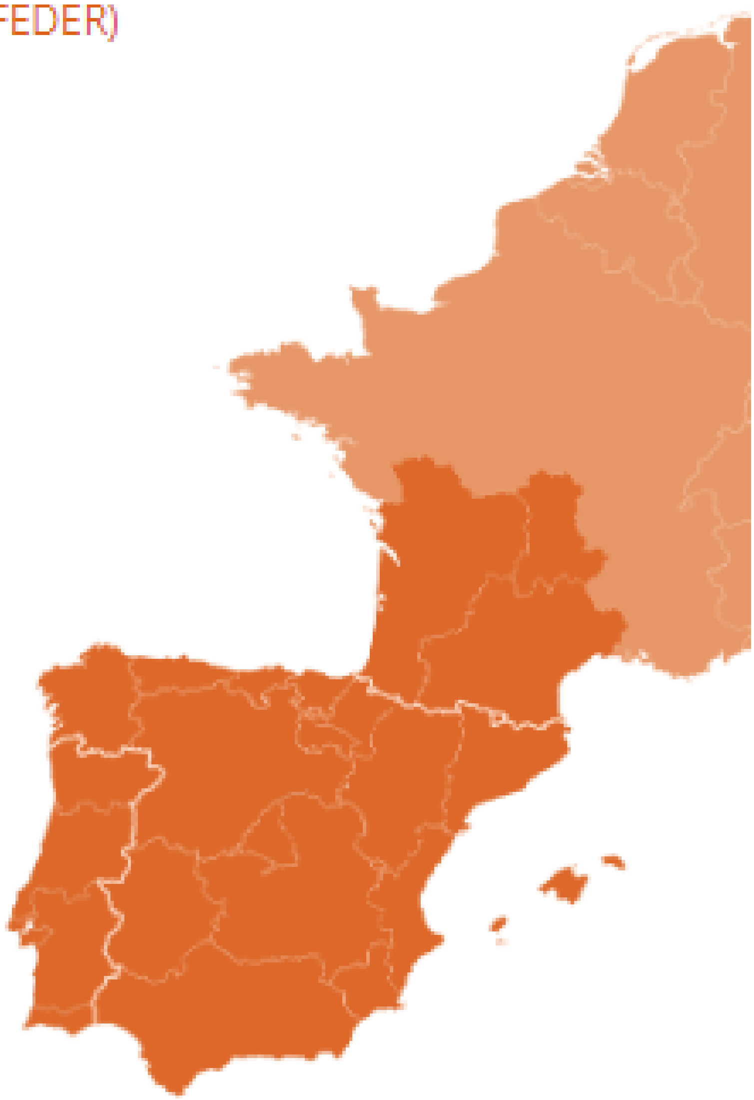
GestEAUr

Gestión sostenible y digitalizada del agua en entornos rurales del espacio SUDOE

Proyecto cofinanciado por el Programa Interreg Sudoe a través del Fondo Europeo de Desarrollo Regional (FEDER)

Universidad de Salamanca
Escuela Politécnica Superior de Ávila
aqualia
aqualia Portugal
cnrs
Diputación de Ávila
Universidad de Castilla-La Mancha (UCLM)
cim alto minho – comunidade intermunicipal do alto minho
Águas do Tejo Atlântico – Grupo Águas de Portugal
Pays de Béarn



Strategy to improve water management and increase climate change resilience in SUDOE / E.3.4.1

A.3.4

30/07/2026

Cooperar está en tus manos

INDEX

INTRODUCTION

The Southwestern Europe (SUDOE) region consists of a diverse set of 26 regions across Spain, France, and Portugal, covering approximately 18.3% of the European Union's territory. These areas are home to over 68.2 million people, many of whom reside in **rural municipalities with low population densities** that present unique **logistical and economic challenges** for water resource management. The GestEAUr project, funded under the Interreg SUDOE program, aims to preserve natural capital and reinforce adaptation to climate change within these vulnerable environments.

Rural territories in the SUDOE space currently face a multifaceted crisis. Climate change has significantly perturbed meteorological and hydrological patterns, leading to a paradox of systemic water scarcity alongside an increased frequency of extreme rainfall events. In the Segura Hydrographic Demarcation, for instance, the number of rainy days has decreased while the intensity of individual events—exceeding 40 mm in 24 hours—has risen, escalating the risk of both flash floods and agricultural drought. Furthermore, the impact of agricultural and livestock activities on water quality is profound. High concentrations of nitrates from fertilizers and pesticides contaminate groundwater bodies, making the provision of safe drinking water a continuous challenge.

The **existing infrastructure in these regions is often obsolete and inefficiently managed** due to a lack of specialized technical personnel and financial deficits. Traditional water treatment systems are frequently non-profitable in zones with sparse populations, leading to a persistent decline in service quality and environmental directive compliance. GestEAUr addresses these gaps by **implementing a collaborative strategy that leverages the expertise of institutions** such as the University of Salamanca (USAL), the University of Castilla-La Mancha (UCLM), Centre National de la Recherche Scientifique - PROcédés Matériaux et Energie Solaire (PROMES), Pôle Métropolitain du Pays de Béarn, Diputación de Ávila, Comunidade Intermunicipal do Alto Minho, FCC Aqualia S.A, FCC Aqualia, S.A. – Sucursal em Portugal and Águas do Tejo Atlântico.

