 5.2.4 Extended Environmental Cost-Benefit Assessment (CBA)

To fully assess the economic benefits of water reuse, it is essential to apply extended environmental cost-benefit assessments (CBA) that factor in not only direct savings but also positive environmental externalities. These include:

- ♣ **Reduction of greenhouse gas emissions (GHG avoided):** Reuse decreases reliance on fossil fuels in synthetic fertilizer production and conventional water management, significantly lowering the carbon footprint of the water cycle (World Resources Institute, 2022).
- ♣ **Eutrophication prevention:** The use of treated wastewater limits the uncontrolled release of nutrients into aquatic environments, generating measurable economic benefits in terms of water quality and ecosystem services, estimated by the European Environment Agency (EEA, 2023) to be worth tens of millions of euros annually in regions like the Baltic Sea and Mediterranean.
- ♣ **Monetization of ecosystem services,** including soil stabilization in agricultural areas, aquifer protection, and increased biodiversity linked to improved water and soil quality.

## 5.3 ECONOMIC INSTRUMENTS FOR RESILIENCE

Water resilience is underpinned by economic instruments capable of incentivizing sustainable behaviour, attracting investment, and driving the transition toward circular and equitable water resource management. In an increasingly competitive context, financial leverage—including progressive pricing, tax credits, and blended finance—is crucial for scaling resilient solutions (OECD, 2022; IMF, 2023; European Commission, 2021; EIB, 2023; Water Europe, 2024).

### 5.3.1 Progressive Water Pricing and Reforming Perverse Subsidies

One of the most effective measures for promoting rational and resilient water use is progressive water pricing. According to an OECD report (2022), a progressive tariff structure—where unit prices increase with higher consumption—can reduce water use by 15–20% on average, compared to flat or linear pricing schemes. Notable examples include Spain, Israel, and Australia, where progressive pricing led to immediate consumption reductions and allowed utilities to avoid costly investments in new water infrastructure (Distefano et al., 2025; Tal, 2022).

At the same time, it is essential to reform so-called “perverse subsidies”, which keep water supply costs artificially low, encouraging overuse. According to the IMF (2023), global implicit water subsidies exceed \$400 billion per year, directly undermining investments in efficiency and resilience. Eliminating or restructuring these subsidies would allow for the reallocation of substantial public resources toward more sustainable and resilient initiatives.

The introduction of volumetric-based pricing systems represents a key driver for efficient water management in agriculture. In Italy, the adoption of tools aligned with the “polluter pays” principle remains uneven: only a few regions have implemented full cost recovery as mandated by the Water Framework Directive (WFD) (Buttinelli et al., 2024). Broadening the use of metering systems can generate consistent price signals and encourage lower water intensity practices.

Cost recovery in the water sector is not limited to direct pricing but can also be supported by indirect economic instruments such as tax incentives, efficiency credits, and targeted subsidies. The experience of the Canary Islands shows that while financial costs are generally covered, environmental and resource-related costs often are not—highlighting the need for more integrated and comprehensive pricing strategies (Santamarta et al., 2024).

### **5.3.2 Tax Credits and Incentives for Resilient Investments**

Economic tools such as tax credits, green incentives, EU funds (e.g., the Recovery and Resilience Facility, Green Deal Fund, REPowerEU), and blended finance mechanisms are essential to attract private capital to water resilience, supporting investment in digital technologies, reuse, and adaptive infrastructure.

According to the European Investment Bank (2023), every euro invested in water resilience generates returns between €2–3, while the World Economic Forum (2023) estimates that 30% of global investments could be funded through blended finance by 2030. Italy’s PNRR allocates €4.4 billion to sustainable water management, focusing on loss reduction and reuse (European Commission, 2022).

Public-private partnerships (PPP), such as the Thames Tideway project in the UK or green urban infrastructure in Paris, demonstrate how multi-stakeholder cooperation enables resilient, bankable solutions. Australia’s “water banking” model in the Murray-Darling Basin, based on dynamic pricing and water rights trading, has proven effective in managing scarcity and climate variability (Matthews et al., 2024; Grafton et al., 2020).

On the regulatory side, the EU Taxonomy and SFDR Regulation promote water disclosure and access to green finance instruments, aligning resilience, transparency, and capital efficiency (OECD, 2022; UNEP FI, 2022).

### **5.3.3 Case Study: Innovative Water Resource Management in the Murray-Darling Basin (Australia)**

The Murray-Darling Basin is one of Australia’s most significant and complex river systems, covering over 1 million km<sup>2</sup> and supplying about 40% of national agricultural output. Over recent decades, the basin has faced recurring and severe droughts, worsened by climate change, threatening its environmental and economic sustainability (Matthews et al., 2024; Wheeler et al., 2020).

In response, an innovative system of water markets and dynamic pricing has been developed, representing one of the most advanced examples of market-based water management. The system allows users (farmers, utilities, and local communities) to buy and sell water entitlements in real-time, based on supply and demand. These entitlements represent specific water volumes and can be traded permanently or temporarily, depending on climatic and economic conditions (Grafton et al., 2020; Matthews et al., 2024).



## **DYNAMIC PRICING AND WATER MARKETS**

This pricing system sets water rates based on scarcity or abundance, adjusting in real-time to ensure efficient distribution, especially during periods of water stress. Prices rise during droughts, incentivizing reduced non-essential use and investment in efficiency. In times of abundance, prices fall, enabling strategic storage and encouraging long-term sustainable investments (Grafton & Wheeler, 2018).

This market mechanism has proven particularly effective in managing critical periods, significantly reducing the socioeconomic costs of droughts. An econometric study by Wheeler et al. (2020) showed that water markets reduced the economic impact of droughts by 30%, compared to periods when water allocation was handled with more rigid administrative methods.

## **THE “WATER BANKING” MODEL**

Alongside water markets, the basin has implemented water banking, allowing water rights holders to “virtually store” unused allocations during favourable seasons for future use in dry periods. This transforms water into a flexible, economic asset, providing value even when it is not physically withdrawn (Matthews et al., 2024).

Water banking also helps stabilize price volatility, giving users greater certainty and reliability. This strategic storage capacity has helped secure production continuity for agriculture and industry, reducing climate and operational risks for local businesses (Wheeler et al., 2020; Young & Esau, 2021).

## **INTEGRATED ECONOMIC AND ENVIRONMENTAL BENEFITS**

The combination of water markets, dynamic pricing, and banking in the Murray-Darling Basin has yielded multiple economic, environmental, and social benefits:

- ♣ **Improved economic efficiency:** Water trading has increased the basin’s overall productivity by reallocating water to higher value uses. Farmers and industries have gained planning certainty, enabling timely technological and infrastructure investments (Grafton et al., 2020).
- ♣ **Reduced drought vulnerability:** Banking flexibility has significantly decreased economic and environmental vulnerability to drought, cutting emergency and extraordinary maintenance costs (Matthews et al., 2024).
- ♣ **Environmental protection:** Efficient resource allocation has left more water for ecosystems, enhancing biodiversity and water quality, while generating additional recreational and tourism-related economic benefits (Young & Esau, 2021).
- ♣ **Enhanced social and institutional capital:** A governance model based on transparency, timely information, and stakeholder engagement has increased trust and cooperation among farmers, water managers, public institutions, and local communities, boosting social cohesion and collective crisis response capacity (Wheeler et al., 2020).

## **IMPLICATIONS FOR OTHER REGIONS**

The Murray-Darling Basin experience is a globally relevant and replicable model, particularly for water- and economically vulnerable regions.

Adapting this approach to local contexts could yield substantial environmental and economic benefits, enabling more sustainable and resilient water management—including in Europe and the Mediterranean, where climate change impacts are increasingly severe.

## 5.4 INSTITUTIONAL INNOVATION AND ECONOMIC GOVERNANCE

Resilient water governance requires moving beyond fragmented, sectoral approaches toward integrated models that combine economics, environmental stewardship, and social cohesion within a systemic vision. Tools such as SEEA environmental accounting (UN, 2021), strategic circularity indicators (Peydayesh & Mezzenga, 2024), and adaptive planning (Haasnoot et al., 2013) are now essential for addressing scarcity, climate crises, and economic risks, as demonstrated by advanced experiences in the Netherlands, Spain, and Australia (Vardon et al., 2025; OECD, 2022; Pot, 2023).

### 5.4.1 Environmental and Water Accounting (SEEA)

A fundamental pillar of institutional innovation in water resource management is the System of Environmental-Economic Accounting (SEEA) — a UN-promoted framework that integrates economic and environmental data into national and regional accounting systems. This tool enables policymakers to account for the real value of water resources, including not only market value but also environmental externalities and ecosystem services (United Nations, 2021).

Recent assessments show that SEEA water accounting has helped several European countries — including the Netherlands, Spain, and Germany — significantly improve water management efficiency, better target public and private investments, reduce environmental costs, and enhance decision-making transparency (Vardon et al., 2025; Water Europe, 2024). In the Netherlands, SEEA adoption has facilitated the identification and implementation of resilient, integrated infrastructure projects, such as rainwater harvesting systems and wastewater reuse facilities.

### 5.4.2 Strategic Indicators for Water Resilience and Circularity

To effectively guide economic water governance, it is essential to adopt integrated strategic indicators that enable systematic assessment of performance and resilience.

Key indicators include:

- ◆ **Water Circular Economy Index (WCEI):** Recently developed, this index measures and compares the performance of national and regional water systems based on key variables such as the percentage of reused water, resource-use efficiency, water stress level, and overall water quality (Peydayesh & Mezzenga, 2024).
- ◆ **Net Water Value (NWW):** Measures the net economic value generated per unit of water used, accounting for both direct productivity and associated environmental costs and operational risks (Matthews et al., 2024).
- ◆ **Resilience Key Performance Indicators (Resilience KPIs):** Monitor a system's ability to absorb shocks, adapt, and transform in response to water crises. Indicators include service reliability, recovery capacity from extreme events, and long-term economic stability (Pot, 2023).

### 5.4.3 Adaptive and Scenario-Based Planning Tools

Given the rising uncertainty linked to climate change and water risks, advanced adaptive and scenario-based planning methodologies are increasingly necessary.

Digital tools like basin-level Digital Twins enable multi-scenario simulations, real-time sensor data integration, and improved predictive capabilities for water planning. The Strategic Investment Pathways methodology (OECD, 2022) further allows for the selection and sequencing of resilient investments based on future hydrological scenarios, considering eco-economic interdependencies and adaptive returns over time (Brown C et al., 2022).

Notably, the Robust Decision-Making (RDM) and Adaptive Pathways Planning (APP) approaches empower public and private stakeholders to assess water-related investments and policies across a wide range of possible futures, explicitly incorporating climatic and economic uncertainty (Haasnoot et al., 2013).

In the Netherlands, the adoption of APP in the Delta Programme has led to the development of a highly flexible and resilient water adaptation strategy, with modular, phased interventions based on changing climate scenarios. This approach has yielded significant economic and environmental savings, enabling targeted and timely investment in resilient infrastructure (Haasnoot et al., 2013).

Similarly, in the UK and Australia, RDM has helped local governments select robust strategies capable of performing well under highly variable climate conditions, greatly reducing emergency and extraordinary intervention costs (Matthews et al., 2024; Young & Esau, 2021).

The experience of the GAP project in Southeastern Anatolia represents a landmark case of water infrastructural regionalism, where water management works—such as dams, canals, and treatment plants—have shaped regional economic and social dynamics. The concept of “*water regionalism*” emphasizes that infrastructures are not merely technical artifacts but active political and territorial agents. Effective integration between water governance and regional planning can enhance adaptive resilience and promote territorial cohesion, even in complex contexts such as the Mediterranean region (Sayan, Bilgen, & Kibaroglu, 2025).