The project has developed a diagnosis in each of the 6 project areas and has produced a *"Catalog of Cost-Effective and Sustainable Solutions"* that allows local authorities to select modular, low-maintenance technologies adapted to their specific territorial needs. Moreover, it is testing innovative solutions to improve the water cycle in rural areas. By viewing the water cycle as a "common good" through territorial cooperation, GestEAUr seeks to bridge the gap between urban and rural water quality and secure the future of the SUDOE territory.

This strategy will be based in the project findings and will constitute a roadmap to improve water management and increase the resilience of SUDOE rural areas in a climate change context.

WATER TREATMENT, USES AND DEMANDS

The **sustainable management of water resources** in rural areas requires a comprehensive understanding of how water is used, how demand is evolving, and which treatment solutions are technically, economically and environmentally suitable for small and dispersed settlements.

Although rural areas are often analysed separately from urban systems, many of their water needs are directly connected to urban water services: drinking water supply for households and public buildings, sanitation, wastewater treatment, stormwater management, small-scale industrial or agri-food uses, tourism-related consumption, and the maintenance of public green areas and local services. However, the specific characteristics of rural contexts — low population density, dispersed settlements, seasonal population changes, limited economies of scale and strong interaction with agricultural land uses — require adapted approaches. Conventional water treatment and management models are not always viable or cost-effective in these territories, which reinforces the need for modular, robust, low-maintenance and affordable solutions.

By **linking uses, demands and treatment options,** this section sets the foundation for the strategic objectives proposed in the following parts of the strategy. These objectives should support rural territories in moving towards a more resilient, efficient and circular water management model, capable of ensuring access to safe water, reducing pressure on conventional resources, improving wastewater treatment and reuse, and strengthening local decision-making in a context of climate uncertainty.

Main urban water uses in rural contexts

The analysis is based on the five GestEAUr study areas: La Moraña, the Guadiana basin, Alto Minho, Portugal Oeste – Torres Vedras, and Béarn. These territories reflect different rural realities across the SUDOE area, ranging from highly dispersed inland municipalities to coastal, mountain, peri-urban and agricultural territories. Despite their diversity, they share common challenges related to low population density, seasonal variability, agricultural and livestock pressures, ageing infrastructure, limited technical and financial capacity, and increasing water stress linked to climate change.

In these rural areas, urban water use cannot be understood only as household consumption. Although **domestic supply and sanitation remain the core functions of the urban water cycle**, water services in rural contexts also support agricultural activity, small industries, agri-food production, tourism, public facilities, local commerce and the maintenance of green and public spaces. This creates a **complex demand profile** in which relatively small and dispersed populations depend on infrastructure that must also respond to seasonal peaks, productive uses and environmental protection needs.

The first and most essential use is **domestic and municipal consumption**. Water is required for drinking, hygiene, household activities, public buildings, schools, local health services, municipal facilities and small commercial activities. In areas such as La Moraña and the Guadiana basin, this basic use is strongly conditioned by the small size and dispersion of settlements. La Moraña includes 56 municipalities with only 19,115 inhabitants and an average density of 14.4 inhabitants/km²; 75% of its municipalities have fewer than 200 inhabitants. In the Guadiana area, the rural character is also evident, with very low population density and many municipalities with fewer than 2,000 inhabitants. The same situation is shared in Bearn, including in mountainous areas that bring other technical challenges (small systems must be created as no connection between settlements is possible).

In Portuguese rural contexts, as observed by Águas do Tejo Atlântico in low-density territories, urban water use presents a particular hybrid profile. Domestic consumption remains the primary use, but it is subject to pronounced seasonal variability driven by tourism, second homes and agricultural labour peaks. In addition, non-household uses — such as agro-industrial facilities, livestock operations, municipal services and irrigation support — exert significant localised pressure on supply systems. These patterns require water systems capable of tolerating sharp demand fluctuations while maintaining drinking water quality under increased raw water stress, particularly during drought periods.

In these territories, domestic water supply is not only a matter of availability, but also of service reliability, quality and affordability. The diagnoses show that rural water systems often depend on a limited number of sources, small treatment facilities, ageing networks and limited municipal budgets. In La Moraña, supply comes either from the Las Cogotas reservoir, used mainly for irrigation and occasionally for some southern municipalities, or from municipal boreholes tapping the aquifer; several local systems experience seasonal changes in operation, especially in summer. In the Guadiana basin, the Mancomunidad de Nogales depends on the Nogales reservoir and its drinking water treatment plant, but the diagnosis reports that water demand had exceeded the plant's treatment capacity. This illustrates a common rural vulnerability: relatively small systems may be sufficient under normal conditions but become very fragile when demand peaks or raw water quality worsens.

The second major use is linked to **agriculture and livestock**. In all five areas, agriculture is not only an external pressure on water resources, but also a central component of local water demand and rural economies. The Guadiana diagnosis highlights the importance of agricultural activities in the economic structure of the territory. In La Moraña, the territory is described as an agricultural plateau where the agricultural sector is considered a key factor in urban water management because of its influence on water availability and quality. In Béarn, agriculture covers approximately half of the territory, combining grasslands, mountain pastures, livestock, large crops, viticulture and other productive systems.

Agricultural water use is therefore both direct and indirect. Directly, it relates to irrigation, livestock watering, cleaning, farm operations and, in some areas, food-processing activities. Indirectly, agriculture affects the urban water cycle through diffuse pollution, especially nutrients, pesticides and other substances that can compromise drinking water quality and increase treatment needs. This is particularly relevant in rural SUDOE areas where agricultural and livestock activity can affect both water quality and availability, while treatment and monitoring capacities remain limited.

The third relevant use is **industrial and agri-food activity**. Rural areas do not necessarily have large industrial concentrations, but they often host small and medium-sized enterprises, food industries, wineries, livestock-related businesses, construction activities, extractive activities or industrial estates connected to local towns. These activities use water for processing, cleaning, cooling, washing, production and sanitation, and may generate wastewater requiring adequate collection and treatment. Torres Vedras is a clear example of a rural-coastal and peri-urban territory with strong agricultural and agro-industrial activity; the diagnosis identifies agriculture as the main development activity, especially viticulture and horticulture, while the secondary sector includes manufacturing industries, particularly agri-food businesses linked to animal feed, meat and dairy processing. Béarn also combines rurality with a diversified industrial base, including chemistry, materials, geosciences, energy, aeronautics and agri-food sectors. In Alto Minho, industrial, wine and food-sector pressures are explicitly identified among the point-source pressures affecting water bodies.

Tourism and seasonal population also play an important role in rural water use. In mountain, coastal and heritage areas, water demand may increase significantly during summer, weekends or holiday periods. This is especially relevant because seasonal demand peaks often coincide with the periods of lowest water availability. La Moraña identifies the need to design supply and sanitation systems capable of responding to seasonal water demands, noting that the highest demand coincides with the lowest water availability. Béarn also shows a seasonal water-resource challenge: its main rivers experience the lowest hydraulicity in August and September, while the territory also hosts tourism and leisure activities, particularly in mountain areas.

Across the five territories, the **management challenge** is therefore not only the amount of water consumed, but the mismatch between scattered demand, seasonal peaks, infrastructure capacity and limited local resources. Low population density increases the length and cost of networks per user, reduces tariff income, complicates maintenance and makes infrastructure renewal more difficult. In Béarn, drinking water services serve a dispersed territory through extensive networks, while the diagnosis highlights the rural character of the service and the challenges associated with serving hamlets and scattered settlements. In Alto Minho, dispersed settlement patterns also create challenges for the planning, operation and maintenance of essential infrastructure, including water supply and sanitation.

Wastewater collection and treatment are equally important urban water uses in rural contexts. Domestic, agricultural-related, industrial and tourism use all generate wastewater flows, but low-density territories often struggle to justify conventional centralised systems. Torres Vedras presents relatively high sanitation coverage, yet the diagnosis still identifies collective septic tanks and some untreated wastewater discharges as sources of negative impacts on water bodies. This confirms that even territories with structured systems may still face residual gaps in dispersed areas, making decentralised, modular and nature-based solutions relevant.

In conclusion, urban water use in rural contexts is multifunctional. It supports everyday life, public services, agriculture, livestock, local industry, tourism and environmental quality. However, the specific rural conditions identified in the GestEAUr diagnoses mean that rural water systems require adapted management models. These models should combine efficient domestic supply, agricultural and industrial water-use coordination, wastewater treatment and reuse, infrastructure renewal, digital monitoring and governance mechanisms capable of operating beyond individual municipal boundaries.

Main urban water demands in rural contexts

In this context, “demand” should not be understood only as the volume of water required by households, farms, industries or public services. It also refers to the **operational, qualitative, infrastructural and governance requirements** that rural territories place on the urban water cycle.

The diagnoses show that the main demand and challenge shared by the five areas is **quantitative reliability**. Rural territories require secure and stable access to water despite increasing droughts, low-flow periods, seasonal scarcity and climate-related uncertainty. This is particularly relevant in areas where river flows are highly seasonal, where aquifers or reservoirs are under pressure, or where summer demand coincides with reduced resource availability. In these contexts, water security is not only a matter of increasing available volumes, but of ensuring that supply systems are able to absorb fluctuations, diversify resources, reduce losses and maintain service continuity during periods of stress.

A second cross-cutting demand is **qualitative safety**. Across the project areas, the interaction between agricultural activity, livestock pressures and drinking water supply appears as one of the most sensitive issues. Rural water systems must guarantee compliance with drinking water standards while dealing with diffuse pollution, nutrients, pesticides, pathogens and other substances that may affect raw water quality. The diagnoses therefore point to a common demand for treatment solutions capable of removing nitrates, pathogens and emerging contaminants, while remaining feasible for small and medium-sized rural systems. This demand is especially relevant where agricultural continuity, environmental protection and public health protection must be balanced within the same territory.

The third common demand is **efficiency and maintenance of infrastructure**. Low-density rural areas often operate long and dispersed networks with limited financial, technical and human resources. As a result, leakage, non-revenue water, ageing pipes, small treatment facilities and insufficient monitoring capacity become structural problems. The demand expressed by these territories is therefore not only to build new infrastructure, but to improve the performance, maintenance and resilience of existing systems. A “leak-free” or low-loss infrastructure model is essential to reduce unnecessary abstraction, avoid energy waste, improve cost recovery and protect scarce water resources.

The fourth major demand is **adaptation to seasonal and variable demand patterns**. The previous subsection showed that rural urban water use is hybrid: domestic consumption remains central, but it coexists with agricultural, livestock, agro-industrial, tourism, public-service and irrigation-related uses. This produces demand peaks that are often difficult to predict and manage, especially during summer, holiday periods, agricultural campaigns or drought episodes. In Portuguese rural contexts, as observed by Águas do Tejo Atlântico in low-density territories, domestic consumption remains the primary use, but it is subject to pronounced seasonal variability driven by tourism, second homes and agricultural labour peaks. In addition, non-household uses — such as agro-industrial facilities, livestock operations, municipal services and irrigation support — exert significant localised pressure on supply systems. These patterns require water systems capable of tolerating sharp demand fluctuations while maintaining drinking water quality under increased raw water stress, particularly during drought periods.