#### **5.4.4 Implications for European and Global Water Governance**

The combination of integrated accounting (SEEA), advanced water performance indicators, and robust decision-making tools represents a reference model for effective and resilient water governance. At the European level, these instruments are fully aligned with the EU Climate Adaptation Strategy, the Green Deal, and the EU Taxonomy, providing a solid foundation for achieving climate and economic resilience goals (European Commission, 2021).

At the global level, the dissemination of these advanced governance practices presents a strategic opportunity to enhance the economic and environmental sustainability of regions most vulnerable to water-related risks, with significant long-term benefits in terms of economic stability, social equity, and environmental health (United Nations, 2021; OECD, 2022).

#### **5.4.5 Equity, Environmental Justice, and the Right to Water**

The transition toward circular and efficient water management must include a social dimension, which is a core pillar of sustainable development. In line with SDG targets 6.1 and 6.2 of the United Nations 2030 Agenda — which aim to ensure universal access to safe drinking water and sanitation — water governance models must integrate an approach explicitly oriented toward equity, environmental justice, and protection of vulnerable groups. Unequal access to water resources is a clear manifestation of socio-territorial inequality. According to the SDG6 Update 2021, nearly 2 billion people worldwide lack access to safe drinking water when needed, and more than 673 million still practice open defecation (Arora & Mishra, 2022). Moreover, women and girls account for 80% of the water collection workforce in rural areas, facing disproportionate impacts in terms of time, health, and educational opportunities.

To address these imbalances, governance strategies must:

- ◆ Integrate distributive and intergenerational justice indicators in ex-ante evaluations of water policies.
- ◆ Promote equitable access to water services through progressive tariffs, targeted subsidies, and solidarity funds.



- ✦ Strengthen community participation in decision-making, in line with SDG target 6.B, through inclusive and transparent governance tools.
- ✦ Provide compensation mechanisms for populations most affected by water stress, pollution, or high-impact infrastructure projects.

In this context, the formal recognition of the human right to water — established by the United Nations in 2010 — must translate into concrete actions by regulators and service providers, ensuring that efficiency does not compromise equity and that the economic sustainability of water systems is not pursued at the expense of social sustainability.

As emphasized by Arora and Mishra (2022), improving the quality of governance also depends on the integration of social criteria into planning and reporting frameworks, especially in densely populated, rapidly expanding, or water-exclusion-prone urban areas.

### 5.4.6 Stakeholder Mapping and Decision Flows in Circular Water Governance

Effective water governance cannot rely solely on advanced technical, accounting, or regulatory tools. Rather, it requires a systematic and conscious mapping of all involved stakeholders, their functional roles, and the decision-making relationships that structure their interactions. The transition toward a circular water economy is a complex, multi-level, and cross-sectoral process that interweaves public mandates, private interests, scientific knowledge, and civic engagement.

Functional Category	Key Stakeholders (Examples – EU / International)	Primary Role in the Decision-Making Cycle
<b>1. Regulators and Policy-Makers</b>	- European Commission (DG ENV, DG AGRI) - National Ministries of Environment - Independent Regulatory Authorities (e.g. for water/energy) - River Basin Authorities - Regional and local governments	<b>Rule Setting and Strategic Oversight:</b> Define regulatory frameworks, strategic goals (e.g. reuse targets, quality standards), tariff schemes, and investment plans. Act as public interest guarantors and multi-level coordinators.
<b>2. Operators and Implementers</b>	- Water utilities (e.g. integrated service providers) - Water-intensive industries (chemical, agri-food, textile, energy) - Irrigation and land reclamation consortia	<b>Execution and Service Delivery:</b> Design, build, and manage infrastructure (networks, treatment plants, reservoirs). Responsible for water service provision and practical implementation of circular solutions.
<b>3. Users and Beneficiaries</b>	- Citizens (domestic use) - Farmers (irrigation use) - Industries (process use) - Nature and ecosystems (seen as “water users”)	<b>Demand Actors and Legitimizers:</b> Express water demand and legitimize the system through behaviours (consumption, payment, social acceptance). They are recipients and co-actors of sustainable water governance.
<b>4. Enablers and Influencers</b>	- Financial institutions (e.g. EIB, development banks, blue/green funds) - Universities and research centres - Technology providers and consultants - Civil society and NGOs (e.g. WWF, Water Europe, local committees)	<b>Resource and Intelligence Providers:</b> Provide capital (e.g. blended finance, PPP), innovation (e.g. digital twins), data, and social legitimacy (“license to operate”). Enable systemic circular transition through technical, financial, and social leverage.

This stakeholder map summarizes the key actors in the water cycle:



Circular water governance unfolds through five interconnected phases:

1. **Strategic Planning**: Definition of goals, regulations, and policy direction by regulatory institutions.
2. **Design and Investment**: Translation of objectives into concrete projects, with contributions from financial, technological, and scientific actors.
3. **Implementation and Management**: Construction and operational management of water infrastructure and services.
4. **Monitoring and Evaluation**: Measurement of performance, compliance, and impact.
5. **Feedback and Adaptation**: Ongoing strategy updates based on collected data.

Each phase engages different categories of stakeholders in a circular system that enables learning, adaptation, and co-design.

This dynamic approach ensures resilience, inclusiveness, and alignment across environmental, economic, and social objectives.

Water governance is thus the outcome of the interaction between multiple value paradigms—technocratic, market-based, and ecological—that coexist and reinforce one another (Schulz et al., 2024). The “*value of water*” is not solely monetary; it also encompasses social, cultural, and ecological dimensions. This perspective calls for a multi-level assessment in the design of pricing mechanisms, water rights allocation, and planning tools.

## 5.5 SECTORAL PRIORITIES AND INTEGRATED ECONOMIC ASSESSMENTS

To be effective and measurable, water resilience must translate into differentiated sectoral strategies that capture the economic, environmental, and social benefits of sustainable resource use. Proper integrated economic evaluation enables the identification of priority sectors, intervention opportunities, and expected returns — both in terms of risk mitigation and enhanced competitiveness.

### 5.5.1 Sectoral Risk–Opportunity Matrix for Water Resilience

The transition to resilient and circular water systems requires analytical tools that effectively integrate environmental, economic, operational, and climate criteria. In this context, the following sectoral risk–opportunity matrix offers a concise assessment framework to guide investment, planning, and regulation in the water cycle — with a focus on systemic sustainability, climate neutrality, and multisectoral efficiency (OECD, 2022; Water Europe, 2024).

Technologies and sectors were evaluated along five key qualitative dimensions, on a scale of 1–3 (1 = low, 3 = high), based on real-world case studies, scientific literature, and multilateral policy reports:

- ❖ **Operational Risk:** Measures technical complexity, failure probability, and dependence on critical infrastructure or emerging technologies (UNEP, 2021).
- ❖ **Climate Risk:** Reflects vulnerability to extreme events (droughts, heavy rains) and resilience under uncertain hydro-climatic scenarios (Liu et al., 2022; Haasnoot et al., 2013).
- ❖ **Environmental Opportunities:** Assesses the potential for impact mitigation, resource recovery (nutrients, energy), and water footprint reduction (ISO 14046; Peydayesh & Mezzenga, 2024).
- ❖ **Economic Opportunities:** Analyzes net economic return, avoided costs, and bankability of each solution (Matthews et al., 2024; Pot, 2023).
- ❖ **Territorial Scalability:** Estimates replicability across regulatory, climatic, and socioeconomic contexts (Arora & Mishra, 2022; Water Europe, 2024).

Sector / Technology	Operational Risk	Climate Risk	Environmental Opportunities	Economic Opportunities	Territorial Scalability
<b>Manufacturing (MBR + internal reuse)</b>	Medium	Medium	High	High	High
<b>Agri-food (constructed wetlands + irrigation reuse)</b>	Low	High	High	Medium	Medium
<b>Urban sector (NEWater + smart metering)</b>	High	High	High	High	High
<b>Sludge treatment (biogas + struvite)</b>	Medium	Low	Medium	High	Medium
<b>Green infrastructure (biofilters + infiltration basins)</b>	Low	Low	High	Medium	High

<b>Desalination (RO + solar energy)</b>	High	Medium	Medium	Low	Medium
<b>Heat recovery from wastewater (district heating)</b>	Medium	Low	High	High	Medium

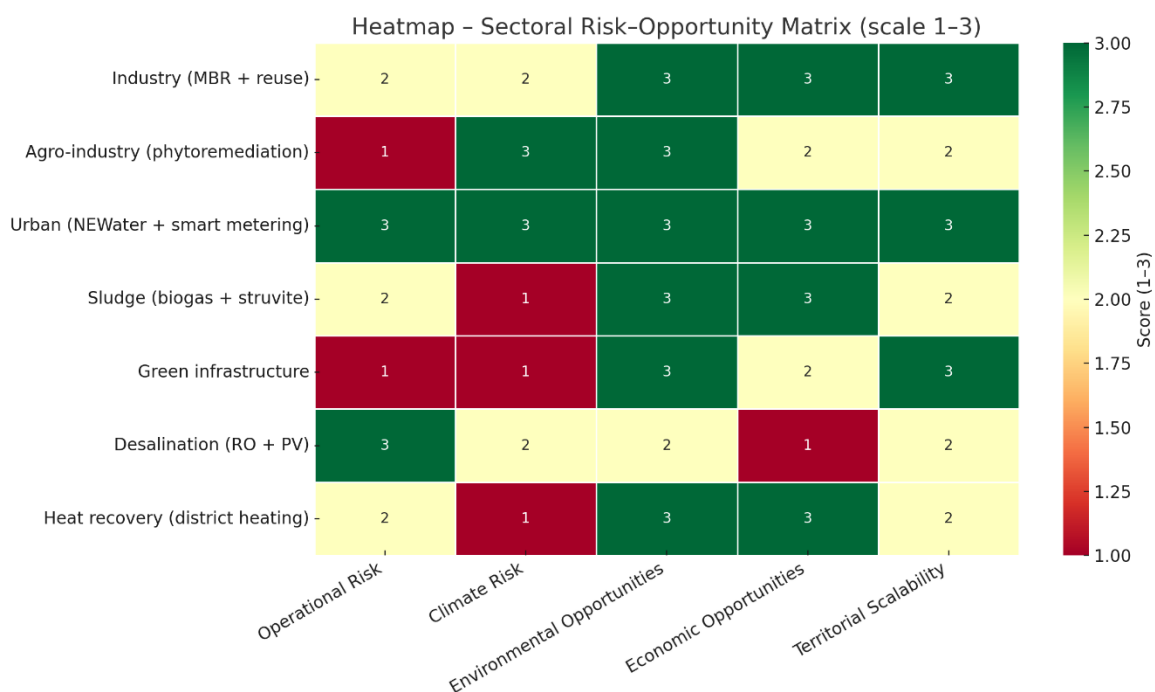
Figure 6 presents this matrix as a **1–3 scale heatmap**, where colours visually highlight the relative performance of each option.

- **Green shades** indicate favourable conditions (e.g., high opportunity or low risk);
- **Red shades** highlight critical areas.

This **heatmap is based on raw, unweighted descriptive values** and **does not produce a composite score**.

Its purpose is to **visually explore relationships** between technological profiles and application contexts (OECD, 2022; WR4ER Framework; Pot, 2023).

Figure 4 Heatmap Sectoral Risk–Opportunity Matrix (scale 1–3)



The full methodology for scoring, weighting, and calculation is detailed in Appendix A.

### 5.5.2 Agriculture

Agriculture is the largest global user of water resources, accounting for about 70% of total withdrawals, mainly for irrigation (FAO, 2021). In regions facing growing water scarcity and climate variability, the reuse of treated wastewater (RW) offers an effective adaptation strategy, ensuring production continuity and delivering significant economic and ecological benefits.

Beyond its irrigation function, RW provides intrinsic fertilizing value due to the presence of macro- and micronutrients — especially nitrogen (N), phosphorus (P), and potassium (K) — which can partially or fully replace synthetic fertilizers, lowering both demand and associated costs (Lorenzo López & Expósito, 2025).