The diagnoses also reveal a growing demand for **reuse and alternative water resources**. In rural contexts, treated wastewater, rainwater and regenerated water can contribute to reducing pressure on conventional resources, especially for irrigation, municipal uses, green areas, aquifer recharge or other non-potable applications. However, reuse must be accompanied by adequate treatment, monitoring, social acceptance and clear governance arrangements. This demand is particularly relevant in territories where water scarcity, agricultural needs and environmental protection converge, and where conventional supply options are increasingly insufficient or costly.

Another important demand concerns **simplified digital governance**. Rural operators and local authorities need tools that improve decision-making without adding excessive technical complexity. The diagnoses point to the need for accessible systems that help anticipate seasonal demand peaks, monitor water quality, identify risks, support infrastructure planning and assess uncertainty. Rather than relying exclusively on complex SCADA-type systems, many rural operators require practical tools that can integrate data, model uncertainty through probabilistic approaches and provide clear operational recommendations. In this sense, SID_AQUARURAL responds to a strategic demand for a simple, visual and decision-oriented digital tool capable of supporting the management of drinking water, wastewater treatment, reclaimed water and aquifer recharge.

From an operator standpoint, Águas do Tejo Atlântico identifies an additional transversal demand: **operational simplicity and resilience**. Rural municipalities require treatment and monitoring solutions that are not only technically effective, but also easily transferable to local operational teams. These solutions should have low dependency on external suppliers, reduced need for continuous parametric calibration, and sufficient robustness to operate under variable hydraulic and water-quality conditions. This reinforces the value of combining automation, probabilistic decision-support, decentralised treatment units and nature-based solutions adapted to the scale and capacities of rural territories.

Overall, the five diagnoses show that rural urban water demand in the SUDOE area is defined by a combination of pressures: reliable supply under climate stress, safe drinking water in agricultural territories, efficient and well-maintained infrastructure, capacity to respond to seasonal peaks, reuse of alternative resources, and accessible digital governance. These common demands provide the basis for defining long-term strategic objectives focused on resilience, quality, efficiency, decentralisation and operational feasibility in rural water management.

Available treatments for the integrated urban water cycle management in rural contexts

Building on the previous analysis, the GestEAUr strategy identifies a set of treatment solutions that can support a more resilient, efficient and decentralised management of the urban water cycle in rural contexts. The five project areas show that rural water systems require technologies that are not only technically effective, but also affordable, modular, easy to operate and adaptable to variable water quality and seasonal demand.

The GestEAUr strategy therefore promotes a transition from conventional, centralised and high-energy infrastructure towards modular, cost-effective and resilient technologies adapted to rural conditions. These solutions are not intended to replace all existing infrastructure, but to complement and optimise it through flexible treatment units, advanced monitoring, reuse-oriented systems and decentralised approaches. Central to this approach is the **Catalogue of Cost-Effective and Sustainable Solutions**, developed under E1.2.1, which provides a menu of validated techniques for drinking water treatment, wastewater depuration and water reuse in rural areas.

The available treatments can be grouped into four main categories: **potabilization and drinking water quality improvement; wastewater depuration through nature-based solutions; advanced oxidation and photochemical processes for depuration; and advanced reuse systems combining membranes, disinfection and digital monitoring**.

Potabilization and drinking water quality improvement

In rural contexts, drinking water treatment must address a wide range of challenges: turbidity, variable chemical loads, nitrates, arsenic, pesticides, pathogens, organic matter and disinfection by-product precursors. These issues are often intensified by agricultural activity, low-flow conditions, ageing infrastructure and the limited capacity of small systems to absorb sudden changes in raw water quality.

The GestEAUr catalogue includes conventional and advanced solutions adapted to these challenges. Technologies such as **PURASAND®** and **CLARIFAST®** respond to traditional rural treatment needs, especially high turbidity and variable particulate loads. PURASAND® is based on a continuous sand-washing system that allows filtration to continue without the need for shutdown during cleaning, reducing energy consumption by approximately 20% and reagent use by approximately 30% compared with conventional filters. These systems are particularly relevant for small or medium rural supply systems where operational continuity and low maintenance are essential.

For chemical contamination, GestEAUr has tested membrane-based and electro-assisted treatment solutions through **Pilot Action 1**. This pilot focuses on transportable modules combining electro-assisted technologies, membrane processes and in situ oxidant generation. Its objective is to remove contaminants such as nitrates, arsenic and pesticides, while improving microbiological safety and reducing dependence on externally supplied chemicals.

In **La Moraña**, Aqualia installed a pilot-scale **reverse osmosis system** at the Tiñosillos Drinking Water Treatment Plant in Ávila (Figure 1). This system operates to remove nitrates and other contaminants from drinking water, responding directly to one of the most common problems identified in rural agricultural territories: the presence of nitrates associated with diffuse agricultural pressures.

Figure 1. Reverse Osmosis pilot plant in Tiñosillos DWTP (Ávila, Spain)

In the **Guadiana basin**, at the Drinking Water Treatment Plant of the Mancomunidad de Nogales in Badajoz, a **nanofiltration unit** and an additional **activated carbon adsorption system** have been installed (Figure 2). These units aim to remove trihalomethane precursors and other compounds associated with drinking water disinfection by-products, which have historically been recurrent in the region. The combination of nanofiltration and activated carbon allows the treatment line to address both dissolved contaminants and organic precursors that may compromise the safety and acceptability of drinking water.