### **DIRECT ECONOMIC VALUE: AVOIDED FERTILIZER COSTS**

A study conducted in Andalusia, Spain found that using RW in fertigation led to an average 40% reduction in fertilization costs, equivalent to approximately €150–250/ha per season, depending on crop type, nutrient content in the effluent, and local fertilizer price structures (Lorenzo López & Expósito, 2025).

According to IWMI (2022), widespread adoption of RW in Mediterranean horticulture could result in annual savings of over €500/ha, thanks to reduced chemical inputs, lower soil disturbance, and fewer losses from water stress.

### **ECOSYSTEM SERVICES FROM RESILIENT IRRIGATION**

When safely managed, RW also supports the restoration of key hydrological and climate-related ecosystem services:

- ♣ **Aquifer Recharge:** In well-drained agricultural soils, infiltrated water contributes to aquifer regeneration, easing pressure on groundwater withdrawals. In areas like Murgia (Italy) and Almería (Spain), Managed Aquifer Recharge (MAR) pilot projects have achieved net recharge of 1,000–3,000 m<sup>3</sup>/ha/year (WWAP, 2023).
- ♣ **Carbon Sequestration (Carbon Farming):** RW enriched with organic matter can increase soil carbon content, enhancing fertility and water retention. The European Soil Partnership (2022) estimates that a 0.4% annual increase in organic carbon in soils can sequester approximately 1.2–1.5 tCO<sub>2</sub>eq/ha/year.

### **CLIMATE MITIGATION: AVOIDED EMISSIONS**

RW reuse significantly reduces greenhouse gas emissions:

- ♣ **Less use of nitrogen fertilizers** → lower N<sub>2</sub>O emissions (a gas 298 times more potent than CO<sub>2</sub>).
- ♣ **Reduced industrial fertilizer production** → less fossil energy use and CO<sub>2</sub> emissions.

According to FAO (2021), each ton of avoided nitrogen fertilizer results in 3–5 tCO<sub>2</sub>eq saved. Applying this to RW, the conservative estimate is 0.5–1.2 tCO<sub>2</sub>eq/ha per irrigation season, depending on effluent composition.

### **EXTENDED ECONOMIC ASSESSMENT: SYSTEMIC VALUE**

Combining direct savings, avoided emissions, and ecosystem services, the total economic value of reuse in agriculture can exceed €600–800/ha/year, including:

- ♣ €150–250: avoided fertilizer costs
- ♣ €100–150: energy value from reduced chemical input
- ♣ €200–300: the monetized value of avoided GHGs and aquifer recharge (based on ETS prices and carbon shadow pricing)

These results justify economic incentive policies for agricultural reuse (e.g., reduced tariffs, payments for ecosystem services, carbon farming credits), already being implemented in European regions such as Apulia (Italy), Catalonia (Spain), and Provence (France) (Water Europe, 2024).



### 5.5.3 Industry

The industrial sector is increasingly exposed to risks related to water scarcity and supply instability, directly impacting operations, costs, reputation, and financial value. In this context, efficient and resilient water management is no longer merely an environmental issue, but a key driver of ESG competitiveness and capital access.

According to CDP Water (2023), over 60% of global companies identified physical water risks with “significant” or “severe” financial implications. Conversely, companies implementing advanced systems for monitoring, reuse, industrial symbiosis, and water withdrawal reduction have reported easier access to capital on more favourable terms (interest rates, insurance premiums, credit ratings).

#### **ESG AND WATER MANAGEMENT: A GROWING CORRELATION**

The “E” pillar of ESG finance has seen a growing emphasis on water metrics:

- ESG rating agencies (e.g., Sustainalytics, MSCI, S&P Global) now include indicators such as water stress, water use per unit of value-added, presence of water-related targets, and climate adaptation strategies linked to water.
- Companies that transparently report their Water Footprint and integrate water risk management plans into annual reports tend to receive higher ESG scores and greater institutional investor trust (UNEP FI, 2022; CDP, 2023).

*Example:* Nestlé, Danone, Unilever, and other water-intensive companies have linked their consumption reduction and effluent quality improvements to binding financial targets, achieving lower weighted average cost of capital (WACC) and reduced water risk ratings in emerging markets.

#### **CRITICAL TECHNOLOGIES: SEMICONDUCTORS AND GREEN HYDROGEN**

Special attention must be paid to the rising water pressure exerted by advanced tech sectors such as semiconductors and green hydrogen. Although they use less water overall than traditional manufacturing, these sectors are extremely sensitive to water risk and hold systemic strategic value.

Semiconductor manufacturing requires 2,000–7,000 litres of ultrapure water (UPW) per chip, with facilities like TSMC and Intel consuming over 150,000 m<sup>3</sup>/day — comparable to a mid-sized city’s needs (ESIA, 2023; Uptime Institute, 2022). Even minor contamination can shut down production. Leading companies now adopt closed-loop systems with MBR and reverse osmosis, cutting net demand by up to 75%, and integrating digital twins for predictive water management (Intel, 2022; Water Europe, 2024).

Green hydrogen production via electrolysis consumes 9–12 litres of deionized water per kg of H<sub>2</sub>. According to IEA (2022), achieving EU targets by 2050 would require over 21 billion m<sup>3</sup>/year — roughly 25% of total EU urban water use. The most advanced strategies rely on treated wastewater or desalinated seawater but face major cost and quality challenges (Hydrogen Europe, 2023).

Both sectors have the highest marginal value per m<sup>3</sup> of water and extreme vulnerability to disruptions, making them top priorities for water-sensitive industrial policies and resilient infrastructure planning.

Water risk in these sectors is not just environmental — it is also financial and geopolitical. Short water interruptions have already led to:



- ✦ Production shutdowns (e.g., TSMC, 2021, Taiwan),
- ✦ Global chip price spikes,
- ✦ Supply chain disruptions in automotive, medical, and ICT sectors.

Thus, preventive water resilience is considered a prerequisite for Europe's technological and industrial sovereignty by ESG analysts and financial institutions.

Necessary measures include:

- ✦ **Water-sensitive industrial policies** (proactive supply planning),
- ✦ **Green financing tied to sustainable water management** (e.g., Green Bonds, SLL),
- ✦ **Mandatory certifications and disclosure** of water footprint and resilience plans (e.g., Water Footprint, ISO 46001, CDP Water Disclosure).

### **FINANCIAL INSTRUMENTS LINKED TO WATER MANAGEMENT**

Recent years have seen a rapid growth of water-related financial instruments, especially within sustainable and climate finance:

- **Green Bonds:** Debt instruments for environmental projects, including water treatment infrastructure, reuse, efficiency, and resilience. In 2022, over \$40 billion in green bonds were issued for water projects, with demand exceeding supply by 25% (Climate Bonds Initiative, 2023).
- **Sustainability-linked loans (SLLs) and water-linked loans:** Loans whose interest rates are tied to measurable water performance targets (e.g., m<sup>3</sup> reduction, reuse percentage, ISO 46001 certification). Companies meeting high water standards benefit from lower interest rates or more flexible repayment terms (UNEP FI, 2022).
- **Water Footprint Certification and Blue Rating:** Voluntary schemes certifying companies or supply chains with strong water practices, improving their bankability and access to EU or multilateral funding (Water Footprint Network, 2023).

*Case Study:* In 2021, L'Oréal secured a €3 billion sustainability-linked loan, with the interest rate tied, among other factors, to targets for reducing water withdrawals per unit of production. Failure to meet targets results in a 1% annual rate penalty (Bloomberg, 2022).

#### **5.5.4 City**

In today's urban context, water resilience is not only about the technical continuity of services — it is a structural determinant of public health, social equity, and territorial cohesion. Cities are highly vulnerable to water shocks, yet they also hold exceptional capacity to innovate in sustainable and integrated water management.

### **ACCESSIBILITY AND WATER JUSTICE**

Water justice is the principle that equitable, safe, and sustainable access to water is a fundamental human right and a prerequisite for full participation in urban life. However, disparities in access to drinking water and sanitation services persist in both European and global cities, often concentrated in low-income or peripheral neighbourhoods (UN-Habitat, 2022).

According to the European Environment Agency (2023), low-income urban households spend up to 6% of their disposable income on water services, compared to 2–3% for higher-income

brackets. Moreover, even short-term water outages disproportionately impact vulnerable communities, with amplified health and economic consequences.

*Example:* In Marseille, an OECD (2021) study found that integrating social tariffs and investing in secondary network upgrades in marginal areas improved accessibility and reduced water bill arrears by 30%, strengthening urban social cohesion.

### **PUBLIC HEALTH AND AVOIDED COSTS**

Integrated urban water management — including wastewater treatment, urban drainage, and stormwater control — helps prevent waterborne diseases, improve hygiene, and reduce public healthcare costs.

According to WHO (2022), each €1 invested in resilient water and sanitation infrastructure in urban areas generates €3–7 in health benefits, by reducing gastrointestinal diseases, skin infections, school absenteeism, and hospitalization costs. Cities with decentralized treatment systems and safe sewer networks show a 40–60% lower incidence of waterborne illnesses compared to areas with degraded or intermittent infrastructure.

*Example:* In Lima, Peru, the introduction of constructed wetlands and reuse for urban irrigation helped avoid around \$2 million/year in healthcare costs, while improving environmental quality and local food security (World Bank, 2023).

### **INTEGRATED AND MULTISECTORAL URBAN RESILIENCE**

Cities are complex systems where water resilience intersects with other infrastructures: energy, mobility, food security, and civil protection. Water serves as a “systemic cohesion factor”, enabling truly integrated and sustainable urban planning.

Tools like the City Water Resilience Framework (CWRf), developed by Arup and the Rockefeller Foundation (2019), assess urban water resilience across multiple dimensions, including:

- ◆ Infrastructure capacity to withstand climate shocks,
- ◆ Availability of decentralized emergency systems,
- ◆ Multilevel water governance,
- ◆ Inclusion of vulnerable communities in urban planning.

Cities such as Singapore, Cape Town, and Copenhagen have shown that investment in nature-based solutions, urban reuse, and water digitalization enhances not only technical efficiency but also collective adaptive capacity, strengthening economic and social resilience (Pot, 2023; OECD, 2022).

### **5.5.5 EU Focus Emerging Strategic Sectors**

The 2024 Water Europe report identifies several strategic industrial sectors that depend on continuous and secure water access to thrive. These include:

- **Semiconductor manufacturing**, with water consumption exceeding 7,000 litres per chip.
- **Data centres and cloud computing**, with growing needs for sustainable cooling.
- **Green hydrogen** is produced via electrolysis, which requires ultrapure water.

These high-tech sectors are among the main recipients of public and private investment under the European Green Deal, REPowerEU, and the Net-Zero Industry Act.

Ensuring water resilience in these sectors is therefore a key enabler of European industrial sovereignty (Water Europe, 2024).

## 5.6 SECTORAL RETURNS AND INTEGRATED ECONOMIC PRIORITIES

To maximize the effectiveness and equity of investments in water resilience, it is essential to adopt a sector-specific approach that considers marginal efficiency costs, economic returns per cubic meter, and avoided damages. Resilience does not have a uniform value — its effects vary significantly depending on sectoral vulnerability and the value added associated with water use.

The following table summarizes the main comparable economic parameters, offering a strategic guide for intervention prioritization and the selection of effective financial instruments:

Table 6 – Source: Water Europe (2024), OECD (2022), EIB (2023), World Bank (2023), Pot (2023), Matthews et al. (2024).

Sector	Gross Value Added per m <sup>3</sup> (€)	Marginal Efficiency Cost (€ per m <sup>3</sup> saved)	Interruption Risk	Avoided Economic Damage (€ per m <sup>3</sup> not delivered)
<b>Agriculture</b>	1–3	0.20–0.50	High (climate-driven)	2–5
<b>Manufacturing Industry</b>	20–40	0.50–1.20	Medium (supply chain)	30–80
<b>Cities / Urban Services</b>	30–70	1.00–2.00	Medium-High (health, hygiene)	50–150
<b>Advanced Technologies (e.g., semiconductors)</b>	100–500+	2.50–5.00	Very High (ultrapure production)	500–2000

These data show that, despite higher efficiency costs, water-intensive high-tech sectors (e.g., semiconductors, data centres, green hydrogen) yield the highest economic returns and face critical losses in the event of water disruption — justifying dedicated policies and tailored financial tools.

Conversely, sectors like agriculture, while less profitable per m<sup>3</sup>, are strategically vital for food security, environmental co-benefits, and ecosystem regeneration.

An integrated economic assessment of water resilience — based on value-added, systemic risk, and avoided damages — should therefore serve as a guiding criterion for future investment, planning, and regulation strategies.

This approach enables effective alignment between sectoral priorities, environmental objectives, and economic instruments, transforming resilience into a collective asset with high systemic return.

## 5.7 TABLES AND COMPARISON

### 5.7.1 Table: Integrated Economic Returns by Sector

Sector	Value Added per m <sup>3</sup> (€)	Marginal Efficiency Cost (€)	Avoided Damages (€ per m <sup>3</sup> )	Additional Benefits
Agriculture	1–3	0.20–0.50	2–5	Fertigation, carbon sequestration, aquifer recharge
Industry	20–40	0.50–1.20	30–80	ESG compliance, access to sustainable finance
Cities	30–70	1.00–2.00	50–150	Public health, water justice, urban cohesion
Tech Sectors	100–500+	2.50–5.00	500–2000	Industrial sovereignty, production continuity

Sources: Water Europe, BEI, FAO, IWMI, OECD, World Bank.

### 5.7.2 Table: Economic and Financial Instruments for Water Resilience

Instrument	Main Function	Application Scope	Examples / Sources
Progressive Tariffs	Reduce waste, incentivize efficiency	Domestic, Agricultural, Industrial	OECD (2022), García-Valiñas et al.
Tax Credits / Incentives	Stimulate private investment in resilience	Water companies, SMEs, local utilities	EIB (2023), EU Taxonomy (2021)
EU Funds (PNRR, Green Deal)	Co-finance strategic infrastructure	Public sector and PPPs	European Commission (2022)
Blended Finance	Mobilize private capital with public guarantees	LMICs, large-scale projects	WEF (2023), World Bank (2023)
Sustainability-linked Loans	Reward ESG and water performance	Corporations, multinationals	UNEP FI (2022), CDP (2023)

### 5.7.3 Table: Governance and Resilience Measurement Tools

Tool / Indicator	Description	Application	Sources / Pilot Countries
SEEA – Environmental Accounting	Integrates water value into public accounts	Public economic planning	UN 2021, Netherlands, Germany
Net Water Value (NWW)	Net value generated per m <sup>3</sup> , accounting for environmental costs	Project evaluation	Matthews et al. (2024)
Water Circular Economy Index	Measures circularity of the water system (reuse, losses, quality)	Sectoral monitoring	Peydayesh & Mezzenga (2024)
Resilience KPIs	Indices on shock absorption, flexibility, adaptation	Governance and planning	Pot (2023), Haasnoot et al. (2021)
Adaptive Pathways & RDM	Long-term flexible scenario planning	Climate adaptation	Delta Program NL, UK Water Strategy



**5.7.4 Table: Indicators of Equity and Social Inclusion in Water Governance**

<b>Category</b>	<b>Indicator</b>	<b>Description</b>	<b>Source / Reference Standard</b>
<b>Universal Access</b>	% of population with access to safe water services	Measures the population served with drinking water that meets safety standards	SDG 6.1; WHO/UNICEF JMP
<b>Service Quality</b>	Average service continuity (hours/day)	Measures continuity in water provision, identifying regular or systemic outages	ISO 24510; SDG 6.1
<b>Economic Accessibility</b>	Water tariff burden on vulnerable households	% of income spent on water services by households in the lowest income deciles	OECD affordability metrics; GLAAS
<b>Territorial Equity</b>	Disparity in access between urban and rural areas	Urban-to-rural coverage ratio or other geographic disaggregation	SDG 6.1 disaggregated
<b>Gender Inclusion</b>	% of women in decision-making roles in water governance	Female representation in management boards, basin authorities, local committees	SDG 5; 6.B; Gender Water Alliance
<b>Community Participation</b>	Existence of public consultation mechanisms	Presence and frequency of public consultation or consent processes	SDG 6.B; Aarhus Convention
<b>Protection of Vulnerable Groups</b>	Access for informal populations, migrants, remote communities	Availability of accessible water services in marginalized or unrecognized areas	UN-Habitat; GLAAS
<b>Environmental Justice</b>	Exposure to contaminated sources or water risk	Incidence of water pollution near low-income or minority communities	WHO; EPA EJScreen (USA)
<b>Right to Water</b>	Legal and operational recognition of the human right to water	Existence of laws ensuring free or affordable minimum water access	UN Resolution 64/292 (2010); CESCR General Comment No. 15

## 5.8 KEY POINTS

### **Beyond Efficiency: Resilience**

Water efficiency alone is no longer sufficient; transformative water resilience is now a strategic asset for adapting to climate change, protecting economic stability, and ensuring systemic security (Matthews et al., 2024).

### **The Economic Value of Resilience**

Investments in water resilience could generate net returns of €100–120 billion/year in Europe by 2030, by reducing systemic losses, macroeconomic vulnerabilities, and emergency costs (Water Europe, 2024; World Bank, 2023).

### **Water Reuse and Integrated Benefits**

The reuse of treated wastewater reduces supply costs, enables nutrient recovery, supports sludge-to-energy conversion, and generates monetizable environmental co-benefits (FAO, 2021; IWMI, 2022; EEA, 2023).

### **Enabling Economic Instruments**

Progressive tariffs, tax incentives, EU funds, and blended finance are key levers for scaling resilient solutions. PPP models and the Australian “water banking” approach provide replicable examples (OECD, 2022; Matthews et al., 2024).

### **Governance and Strategic Accounting**

Resilience demands institutional innovation, including SEEA accounting, advanced indicators (NWV, WCEI, KPIs), and robust scenario-based decision-making approaches (Vardon et al., 2025; Pot, 2023; Haasnoot et al., 2021).

### **Sectoral Priorities and Differentiated Returns**

Water-intensive sectors like tech and industry offer the highest economic returns per m<sup>3</sup>, but sectors like agriculture and cities deliver critical environmental, social, and climate co-benefits essential to territorial cohesion (CDP, 2023; UNEP FI, 2022; WHO, 2022).

## 6 CONCLUSION

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### 6.1 SUMMARY OF FINDINGS BY SECTOR

The analysis in the previous chapters shows that water scarcity is emerging as a critical vulnerability and transformation factor across major production and territorial sectors. Each sector examined — agriculture, manufacturing, wastewater treatment — presents specific patterns of consumption, risks, and opportunities, but also shares common needs: efficiency, innovation, and systemic integration.

#### **AGRI-FOOD SECTOR**

Agriculture is the largest global consumer of water resources, accounting for approximately 70% of total withdrawals. This dependency makes it extremely vulnerable to declining availability and climate variability (FAO, 2021; Liu et al., 2022). Emerging solutions include high-efficiency irrigation technologies (drip, sprinkler), digital monitoring and control for precision irrigation, and the reuse of treated wastewater integrated with nutrient recovery. In favourable contexts, these practices can cut water demand by up to 50%, contributing to agroecological resilience and food security (Rastogi et al., 2024).

#### **MANUFACTURING AND CHEMICAL INDUSTRY**

Industrial processes consume large volumes of water for cooling, cleaning, production, and material transport — while also generating complex and hard-to-treat effluents. Water scarcity is now seen as a concrete operational risk, affecting both production continuity and access to vital inputs (Karki & Rao, 2023). Effective responses include internal recycling systems (closed loop), real-time digital monitoring (IoT, SCADA), and environmental reporting using voluntary standards (ISO 14046, ESG reporting). Systemic adoption of these practices could reduce water withdrawals by up to 60% in high-intensity sectors (Karki & Rao, 2023).

#### **WASTEWATER AND SLUDGE TREATMENT**

Traditional treatment plants are often based on a linear paradigm focused only on discharge and pollution removal. This leads to high energy use and limited resource recovery. Emerging models aim at multifunctionality: reuse of treated water, biogas production from sludge, and nutrient extraction (e.g., struvite, ammonia). Advanced technologies such as AOP (Advanced Oxidation Processes), reverse osmosis membranes, and selective separation allow for greater recovery efficiency and improved effluent quality. Plants designed with circular logic can now meet 50% to 80% of their energy needs while producing value-added by-products (Taron et al., 2023).

#### **URBAN SYSTEMS AND WATER INFRASTRUCTURE**

Urban water networks, often obsolete and fragmented, show high loss rates — up to 40% in some areas — and face growing pressure from urbanization, climate change, and competing uses. Digitalization through smart metering and digital twins enables predictive and efficient management. At the same time, decentralized solutions (e.g., containerized modules, urban constructed wetlands) and nature-based systems (rain gardens, multifunctional basins) are expanding, enhancing resilience and reducing the load on central systems. Smart urban investment can reduce water losses by 30–50%, boosting climate adaptation and urban water security (Delgado et al., 2024).

Efficient and resilient water management is a strategic driver of multisectoral sustainability. Technical solutions exist and are proven; the main challenge remains their large-scale adoption through enabling policies, adequate financial instruments, and a shared water value culture.

### 6.1.1 Governance models and economic instruments for water efficiency

The success of water efficiency strategies largely depends on governance frameworks that combine smart regulation, economic tools, and adaptive mechanisms.

Three exemplary international approaches stand out:

- In Australia, the Murray-Darling Basin operates one of the most advanced systems of regulated and market-based allocation, with a cap-and-trade model that has incentivized efficient irrigation technologies while maintaining agricultural profitability under water stress (Grafton et al., 2011).
- In Europe, the Water Framework Directive (WFD) promotes an integrated river basin planning approach, based on cost-recovery principles and economic instruments (e.g., tariffs, abstraction charges). However, implementation remains uneven across Member States, requiring greater transparency and accountability (European Commission, 2021).
- In emerging contexts, hybrid models are emerging that blend adaptive regulation, digital technologies, and community-based management. Cases from Chile, India, and South Africa show that local water rights markets and public accounting platforms can enhance efficiency even in institutionally fragile environments (Leijnse et al., 2024; Wada et al., 2017).

The adoption of well-designed market instruments (e.g., tradable water rights, fiscal incentives, progressive tariffs) and the strengthening of multilevel institutions are confirmed as crucial enablers of the transition toward sustainable, transparent, and resilient water systems.

## 6.2 OPERATIONAL RECOMMENDATIONS FOR BUSINESSES, REGULATORS, AND POLICYMAKERS

The transition toward efficient, circular, and resilient water use requires concrete actions from all stakeholders in the water value chain. The following recommendations are structured by target group and based on evidence from case studies, sectoral analysis, and international regulatory frameworks. They aim to translate the water sustainability paradigm into practical action across business, territorial, and institutional levels.

### FOR BUSINESSES AND INDUSTRIAL OPERATORS

#### 1. Measure and manage water efficiency as a strategic KPI.

Integrate water indicators (e.g., m<sup>3</sup>/unit, % reuse, water footprint) into management control systems and ESG reporting, with measurable annual targets.

#### 2. Adopt advanced treatment and recovery technologies.

Invest in MBRs, reverse osmosis, AOP, and selective separation to increase internal recycling rates and recover energy and nutrients from wastewater.

#### 3. Digitalize water systems.

Implement smart metering, IoT sensors, and SCADA platforms to optimize resource use, prevent losses, and reduce operating costs.