Figure 2. Nanofiltration pilot plant in Nogales DWTP (Badajoz, Spain)

Figure 3. Activated carbon pilot plant in Nogales DWTP (Badajoz, Spain)

In Portugal, the initial plan of Aqualia Portugal was to implement a reverse osmosis unit in **Elvas**. However, the analyses carried out over recent months did not show arsenic concentrations exceeding the regulatory limit of 10 µg As/L. The average arsenic concentration measured in Elvas during 2025 was 7.48 ± 0.33 µg As/L, remaining consistently below the threshold. For this reason, deployment of the reverse osmosis pilot unit at this location was not justified, as it would involve additional transport and energy costs to treat a contaminant that was not present above the limit in that borehole.

As an alternative, a portable **hollow-fibre nanofiltration unit** is being tested at another Aqualia Portugal facility in **Fundão (**Figure 4**)**, where arsenic exceedances above 10 µg As/L have been recorded. In this case, the average arsenic concentration measured at the Fundão borehole during 2025 was 65.92 ± 32.92 µg As/L, confirming the presence of arsenic above the regulatory limit. The use of a portable nanofiltration unit is operationally more appropriate because the installation does not have sufficient available space to accommodate the reverse osmosis pilot unit. This decision maintains the project's objective of testing membrane-based solutions while adapting the intervention to the actual risk, infrastructure constraints and operational feasibility of the site.

Figure 4. Monte Leal Installation – Fundão.

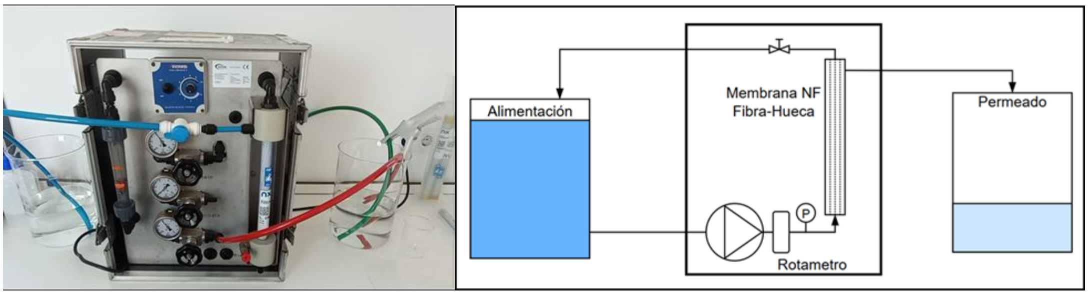


Figure 5. Picture and Diagram of the nanofiltration unit

<u>**Electrochemical oxidant generation and advanced oxidation processes**</u>

Conventional rural water treatment has traditionally relied on physical-chemical processes such as coagulation-flocculation, sedimentation, sand filtration and chlorination. While these processes are effective for suspended solids and pathogens, they present limitations in relation to contaminants of emerging concern, pesticides, pharmaceuticals, disinfection by-products and chemical supply logistics. In remote or low-density rural areas, the regular supply, storage and handling of reagents can be particularly challenging.

Advanced oxidation processes respond to these limitations by generating highly reactive species capable of degrading organic pollutants and inactivating pathogens. Within GestEAUr, special attention is given by the University of Castilla La Mancha (UCLM) to **electrochemical advanced oxidation processes**, which use electrical energy to generate oxidants in situ. These systems can produce ozone, hydrogen peroxide and peroxone mixtures directly on site, reducing dependence on external chemicals and enabling integration with photovoltaic energy.

Two previous European projects have informed UCLM for the design of the GestEAUr pilot plant. The **SERPIC project** developed a multi-barrier system for wastewater reuse and improved discharge to surface water bodies. For irrigation reuse, membrane nanofiltration removed more than 90% of contaminants of emerging concern while preserving macro-nutrients such as nitrogen and phosphorus, which can be beneficial for agriculture. A subsequent electrochemical ozone disinfection step ensured microbiological safety in line with Regulation (EU) 2020/741 on minimum requirements for water reuse. For improved discharge, the concentrate stream from nanofiltration was treated by electrochemical oxidation combined with light irradiation, achieving approximately 80% reduction of contaminants of emerging concern in the concentrate.

The **SafeWaterAfrica project** demonstrated an autonomous, off-grid treatment system for rural communities. It combined pre-treatment using a saline coagulant with electrochemical generation of oxidants, including ozone, to eliminate pathogens and degrade organic contaminants such as pesticides. This project validated the technical and operational feasibility of solar-powered electrochemical ozone generation under field conditions in low-resource settings.

Building on these experiences, the University of Castilla-La Mancha has designed and developed a novel pilot plant within GestEAUr for rural water treatment. This plant is based on the in situ electrochemical generation of ozone, hydrogen peroxide and peroxone using 3D-printed electrochemical reactors powered by photovoltaic panels. The system has been designed primarily to address microbial contamination, although it can also be tested for the degradation of organic micropollutants, including pesticides and pharmaceuticals.

Ozone is a particularly relevant oxidant because of its strong oxidative capacity, its decomposition into non-toxic oxygen and its applicability to pathogen disinfection, degradation of micropollutants, removal of taste and odour compounds, decolourisation and oxidation of dissolved metals such as iron, arsenic and manganese. Conventional ozone generation by corona discharge has two main limitations: inefficient gas-to-liquid mass transfer and low energy efficiency, with only 4–12% of the input energy effectively used for ozone production. Electrochemical ozone generation provides an alternative by producing ozone directly through water oxidation at the anode:

$$\mathbf{3\ H_2O \rightarrow O_3 + 6\ H^+ + 6\ e^-}$$

This process allows real-time control of ozone output through the applied current, direct compatibility with renewable energy sources, compact design and decentralised deployment. The use of 3D printing for reactor fabrication enables the optimisation of interelectrode distance, flow distribution channels and gas disengagement zones, improving mass transport, gas-liquid separation and ozone evacuation.