#### 4. Promote industrial symbiosis and joint management.

Develop partnerships to share infrastructure, discharges, and recovered resources within industrial clusters, improving overall efficiency and economies of scale.



#### **5. Invest in internal awareness and water literacy.**

Raise awareness among operational and strategic staff about the importance of water efficiency through sustainability programs, technical training, and internal incentives.

### **FOR REGULATORY AGENCIES AND WATER AUTHORITIES**

#### **1. Set clear technical standards and regulatory limits for reuse.**

Introduce differentiated quality standards for agricultural, industrial, civil, and environmental uses, as outlined in **EU Regulation 2020/741**.

#### **2. Simplify permitting for decentralized treatment.**

Facilitate the adoption of local and modular plants (e.g., containerized units, nature-based solutions) through technical guidelines, advisory desks, and design incentives.

#### **3. Integrate economic instruments to promote efficiency.**

Apply progressive tariffs, tax incentives for water-efficient technologies, tax credits, and pay-for-performance schemes.

#### **4. Strengthen monitoring and transparency in water use.**

Require annual water reports from industrial and municipal facilities; publish regional data on water stress, discharge quality, and reuse applications.

#### **5. Coordinate at basin and district levels.**

Align water, environmental, industrial, and agricultural planning using tools such as **water accounting, water stewardship, and multistakeholder platforms**.

### **FOR POLICYMAKERS AND CENTRAL INSTITUTIONS**

#### **1. Recognize water as a priority asset in the ecological transition.**

Integrate water management into industrial, agricultural, and urban policies in line with the **EU Green Deal**, the **2030 Agenda**, and **PNRR** funding.

#### **2. Fund the rollout of circular infrastructure.**

Provide financial support for pilot projects, smart water districts, urban digital twins, and closed-loop models through structural funds and partnerships.

#### **3. Promote research and applied innovation.**

Invest in centres of excellence for advanced treatment, sensor technologies, predictive water management, and resource recovery from wastewater.

#### **4. Foster a culture of reuse and water justice.**

Launch public campaigns to build acceptance of water reuse, increase awareness of water's value, and promote equitable access.

#### **5. Support standardization and international regulatory convergence.**

Cooperate at European and global levels to harmonize definitions, indicators, and certifications (e.g., ISO, GRI, CDP Water, AWS), facilitating comparability and access to sustainable markets.



### 6.2.1 Sustainable Finance and ESG Metrics as Levers for Water Efficiency

In today's context, marked by growing investor pressure on ESG criteria, optimizing water use is becoming a central element in corporate sustainability assessments.

The inclusion of water metrics in ESG frameworks — such as GRI 303, ISO 14046 certification, or CDP Water disclosure — is not merely a reputational obligation, but a gateway to sustainable finance (GRI, 2018; ISO, 2014; CDP, 2023).

Instruments such as green bonds, sustainability-linked bonds, and SDG-linked loans explicitly tie capital access to measurable environmental performance, including water efficiency. For example, a company that demonstrates reduced water withdrawals per unit of output or increased reuse rates can secure more favourable financing terms (OECD, 2020; European Commission, 2023). Similarly, tax credits for investment in water-efficient technologies — such as membrane systems, SCADA platforms, and reuse treatments — offer strong incentives for a green transition, especially for SMEs (UNEP FI, 2021).

#### **WATER FINANCE AND INNOVATIVE INVESTMENT INSTRUMENTS**

The role of sustainable finance has been further reinforced by the EU Taxonomy, which defines technical criteria for economic activities aligned with environmental objectives — including sustainable water management (European Commission, 2020). In this regulatory context, water metrics — such as the reuse ratio, leakage rate, or volume of water saved per unit of output — are becoming key indicators for project bankability and creditworthiness assessment.

Sustainability-linked bonds and green loans directly link capital costs to the achievement of measurable targets, such as reduced water withdrawals or improved process efficiency. This enables high-performing companies to access capital on incentivized terms, driving transformation in industrial models. Public institutions also play a role by offering tax breaks and subsidized loans to stimulate investment in resilient water infrastructure and low-impact technologies.

To maximize the impact of these tools, companies must adopt real-time digital monitoring and reporting systems, and for regulators to ensure that water becomes a core element in both the Taxonomy and ESG benchmarks. In this way, water efficiency evolves from a technical parameter to a strategic asset, with direct implications for financial resilience and industrial competitiveness (World Bank, 2022).

Beyond environmental and technical performance indicators, a comprehensive ESG framework oriented toward water resilience must also include social metrics to assess equity, distributive justice, and the human right to water. These dimensions are critical to ensure that efficiency and circularity strategies do not generate regressive effects but rather help reduce inequalities in access to water and sanitation services.

Key social indicators include:

- ♣ **Economic accessibility:** share of income spent on water services by vulnerable households
- ♣ **Service coverage:** % of the population served in rural, informal, or marginalized areas
- ♣ **Participatory mechanisms:** presence of public consultations or community decision-making processes
- ♣ **Gender inclusion:** representation of women in water governance bodies
- ♣ **Protection of at-risk groups:** attention to children, people with disabilities, migrants, or Indigenous populations



These indicators align with SDG 6.1 (universal access to safe drinking water) and SDG 6.2 (adequate and dignified sanitation for all) and support monitoring of the "leave no one behind" principle of the 2030 Agenda (United Nations, 2015).

Systematically integrating these aspects into corporate ESG reporting and sustainable investment criteria (green bonds, impact finance, blended finance) improves social accountability while also enhancing legitimacy and stakeholder trust in water sector transformation strategies.

#### **Operational Notes: Practical Tools to Integrate Equity into ESG Frameworks and Water Governance**

It is recommended to integrate the social indicators mentioned above into the multi-objective monitoring frameworks of water policies, in synergy with existing tools such as:

- **GRI 303** (Disclosure on Water and Effluents)
- **ISO 14046** (Water Footprint)
- **SEEA-Water** (System of Environmental-Economic Accounting for Water)

These indicators can be used:

- Ex ante: to assess the social impact of new tariff structures, infrastructure projects, or regulatory reforms.
- Ex-post: to measure actual effects on service accessibility, continuity, or territorial disparity reduction.

Integrating these indicators into corporate ESG reports and the strategic plans of regulatory authorities reinforces the "leave no one behind" principle (2030 Agenda), making equity and social resilience in the water sector concrete and measurable.

### **6.3 EVIDENCE FROM CASE STUDIES: OPERATIONAL LESSONS FOR THE TRANSITION**

The analysis of case studies presented in Section 4.4 confirms that the transition toward efficient and circular water use is not only desirable but technically feasible and already underway across a wide range of contexts. These experiences offer valuable insights for future action, providing empirical evidence on enabling factors, common barriers, and measurable outcomes.

#### **CONSORTIUM AND DISTRICT-LEVEL EFFICIENCY (ITALY)**

The cases of Prato and Modena demonstrate the effectiveness of consortium models for industrial and agricultural water reuse. The integration of MBR, ozonation, and nutrient recovery has helped overcome regulatory limitations and management fragmentation, improving competitiveness and reducing groundwater withdrawals. Collective investment and shared management emerge as key levers for economies of scale and territorial resilience.

#### **HIGH-TECH INDIRECT POTABLE REUSE (SINGAPORE, DURBAN)**

The NEWater program in Singapore and the reuse system in Durban show how high standards of water quality and safety for indirect potable reuse can be achieved even in infrastructurally fragile settings.



Their success lies in the combination of advanced treatment (MBR, reverse osmosis, UV), multilevel governance, and transparent public communication — all of which help overcome social acceptance barriers.

### **INDUSTRIAL SYMBIOSIS AND MULTI-RESOURCE RECOVERY (NETHERLANDS)**

The Waternet experience in Amsterdam highlights the potential for synergies between the water, energy, and agricultural sectors: heat recovery from wastewater, biogas production, and struvite recovery from sludge showing how water infrastructure can become a key node in the urban bioeconomy.

Digital control systems, such as digital twins, are enabling tools for dynamic optimization.

### **DECENTRALIZED AND ADAPTIVE APPROACHES (MEXICO CITY, TAMIL NADU, LIMA)**

In resource-limited contexts, decentralized models show strong potential for boosting local resilience and easing pressure on centralized systems. Containerized treatment units, community-scale constructed wetlands, and multifunctional green infrastructure have demonstrated both technical and social effectiveness.

In particular, active community involvement and modular design are crucial for long-term sustainability.

### **Southeastern Anatolia**

Another operational lesson comes from Turkey's experience in Southeastern Anatolia, where the large-scale water infrastructures of the GAP project have given rise to an advanced example of functional water regionalism. In this context, water is not merely a physical resource but a structuring element of space, economy, and governance in a systemic manner.

Water infrastructures—dams, canals, pumping stations—act as regional integration mechanisms, generating significant impacts on agricultural productivity, employment, and institutional cohesion. This type of approach suggests that even in European or Mediterranean contexts, it is possible to develop regional water hubs capable of triggering institutional innovation, integrated planning, and multi-scalar resilience (Sayan et al., 2025).

### **MULTILATERAL PROGRAMS AND REPLICABILITY (WICER, WORLD BANK)**

The WICER program, which combines appropriate technologies, local participation, and tailored financial instruments, underscores the importance of adapting solutions to the environmental, institutional, and socioeconomic context.

Replicability depends not on universal technology but on the transferability of governance models.

### **OPERATIONAL SYNTHESIS**

From the comparative analysis, five strategic levers consistently emerge in successful experiences:

1. Technological integration across treatment, resource recovery, and digitalization
2. Consortium-based or multilevel management to overcome fragmentation
3. Active community participation, especially in decentralized settings
4. Economic sustainability and scalability, enabled by partnerships and flexible instruments

#### 5. Adaptive governance, capable of aligning innovation with social acceptance

These elements offer practical guidance for developing effective water industrial policies, rooted in real-world cases and capable of steering a systemic transition based on evidence.

In this regard, a comparative analysis conducted by McLennan et al. (2024) across six EU Member States highlights that, despite the transformative potential of Regulation (EU) 2020/741 on agricultural water reuse, significant barriers to its full implementation remain. In particular, operational challenges are noted in relation to adaptation costs, regulatory inconsistencies between national and supranational levels, and the physical distance between treatment plants and irrigable agricultural areas.

These obstacles underscore the need to strengthen institutional coordination, invest in intermediate infrastructure, and promote more integrated territorial governance, so that EU regulations can be effectively translated into local practices.

### 6.4 TIMEFRAMES FOR INTEGRATED WATER RESILIENCE

The transition toward resilient and circular water management requires a clear, staged vision over time. The necessary transformations — infrastructural, regulatory, technological, and cultural — cannot occur simultaneously but must follow a progressive implementation pathway, distinguishing between high-priority actions and long-term consolidation measures.

In this perspective, we propose a three-phase strategic roadmap, inspired by the Adaptive Pathways approach (Haasnoot et al., 2013) and aligned with the goals of SDG 6, the European Green Deal, REPowerEU, and the Net-Zero Industry Act. This temporal structure links the risk–opportunity analysis (see Chapter 5) with operational planning, enabling a more transparent and efficient allocation of resources and instruments.

Supporting this gradual logic, the OECD (2022) has developed the Strategic Investment Pathways (SIPs) approach. This model builds dynamic portfolios of resilient water interventions, planned according to adaptive, scenario-tested logic across climate, financial, and regulatory variables. SIPs are structured in phases:

1. Identifying shared resilience goals
2. Selecting technical and institutional options
3. Building flexible investment pathways
4. Defining decision triggers and periodic updates

Their value lies in avoiding infrastructure lock-in, ensuring policy coherence over time, and fostering proactive governance that can adapt to evolving environmental and socioeconomic conditions. SIPs are especially effective in linking water resilience to the energy transition, bridging public planning with sustainable finance criteria.

**WATER RESILIENCE ROADMAP – 2025 / 2030 / 2050**

Time Horizon	Main Objectives	Priority Actions	Key Indicators
<b>2025–2027</b>	Mitigate immediate risks and systemic losses	- Reduce urban water losses - Introduce progressive tariffs - Mandatory water audits for high-use industries - Set minimum ESG water KPIs	• % network losses • €/m <sup>3</sup> saved • No. of companies with water ESG reporting
<b>By 2030</b>	Build resilient and enabling water infrastructure	- Systemic reuse in agriculture and industry - Regional water resilience plans - Flow digitalization - Reform incentives and subsidies	• m <sup>3</sup> /year reused • % territory with resilience plans • % CAPEX for water resilience
<b>By 2050</b>	Integrate water into climate–industry–territory strategies	- Closed-loop industrial systems - Synergies with green hydrogen - Hydro-compatible climate and industry plans - Monetize ecosystem services	• % closed-loop industry • % H <sub>2</sub> from wastewater • NWV in public accounts

This timeline allows for the alignment of:

- **Low marginal cost actions** (e.g., leak reduction, agricultural reuse);
- **Systemic regulatory reforms** (e.g., revision of tariffs and subsidies);
- **Long-term strategic investments** (e.g., green hydrogen, industrial closed loops).

The matrix (Figure 7) provides a concise and comparative overview of the level of sectoral engagement across different time horizons in the water transition (2025–2050). The goal is to facilitate the identification of strategic priorities and intersectoral synergies over time.

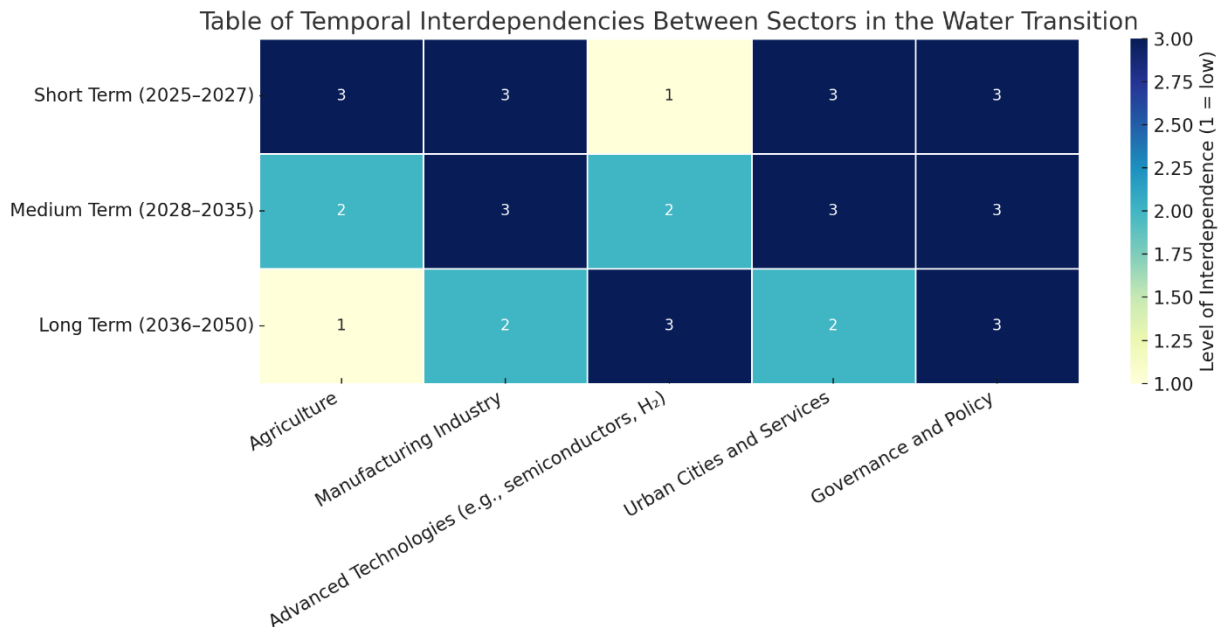


Figure 5 Table of Temporal Interdependencies Between Sectors in the Water Transition

Time Horizon	Operational Description
<b>2025–2027</b>	Urgent, ready-to-implement actions
<b>2028–2035</b>	Infrastructure building, regulation, scaling
<b>2036–2050</b>	Systemic integration and long-term impact



**Agriculture and Cities:** Immediate and critical role (2025–2027), due to direct exposure to water stress and high potential for rapid interventions (e.g., irrigation reuse, leak reduction, social tariffs). Their operational adaptability is essential to system stabilization.

**Manufacturing Industry:** Involved across all phases — pilot and retrofit in the short term; scaling via policy in the mid-term (2028–2035); full closed-loop and energy–water symbiosis by 2036–2050.

**Advanced Technologies** (e.g., semiconductors, green hydrogen, data centres): Strategic by 2050 due to ultrapure water needs and energy integration. Interdependence with other sectors (industry, energy, governance) will grow exponentially.

**Governance and Policy:** Act as cross-cutting enablers. Their early involvement is key to ensuring regulatory coherence, economic tool effectiveness, and decision-level integration (local–national–EU).

For the full methodology, see Appendix B – Construction of the Sectoral Temporal Matrix.

The transition process faces time-dependent obstacles that require dynamic, coordinated, and adaptive solutions.

A realistic planning approach must acknowledge that certain barriers — regulatory, technological, financial, or social — emerge or diminish at different moments, directly influencing the feasibility and urgency of interventions.

Barrier Type	Short Term (2025–2027)	Mid Term (2028–2035)	Long Term (2036–2050)
<b>Regulatory</b>	Uncertainty around reuse, slow permits	Need for EU–local harmonization, ESG regulation	Climate legislation updates
<b>Technological</b>	High upfront costs, system complexity	Advanced maintenance, full digitalization	Obsolescence and lifecycle renewal
<b>Financial</b>	Credit access for SMEs, early investments	Infrastructure amortization, tariff stability	Integration into multi-year public budgets
<b>Social</b>	Low reuse acceptance, local opposition	Equity in access, progressive tariffs	Intergenerational justice, future inclusion

In the 2025–2027 period, priority actions must focus on removing regulatory and procedural barriers through the simplification of authorization processes for water reuse, the adoption of shared technical standards, and the definition of sector-specific operational guidelines. At the same time, it will be strategic to promote pilot and demonstration projects capable of testing innovative solutions in real and transferable contexts. A further pillar will be the strengthening of monitoring and transparency systems through the introduction of digital tools and standardized indicators to support reporting and stakeholder engagement.

In the medium term (2028–2035), the main objective will be the consolidation and scaling of already tested circular water management models through deployment policies, regulatory interoperability, and support for the transition in less-equipped territories. During this phase, it will be essential to activate stable and large-scale financing mechanisms, such as incentive-



based tariffs, revolving funds, tax credits, and blended finance. In parallel, it will be necessary to develop and implement a coherent set of resilience indicators to measure the effectiveness of water policies in environmental, economic, and social terms.

Finally, in the 2036–2050 period, the challenge will be to ensure the long-term sustainability of the water transition, by transforming management systems into resilient and adaptive infrastructures capable of generating systemic value over time. This requires the activation of virtuous cycles between technological innovation, multilevel governance, and environmental and social co-benefits, within a regulatory and financial framework integrated with climate, industrial, and territorial agendas.

## **6.5 TOWARDS A RESILIENT AND CIRCULAR INDUSTRIAL WATER STRATEGY**

Water is now one of the most critical resources for the sustainability and competitiveness of industrial economies. In a context marked by increasing water stress, climate crises, and regulatory and technological transformations, building a resilient and circular water strategy is not merely an opportunity—it is a structural necessity.

Linear management models—withdraw, use, discharge—are limited in terms of environmental impacts, operational costs, and vulnerability to external shocks. In contrast, the circular approach, based on reduction, reuse, recovery, and regeneration, increases water security, reduces dependence on primary resources, improves efficiency, and generates value from wastewater.

Industrial water resilience requires an integrated, multi-level approach. Key elements include the adoption of innovative tools for circular water economy—such as membrane systems, real-time digital control tools, and energy and nutrient recovery solutions. Additionally, cross-sectoral planning is essential to effectively link water, energy, agriculture, and manufacturing flows through industrial symbiosis and shared management models.

Recent international research underscores the importance of integrating industrial water symbiosis approaches, treating water as a cross-sectoral exchange vector. According to Ali and Acquaye (2024), quantitative models for water-material symbiosis can reduce freshwater demand by up to 45% in industrial zones, by enabling reuse between neighbouring plants, shared treatment infrastructure, and secondary markets for treated water resources.

These models employ optimized flow networks, environmental indicators (e.g., water-carbon LCA), and multi-objective simulations to assess efficiency scenarios and co-benefits. Systemic integration of water symbiosis enhances operational resilience, economic competitiveness, and ESG compliance—making it a cornerstone of circular industrial strategy. Another enabling factor is the use of advanced tools for measuring circularity, such as the Process Circularity Index (ProCI) proposed by Pilipenets et al. (2025). Designed for industrial production systems, this indicator integrates variables such as water, energy, and material flows, along with associated emissions, enabling a more comprehensive and comparable assessment of circular performance. Looking ahead, metrics like ProCI can support the shift from linear efficiency to systemic industrial resilience—grounded in adaptive optimization, environmental accountability, and digital innovation.

Equally crucial is multi-level governance, which promotes coordination among public bodies, businesses, and local communities, enabling co-designed adaptive solutions. Financial and regulatory instruments are needed to support circularity—making technologies scalable and bankable through clear reporting standards and water performance indicators.

In this scenario, industry can act as a driver of transformation—not only as a responsible consumer but as a regenerative producer: capable of treating water as a shared, renewable, and



strategic resource. A water-resilient company invests in innovation, measures and communicates its impacts, collaborates at the local level, and actively positions itself in sustainability-oriented markets (ESG, green finance, carbon neutrality).

At the macro level, the industrial water strategy must become an integral part of the ecological, digital, and production transitions, contributing to the achievement of Sustainable Development Goals (SDGs 6, 9, 12, and 13), decarbonization, and the development of production systems capable of adapting and thriving in a changing hydrological context.

Documented experiences in emerging contexts such as Durban, Tamil Nadu, and Lima demonstrate that even resource-limited regions can adopt effective circular solutions, through decentralized approaches, green infrastructure, and community engagement. These cases highlight that the water transition cannot rely solely on high-tech and capital-intensive solutions; instead, it must be based on accessibility, flexibility, and water justice. Ensuring replicability and adaptability—especially in fragile or informal settings—is essential for building a truly resilient global industrial strategy. A public policy geared toward water circularity must therefore integrate territorial equity, support low-tech innovation, and promote inclusive governance models capable of reinforcing social cohesion.

To support this systemic vision, it is essential to adopt polycentric governance models that go beyond the binary of centralized vs. decentralized management. Established experiences such as Japan's RCES (Regional Circular and Ecological Sphere) or the IWRM (Integrated Water Resources Management) approach show how co-management of water—based on shared responsibilities, active participation, and institutional flexibility—is key to ensuring resilience, equity, and adaptability of circular solutions. These models emphasize integration between government levels, productive sectors, and local actors, providing a coherent framework for addressing complex challenges in evolving water environments (Savelli et al., 2021).

Building a resilient and circular industrial water strategy means systemically addressing one of the defining challenges of the 21st century. It means treating water not just as an input, but as an invisible infrastructure that connects environment, economy, and society.