Hydrogen peroxide is another relevant oxidant for rural water treatment. It is generated electrochemically through the two-electron reduction of dissolved oxygen at the surface of a gas diffusion electrode:

$$\mathbf{O_2 + 2H^+ + 2e^- \rightarrow H_2O_2}$$

This route enables on-site, on-demand production of hydrogen peroxide without hazardous chemical transport or storage. Recent advances in gas diffusion electrodes and reactor design have achieved Faradaic efficiencies exceeding 90%. Reactor geometry and internal hydrodynamics are particularly important, as turbulent or centrifugal flow patterns can improve mass transfer and hydrogen peroxide yield.

The combination of ozone and hydrogen peroxide forms the **peroxone process**, which generates hydroxyl radicals, among the most powerful oxidising species used in water treatment:

$$\mathbf{2O_3 + 2H_2O_2 \rightarrow 2H_2O + 3O_2 + HO_2\bullet + HO\bullet}$$

This process enhances the degradation of recalcitrant contaminants of emerging concern that are not efficiently removed by conventional treatment or by ozone alone.

Within Pilot Action 1, UCLM has constructed two electrochemical ozone production units, each composed of four individual reactors for the generation of gaseous ozone from water electrolysis. A national patent application for this design was filed on 5 February 2025. Two additional electrochemical hydrogen peroxide production units have also been constructed, each comprising two electrochemical reactors; a separate national patent application was filed on 22 October 2025. Together, these four units form the core oxidant generation infrastructure of Pilot Action 1.

The main advantages of this technology for rural water treatment are:

- generation of oxidants in situ from water and electricity;
- reduced dependence on externally supplied chemicals;
- compatibility with photovoltaic panels and off-grid operation;
- reduced formation of trihalomethanes and haloacetic acids compared with chlorination;
- modular and transportable design;
- medium to low maintenance requirements;
- possibility of local repair and lower dependence on specialised external suppliers.

Preliminary tests for wastewater reuse, carried out in compliance with Spanish Royal Decree 1085/2024 on water reuse, confirm the disinfection potential of the technology for an urban wastewater flow rate of 0.5 m³/h. The results obtained for *Escherichia coli* reduction are shown below.

Oxidant dosage 1 — O_3 (mmol/min)	Oxidant dosage 2 — H_2O_2 (mmol/min)	*E. coli* before treatment (CFU/mL)	*E. coli* after treatment (CFU/mL)
0.3	—	1.4×10^4	1.4×10^2
—	0.7	2.1×10^3	2.1×10^2
0.3	0.7	7.2×10^2	—

These preliminary results indicate that the developed electrochemical technology can substantially reduce microbiological contamination and should be further tested under different water matrices, flow rates and operating conditions.

Wastewater depuration and nature-based solutions

In addition to drinking water treatment, the project addresses the need for wastewater depuration systems adapted to small rural communities. Conventional wastewater treatment can be difficult to operate in low-density areas because of the cost of infrastructure, the limited availability of specialised personnel, energy consumption and maintenance requirements. For this reason, GestEAUr gives particular relevance to **nature-based solutions**, specially constructed wetlands.

Constructed wetlands are a sustainable alternative to conventional wastewater treatment methods. They are especially suitable for small communities where land availability is higher and operational resources are limited. They require lower energy and chemical inputs, have reduced operation and maintenance costs, promote biodiversity and can adapt to different climatic and geographical conditions.

The GestEAUr catalogue includes solutions such as two-stage artificial wetlands and aerated vertical wetlands. Pilot Action 2 advances this approach by testing **electro-stimulated constructed wetlands**, which incorporate carbon-based materials and electrochemical stimulation to improve treatment performance, especially nutrient removal. The system also includes bio-remediation curtains derived from agro-industrial waste, designed to remove heavy metals and organic loads.

Two territorial adaptations have been implemented. In **Ávila**, the wetland system is complemented by two recharge ponds, allowing treated water to be infiltrated into the aquifer as a form of indirect reuse. This approach is particularly relevant in territories where aquifer depletion, seasonal scarcity and the need for managed aquifer recharge are central concerns.

In **Portugal**, two constructed wetlands — one electro-stimulated and one conventional — are being implemented by Aqualia Portugal at the Valada Wastewater Treatment Plant in the municipality of Cartaxo. The plant currently operates with an activated sludge process. The pilot system treats effluent from this existing treatment line and is complemented by an ultrafiltration unit, enabling the reclaimed water to reach the quality required for reuse applications such as irrigation or street cleaning.

The wetlands in Cartaxo operate as downflow vertical-flow systems. Wastewater first passes through pre-treatment, including screening, grit removal and degreasing. It then flows into two interconnected tanks, each with a capacity of 1 m³, connected by communicating vessels and positioned at the same elevation as the combined treatment unit. From there, wastewater is pumped by pulses to two vertical-flow constructed wetlands, each with an approximate capacity of 18 m³.

The wetlands are built using transportable polypropylene modules with dimensions of 5 × 2.5 × 1.5 m. In the electro-stimulated wetland, carbon-based material is used in the denitrification zone to enable electron transfer and promote autotrophic nitrate removal, while minimising sludge production and simplifying sludge management. The nitrification zone includes a blower-based aeration system and several layers of sand and gravel with different particle sizes; this system aims to promote oxygenation of the filter bed, favoring the conversion of ammoniacal nitrogen into nitrate through the nitrification process. Additionally, it contributes to the drying and stabilization of accumulated sludge. Vertically perforated carbon-fibre pipes are installed along the eletro-estimulated basin to improve electron transfer all over the basin. The selected macrophyte species is ***Typha latifolia***.

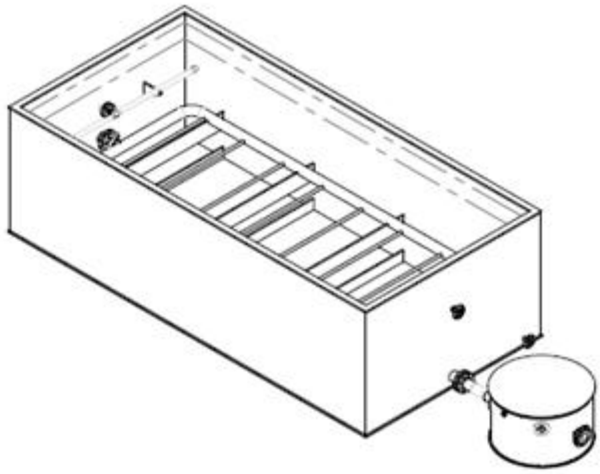


Figure 6. Drawing of the transportable module and its respective recirculation box.

Treated water exits at the bottom of the wetlands, creating a downward flow and a redox potential gradient. Each wetland is connected to a small two-compartment recirculation box: one pump recirculates water back to the wetland, while the other directs the treated flow to a storage tank, allowing the process to continue towards polishing and disinfection. Alternatively, the wastewater can be redirected back to the headworks of the wastewater treatment plant.

For the disinfection and regeneration stage, an **ultrafiltration unit** is installed after the wetlands. This unit removes fine particles and microorganisms such as *E. coli*. The recovered water is then disinfected through chlorination and stored in a reclaimed water tank, where it becomes available for irrigation, street cleaning or other local non-potable uses, according to local needs and regulatory requirements.

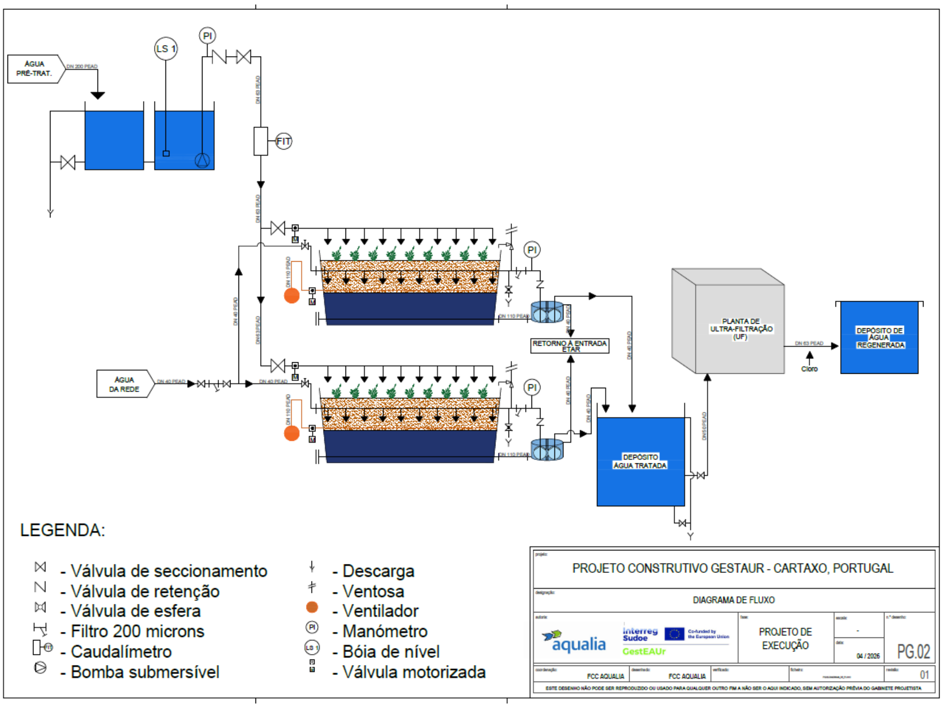


Figure 7. Flowchart of the pilot project implemented at Valada WWTP.

Photochemical processes and solar treatment for advanced reuse

Photochemical processes are emerging as promising technologies for wastewater treatment and reuse, particularly for the removal of contaminants of emerging concern such as pesticides and pharmaceutical residues. These technologies are part of the broader group of **advanced oxidation processes**, which use chemical, photochemical or catalytic activation to generate highly reactive radicals.

Two main classes can be distinguished. **Homogeneous processes**, such as peroxonation, photo-Fenton, ozonation and photolysis, have shown promising results for the elimination of pesticides. **Heterogeneous processes** are mainly represented by photocatalysis, either alone or coupled with other processes such as photochemical, electrochemical or electro-Fenton systems. Solar photocatalysis is particularly relevant because, unlike conventional tertiary treatments such as UV, ozonation or membranes, it can use solar energy and therefore reduce energy dependence.

Within GestEAUr, Pilot Action 3 focuses on solar photochemical treatment for advanced reuse. The system combines electrochemical and photocatalytic processes to provide disinfection and detoxification of wastewater. It is particularly relevant for rural areas with high solar potential, where small volumes of treated wastewater could be regenerated for irrigation, gardening, arboriculture or other non-potable uses.