## 6.6 TABLES AND COMPARISON

### 6.6.1 Sectoral Summary of Water Efficiency

Sector	Critical Issues	Emerging Solutions	Outlook
<b>Agri-food</b>	70% of global withdrawals; highly exposed to climate variability and water scarcity	Efficient irrigation (drip, sprinkler); digital monitoring; reuse of wastewater and nutrients	Up to 50% reduction in demand in selected contexts
<b>Manufacturing and Chemical Industry</b>	High water consumption; complex discharges; growing operational risks	Internal recycling; IoT/SCADA systems; environmental certifications (ESG, ISO 14046)	Up to 60% reduction in withdrawals (e.g., USA)
<b>Wastewater and Sludge Treatment</b>	Linear approach; low resource recovery from effluents	Multifunctional plants; AOP, membranes, selective separation; industrial symbiosis	50–80% energy self-sufficiency; valorised by-products

### 6.6.2 Recommendations by Stakeholder Target

Target	Recommendation	Objective
<b>Companies</b>	Integrate water KPIs into ESG and management systems	Improve efficiency and reporting
<b>Companies</b>	Invest in reuse and digitalisation technologies	Reduce costs and environmental impact
<b>Companies</b>	Promote industrial symbiosis and shared management	Increase competitiveness and resilience
<b>Regulators</b>	Establish regulatory standards for safe water reuse	Ensure quality and safety
<b>Regulators</b>	Introduce economic incentives and pricing tools	Accelerate adoption of efficient solutions
<b>Policymakers</b>	Fund circular infrastructures and R&D	Support innovation and scalability
<b>Policymakers</b>	Promote water culture and water justice	Ensure equitable and sustainable access
<b>Policymakers</b>	Facilitate replication of solutions in fragile and decentralized contexts	Reduce inequalities and ensure fair water access

### 6.6.3 Guidelines for an Advanced Industrial Water Strategy

Strategic Pillar	Key Action
<b>Technological</b>	Deployment of advanced treatment plants and smart sensors
<b>Economic-Financial</b>	Incentives for water reuse and circularity
<b>Regulatory</b>	Harmonized legal framework enabling resource recovery
<b>Operational</b>	Water benchmarks and KPIs by sector and industrial district
<b>Social-Cultural</b>	Education on water value and reuse acceptance

## 6.7 PUNTI PRINCIPALI

### **Water Scarcity Is a Multisectoral and Systemic Challenge**

It affects agriculture, industry, and cities across the board. It cannot be tackled in a sectoral manner but requires integrated responses from public and private actors, as well as local communities.

### **Technologies and Models Already Exist: The Challenge Is Scaling Up**

Solutions for water reuse, digitalisation, and resource recovery are technically mature and operational. What's missing is their systemic adoption, hindered by economic, regulatory, and cultural barriers.

### **Companies Must Treat Water as a Strategic Asset**

Efficiency, resilience, and circularity must be embedded in industrial KPIs. Investing in advanced water management is not only an environmental action, but also an economic and reputational one (ESG, SDG, green finance).

### **Regulatory Authorities Must Enable a Supportive Framework**

Clear standards for reuse, simplified procedures for decentralised treatment, and incentive systems for water efficiency are needed — including progressive pricing mechanisms and performance-based rewards.

### **Policymakers Must Integrate Water into the Ecological Transition**

Water must be included in climate, industrial, and agricultural agendas. A strategic national and European vision is required, encompassing green infrastructure, circular economy, and equitable access to the resource.

### **Towards a Resilient and Regenerative Industrial Water Strategy**

Building a new strategy means:

- ♣ Investing in enabling digital technologies,
- ♣ Promoting symbiosis models and multi-level governance,
- ♣ Making circular solutions bankable through dedicated financial instruments.

## 7 LIMITATIONS OF THE STUDY

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- ♣ **Simplified economic assumptions** – The estimates of added value (1–3 €/m<sup>3</sup> in agriculture; >500 €/m<sup>3</sup> in high-tech) are based on macro-sector averages and do not account for price fluctuations, tax incentives, or local subsidies.
- ♣ **Climate uncertainty** – Water stress projections rely solely on the IPCC SSP2-4.5 scenario. The lack of sensitivity analysis to more severe scenarios (e.g., SSP3-7.0, SSP5-8.5) may underestimate associated risks.
- ♣ **Methodological limitations of the Water-Energy-Food Nexus** – The model used accounts for energy flows only in terms of direct electricity consumption. It does not include the 'embedded' impacts in materials (e.g., cement, steel) or supply chain greenhouse gas emissions.
- ♣ **Limited availability of tariff time series** – International comparisons on water tariffs are based on annual snapshots; monthly or seasonal data, which would allow analysis of volatility and price elasticity, are lacking.
- ♣ **Risk of overgeneralization** – Some policy recommendations (e.g., mandatory 25% reuse by 2030) are derived from regulations in pioneering countries and may not apply to institutional contexts with limited regulatory capacity.

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## APPENDIX A: METHODOLOGY FOR SECTORAL AND TECHNOLOGICAL COMPARATIVE ASSESSMENT

### A.1 Purpose

This appendix outlines the framework used for the comparative classification of key technological and sectoral solutions within the transition toward resilient and circular water systems. The approach integrates environmental, climatic, economic, operational, and territorial criteria, offering a robust basis for:

- strategic investment selection (e.g., NRRP, CAP, REPowerEU),
- ex-ante evaluations in public-private project finance,
- benchmarking of technologies and operational models,
- integrated planning under water stress or energy transition scenarios.

The methodology is consistent with the WR4ER Framework (Matthews et al., 2024), OECD recommendations (2022), and the environmental objectives of the EU Taxonomy and European Green Deal.

### A.2 Evaluation Structure: Criteria and Classification

Each solution is assessed based on five qualitative criteria, using a normalized 1–3 scale. These criteria were selected based on their relevance for systemic resilience and the circular transition.

Criterion	Description	Main Sources
<b>Operational Risk</b>	Management complexity, likelihood of failure, technological maturity	OECD, WR4ER, UNEP (2021)
<b>Climate Risk</b>	Vulnerability to extreme events, dependence on unstable sources	Liu et al., 2022; Haasnoot et al., 2013
<b>Environmental Opportunities</b>	Potential to reduce emissions, withdrawals, pollutant loads	ISO 14046; Water Europe (2024); Peydayesh & Mezzenga (2024)
<b>Economic Opportunities</b>	Net economic return, cost savings, value creation	Matthews et al., 2024; Pot (2023); OECD, 2022
<b>Territorial Scalability</b>	Adaptability to different socio-institutional and geo-climatic contexts	UNEP; Arora & Mishra, 2022

*Each value was assigned based on qualitative evidence, comparative reviews, and exemplary case studies (Singapore, Prato, Lima, Durban, etc.)*

Scoring values:

- **1** = unfavourable/critical condition
- **2** = moderate/acceptable
- **3** = favourable/high resilience or opportunity

For risk criteria, an inverse transformation system is applied for comparability with other criteria (higher score = more favourable condition):

$$v_i = 4 - r_i$$

Where  $r_i$  is the original risk score (1 = low risk → 3 = high risk), and  $v_i$  is the transformed value.

### A.3 Two Representations, One Dataset

The framework can be visualized using two tools based on the same base values:

#### **DESCRIPTIVE HEATMAP**

**A colour-based graphic representation allows:**

- ♣ immediate visibility of differences between options.
- ♣ non-aggregated visual comparability.
- ♣ useful communication for presentations and non-technical summaries.

No weights or formulas are applied.

All criteria have equal visual weight.

#### **WEIGHTED MULTI-CRITERIA MODEL**

**A decision-making tool that:**

- ♣ computes a total composite score per option.
- ♣ integrates differentiated weights per criterion, based on strategic relevance.
- ♣ provides a comparative ranking for project selection, policy design, or technology mix.

### A.4 Weighted Model Formulae

The model uses a **Weighted Linear Combination (WLC)**:

$$Total\ Score = \sum_{i=1}^n v_i \cdot w_i$$

Where:

- $w_i$  = weight of criterion  $i$  (e.g., 0.15 for 15%).
- $v_i$  = normalized score for that criterion.
- $i$  = criterion index, from 1 to  $n$ .
- $n = 5$  (total number of criteria).

#### **Adopted Weights:**

The weights can be adjusted for specific scenarios or derived from participatory processes (AHP, Delphi, etc.).

Criterion	Weight (%)	Rationale
<b>Operational Risk</b>	15%	Determines manageability and unexpected costs
<b>Climate Risk</b>	15%	Critical under climate uncertainty scenarios
<b>Environmental Opportunities</b>	30%	Aligned with EU Taxonomy and climate neutrality
<b>Economic Opportunities</b>	25%	Drives value generation and public/private ROI
<b>Territorial Scalability</b>	15%	Key factor for replicability and equitable benefit distribution

Sources: OECD (2022), WR4ER Framework (Matthews et al., 2024), Pot (2023), EU Green Deal (2021).



## **A.5 Limitations and Potential Developments**

### **Strengths:**

- Transparent and logically traceable.
- Adaptable to different sectoral or geographic contexts.
- Aligned with EU environmental and financial evaluation tools (e.g., SFDR, SEEA-Water).

### **Limitations:**

- Subjectivity in initial score assignment (requires expert validation).
- Fixed weights (not derived from AHP or participatory methods).
- Lack of explicit social criteria (which could be added in future models).

### **Possible Developments:**

- Inclusion of additional criteria (e.g., public acceptability, marginal cost).
- Weight derivation via Delphi or Analytic Hierarchy Process (Saaty, 1980).
- Digitalization into an interactive dashboard for use by policymakers or multi-stakeholder panels.

## APPENDIX B: METHODOLOGY FOR DEFINING THE TIMELINE AND SECTORAL TEMPORAL INTERDEPENDENCIES

### B.1 Purpose and Analytical Structure

The construction of the temporal roadmap and the matrix of sectoral interdependencies is based on a qualitative-quantitative multi-criteria model, aimed at:

- Identifying priority and strategic actions over time (2025–2027, 2028–2035, 2036–2050).
- Assessing the degree of temporal involvement of key sectors (agriculture, industry, technologies, cities, governance).
- Ensuring logical consistency with major reference frameworks: SDG 6, EU Green Deal, Water Europe Vision 2050, REPowerEU strategies, and WR4ER (Matthews et al., 2024).

### B.2 Temporal Horizon

Time Horizon	Operational Definition	Strategic Objective
Short-term	2025–2027	Initial implementation and consolidation of measures already launched or ready for deployment
Medium-term	2028–2035	Infrastructure stabilization, reform of economic instruments, and territorial governance
Long term	2036–2050	Systemic integration of water into climate, industrial, and territorial models

This structure reflects the three-year and decadal cycle of many EU and national strategies (e.g., PNIEC, Water4All, Horizon Europe).

### B.3 Construction of the Sectoral Roadmap

The actions planned for each horizon were selected based on:

- Technological maturity (Technology Readiness Level  $\geq 7$ ).
- Ex-ante cost-effectiveness analysis (Water Europe, OECD, EIB).
- Regulatory and social feasibility.
- Real-world experiences already in the pilot or operational phase (Singapore, Spain, Australia, the Netherlands).

Each action was assigned a set of measurable temporal indicators, normalized on an annual basis.

### B.4 Construction of the Sectoral Interdependency Table

The heatmap of interdependencies between sectors was developed by assigning each sector a score from 1 (weak) to 3 (strong) for each time horizon, according to the following criteria:



Score	Operational Meaning
1	Marginal or delayed contribution
2	Gradual or intermediate role
3	Immediate or systemic involvement

### B.5 Model Limitations and Recommendations

The model is intended for strategic and guiding purposes, not as a substitute for detailed quantitative or modelling sector analyses. It supports:

- Multi-stakeholder programming.
- Communication of investment priorities.
- Temporal and territorial coordination.

## APPENDIX C: OPERATIONAL TOOLKIT FOR THE DESIGN OF RESILIENT INTERVENTIONS IN THE WATER CYCLE

The objective of this toolkit is to provide a concise yet structured tool to support the design, monitoring, and financing of resilient and circular water solutions aligned with the objectives of the 2030 Agenda, the European Green Deal, and national strategies (PNIEC, PNRR, REPowerEU).

### C.1– Decision-Making Flowchart for Identifying Priority Solutions

Guiding Question	Operational Indication
Is the territory subject to chronic water stress?	→ Prioritize reuse and demand management solutions
Are alternative sources available (wastewater, rainwater)?	→ Activate reuse or storage circuits
Is the area agricultural, industrial, or urban?	→ See section C.2 for technology types
Are there regulatory or economic barriers?	→ Refer to section C.3 (support tools)
Is a partnership between local authorities and businesses available?	→ Activate a Living Lab or PPP approach

### C.2 – Map of Circular Solutions by Sector

Sector	Priority Technical Solutions	Main Benefits
<b>Agriculture</b>	Irrigation reuse, fertigation, MAR (Managed Aquifer Recharge)	Reduced withdrawals, fertilizer savings
<b>Industry</b>	MBR, closed-loop systems, water symbiosis	Efficiency, ESG, cost reduction
<b>Urban</b>	Rainwater harvesting, phytoremediation, smart metering	Reduced losses, sanitary resilience
<b>Advanced Tech</b>	Closed-loop cooling, greywater reuse	Operational continuity, environmental rating

### C.3 – Integrated Design Checklist (Multi-Criteria)

#### *Environmental Criteria*

- 30% reduction in withdrawals from conventional sources
- Documented avoided GHG emissions (e.g., ETS, N<sub>2</sub>O)
- Aquifer recharge or reduction of eutrophication

#### *Economic Criteria*

- Positive Life Cycle Cost (LCC) in <10 years
- Expected ROI >7%, including risk scenarios



- Access to funding (EIB, Horizon, Green Bonds)

#### *Social and Governance Criteria*

- Inclusion of marginalized stakeholders (SDG 6.B)
- Fair and transparent pricing
- Compensation mechanisms in case of water use conflicts

#### **C.4 – Indicative KPIs and Targets (Benchmarks)**

<b>KPI</b>	<b>Recommended Threshold</b>	<b>Source</b>
<b>% of reused water over total treated volume</b>	>60%	Water Europe (2024)
<b>Avoided marginal cost (€ per m<sup>3</sup>)</b>	<€1.5/m <sup>3</sup>	OECD (2022)
<b>GHG avoided per hectare (agricultural reuse)</b>	>1 tCO <sub>2</sub> eq/ha	IWMI (2022)
<b>Water Productivity (€ per m<sup>3</sup>) in industry</b>	>€15/m <sup>3</sup>	CDP (2023)

#### **Reference Documents and Standards**

- ISO 14046 – Water Footprint
- GRI 303 – Water and Effluents
- SEEA-Water – United Nations
- EU Regulation 2020/741 – Water Reuse
- Water Resilience Framework – WR4ER (Matthews et al., 2024)

## APPENDIX D: TECHNOLOGY SELECTION GUIDE FOR WATER TREATMENT AND REUSE

This guide supports the selection of the most appropriate technologies for water treatment and reuse in industrial, agricultural, and urban contexts, using a multi-criteria decision analysis (MCDA) approach. Evaluation is based on five qualitative criteria, considering contextual conditions, regulatory constraints, and circularity needs.

### D.1 Evaluation Criteria

Criterion	Description
<b>Removal Efficiency (E)</b>	Capacity to remove key parameters (BOD, COD, nutrients, micropollutants)
<b>Operating Costs (C)</b>	Average OPEX (€/m <sup>3</sup> ) and routine maintenance
<b>Energy Consumption (EN)</b>	Specific energy required (kWh/m <sup>3</sup> treated)
<b>Scalability (S)</b>	Flexibility and replicability across different sizes and territories
<b>Regulatory Barriers (B)</b>	Authorization complexity, reuse standards, and regulatory constraints

#### Rating Scale:

★★★ = high / favourable | ★★ = medium / intermediate | ★ = low / critical

- For **E** and **S**, ★★★ indicates **advantages**.
- For **C**, **EN**, and **B**, ★★★ indicates **higher criticality** (e.g., high cost, complex barriers).

**Table D.2 – Multi-Criteria Comparison of Technologies**

Technology	E	C	EN	S	B
<b>Reverse Osmosis (RO)</b>	★★★	★	★	★★	★★
<b>Membrane Filtration (UF/NF)</b>	★★	★★	★★	★★	★★
<b>Membrane Bioreactors (MBR)</b>	★★★	★	★	★	★
<b>Advanced Oxidation (AOP)</b>	★★★	★★	★★	★	★
<b>Settling + Sand Filtration</b>	★	★★★	★★★	★★★	★★★
<b>Phytoremediation / NBS</b>	★	★★★	★★★	★	★★

#### Legend:

- RO** = Reverse Osmosis
- UF/NF** = Ultra-/Nano-Filtration



- **MBR** = Membrane Bioreactor
- **AOP** = Advanced Oxidation Processes
- **NBS** = Nature-Based Solutions

### Usage Recommendations

Application Context	Recommended Technologies	Operational Notes
<b>Chemical and pharmaceutical industries</b>	RO, MBR	Require pre-treatment and sludge management
<b>Agro-industry</b>	UF/NF, NBS	Good balance between cost and performance
<b>Decentralized urban areas</b>	AOP, UF	Modular and suitable for residential blocks
<b>Small towns and agricultural districts</b>	Phytoremediation, sand filtration	Manageable at community level

### D.3 Methodological Notes

- Scores are based on bibliographic synthesis, technical data from pilot projects (e.g., RichWater, DEMOWARE), and established European experiences (e.g., Spain, Netherlands, Singapore).
- The star system is descriptive and comparative; it does not produce a numerical ranking.
- For in-depth analysis, use weighted MCDA models or interactive dashboards.

### D.4 Potential Future Developments

- Integration of explicit environmental indicators (e.g., carbon footprint, nutrient recovery, water circularity index).
- Addition of social criteria (e.g., public acceptability, local governance, co-benefits).
- Digital integration into GIS tools or decision-making platforms (e.g., Water Europe Marketplace).



## GLOSSARY

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### CHAPTER 1 – INTRODUCTION AND GLOBAL CONTEXT

- ✦ **WEI<sup>+</sup> (Water Exploitation Index Plus):** Measures the level of water stress (>20% indicates criticality).
- ✦ **Water Stress:** A situation where water demand exceeds the local availability of freshwater.
- ✦ **Water Footprint (WF):** Total volume of freshwater used in a process or product (including virtual water).
- ✦ **SDG (Sustainable Development Goals):** United Nations framework for global sustainable development.
- ✦ **Virtual Water:** Amount of water embedded in products through the entire production cycle.

### CHAPTER 2 – SECTORAL FOCUS: AGRICULTURE, INDUSTRY, WASTEWATER

- ✦ **Drip Irrigation:** High-efficiency system delivering water directly to plant roots, minimizing evaporation and runoff.
- ✦ **Subsurface Irrigation:** Irrigation method delivering water underground through porous pipes, enabling localized continuous release.
- ✦ **Greywater:** Domestic wastewater from sinks, showers, and laundry, with low contamination and suitable for easier reuse.
- ✦ **Blackwater:** Wastewater with high pollutant load, from toilets or combined sewers; requires complex treatment for reuse.
- ✦ **MBR (Membrane Bioreactors):** Systems combining biological treatment and membrane filtration to purify wastewater for reuse.
- ✦ **SCADA (Supervisory Control and Data Acquisition):** Digital system for remote monitoring and automation of water and treatment infrastructure.
- ✦ **Industrial Symbiosis:** Integration between industries to share water and energy resources, reducing waste and improving systemic efficiency.
- ✦ **Levelized Cost of Water (LCW):** Economic indicator representing the average cost per unit of water saved or recovered over a system's lifecycle.

### CHAPTER 3 – MEASURING WATER EFFICIENCY

- ✦ **KPI (Key Performance Indicator):** Metric used to monitor the effectiveness of water management strategies.
- ✦ **Reuse Ratio:** Percentage of treated wastewater that is reused, reflecting recovery system efficiency.
- ✦ **Water Intensity:** Volume of water used per unit of product (e.g., m<sup>3</sup> per ton), useful for evaluating process-related water pressure.



- ✦ **Water Accounting:** Systematic process of recording inflows, outflows, losses, and reused water to support sustainable decision-making.
- ✦ **Water Stress Index (WSI):** Ratio of annual water withdrawals to local renewable availability; quantifies regional stress.
- ✦ **SEEA (System of Environmental-Economic Accounting):** UN-endorsed framework integrating economic and environmental data, including water use and condition.
- ✦ **AWS Standard (Alliance for Water Stewardship):** International standard for responsible water management at the watershed level, involving public and private stakeholders.

#### **CHAPTER 4 – TECHNOLOGIES AND INNOVATION**

- ✦ **AOP (Advanced Oxidation Processes):** Treatment methods using free radicals (e.g., •OH) to degrade persistent organic micropollutants.
- ✦ **UF / NF / RO:** Membrane filtration technologies – Ultrafiltration, Nanofiltration, and Reverse Osmosis – with increasing selectivity for particle and solute removal.
- ✦ **Reverse Osmosis (RO):** Pressure-driven process to remove salts, heavy metals, and contaminants from various water sources.
- ✦ **Digital Twin:** Dynamic and interactive digital replica of a water system or plant, enabling real-time operational simulation.
- ✦ **IoT (Internet of Things):** Technology infrastructure with networked smart devices for monitoring and automation of water systems.
- ✦ **Smart Metering:** Intelligent water consumption monitoring using remote-read meters for leak detection and demand optimization.
- ✦ **Phytoremediation:** Eco-friendly water treatment using aquatic plants and microorganisms in constructed wetlands or vegetated beds.
- ✦ **Nature-Based Solutions (NBS):** Infrastructure and management solutions inspired by nature to enhance water quality and resilience.
- ✦ **Modular-Adaptive-Decentralized (MAD):** Scalable, locally adaptable water treatment systems suitable for on-site and circular applications.

#### **CHAPTER 5 – ECONOMY, FINANCIAL TOOLS AND GOVERNANCE**

- ✦ **Blended Finance:** Financial approach combining public and private capital to support public-interest projects, including in the water sector.
- ✦ **PPP (Public-Private Partnership):** Cooperative model between public entities and private actors to implement or manage water infrastructure/services.
- ✦ **Progressive Tariffing:** Pricing scheme where water cost increases with volume used, promoting efficiency and equitable access.
- ✦ **Water ESG:** Integration of sustainable water management into Environmental, Social, and Governance investment frameworks.



- ♣ **Adaptive Pathways:** Dynamic planning approach allowing policy and investment adjustments based on evolving conditions.
- ♣ **Water Banking:** System for storing, conserving, or virtually transferring excess water between users or territories, enhancing flexibility and resilience.
- ♣ **Water Circular Economy Index (WCEI):** Composite index measuring water system circularity via reuse, efficiency, and loss reduction metrics.
- ♣ **Net Water Value (NWV):** Net economic value of water use, factoring in both benefits and associated environmental/social costs.

## **CHAPTER 6 – RECOMMENDATIONS, CASE STUDIES, STRATEGIES**

- ♣ **Fit-for-Purpose Reuse:** Strategy tailoring wastewater treatment quality to its intended final use (e.g., agriculture, industry, domestic) to avoid over-treatment.
- ♣ **Indirect Potable Reuse:** Advanced technique reintroducing treated wastewater into aquifers or reservoirs, followed by additional purification for drinking use.
- ♣ **Co-benefits:** Secondary positive outcomes (environmental, economic, or social) from an intervention designed for different primary purposes (e.g., climate mitigation).
- ♣ **Positive Water District:** Urban model in which a neighbourhood is designed to be water- and climate-self-sufficient through reuse, rainwater harvesting, and NBS.
- ♣ **ZSC – Zero Stress Cities:** Cities implementing integrated strategies to eliminate water stress and enhance resilience via circular planning, smart tech, and participatory management.



## AUTHOR INFORMATION AND LICENSE

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