A new circular basin-type photoreactor has been built at the PROMES laboratory as part of the project. The objective is to test a simple and robust solar treatment technology under natural irradiation conditions and to generate data for scaling up the pilot plant to a full wastewater treatment plant trial. The experimental device consists of a water supply unit, the photoreactor, a treated water collection tank, an artificial lighting system, a pollutant supply system, a control panel, valves, agitation and lighting systems, sensors and data recording equipment.

Figure 8. View of the entire installation for solar experiments consisting of (a) the network water supply tank, (b) the treated water collection tank, (c) the basin-type photoreactor, (d) the artificial lighting system (LED panel and power supply), (e) the pollutant supply system (peristaltic pump), (f) the supply control panel, valves, agitation and lighting and (g) the sensors and power supply.

The photoreactor can operate under artificial and natural irradiation, in both batch and continuous modes. The objective is to evaluate its photo-oxidative capacity in continuous mode under natural solar irradiance. This is technically relevant because solar radiation is variable, depending on meteorological conditions and the daily solar cycle. As a result, the photoreactor operates in transient mode rather than under steady irradiation.

Experiments carried out with continuous feeding at a flow rate of 24 L/h monitored the degradation of three target substances: caffeine (CAF), carbamazepine (CBZ) and diclofenac (DCF). The concentration profiles obtained are characteristic of a photoreactor operating in continuous mode under dynamic irradiation. Diclofenac, the least oxidation-resistant molecule, showed a drastic concentration decrease at the beginning of the day and remained at a very low level while the reactor was exposed to solar irradiation. When solar irradiation dropped to zero, its concentration increased again towards the feed concentration. Carbamazepine and caffeine showed similar but less marked profiles. The maximum degradation rates reached during the day were 39% for CBZ, 61% for CAF and 98% for DCF, consistent with their different sensitivities to photo-oxidation.

The experimental results and associated modelling were then used to simulate photoreactor capacities under irradiation conditions typical of sunny and cloudy days in winter and summer. Daily production capacities were predicted using a 1 m² photoreactor as a reference for scaling up.

These concentration profiles are the 'signatures' of a photoreactor operating in continuous mode under dynamic irradiation. The concentration of DCF, the less oxidation-resistant molecule, drops drastically at the start of the day and remains at a very low level as long as the photoreactor remains exposed to solar irradiation. When solar irradiation becomes zero, the concentration level rises and tends towards the feed concentration. Previous research has established that in the case of a perfectly stirred reactor operating in continuous mode, the concentration level reaches 95% of the steady-state concentration, after a time corresponding to two passage times (i.e. 4 h). The two other molecules showed similar but less marked concentration variation profiles. Analysis showed that the maximum degradation rate reached during the day was 39% for CBZ, 61% for CAF, and 98% for DCF, which is in line with their responses based on sensitivity to photo-oxidation.

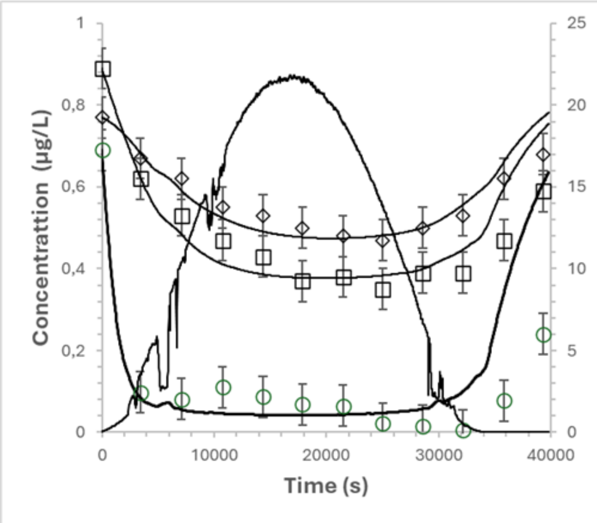


Figure 9. Experiments carried out on the photoreactor feed continuously in continuous mode at a flow rate of 24 l.h-1 and under natural solar irradiations represented by solid curve, with monitoring of the variation of the concentration of three target substance

Daily capacities of photo-reactor (m^3.m-^{2})			
Limit concentration (µg. L^{-1})	**0.5**	**0.25**	**0.1**
July : average	0.623	0.208	0.069
December : average	0.394	0.131	0.044
December : cloudy	0.362	0.121	0.040
December : sunny	0.406	0.135	0.045

The predicted water output was higher in July, although the differences were not proportional to the duration or intensity of solar radiation. This is because the photoconversion rate equation has an order lower than 1, meaning that low sunshine conditions can be relatively favourable in terms of efficiency. The analysis also showed that water production varies strongly depending on the concentration threshold to be achieved. For example, production varies by a factor of 10 between thresholds of 0.5 and 0.1 µg/L. This confirms that the sizing of a solar treatment plant must be defined primarily according to the target quality requirements and intended reuse application, and only secondarily according to monthly sunshine conditions.

Solar photo-oxidation processes therefore offer promising potential for sustainable and low-energy treatment. However, compared with mature tertiary technologies such as membrane processes, activated carbon or ozonation, these oxidation processes remain at a research and demonstration stage. Further testing under real wastewater treatment plant conditions is required to assess robustness, long-term operation and the effect of the treated wastewater matrix, including suspended solids, chemical oxygen demand and temporal variation in effluent composition.

Operational learnings for rural operators

From the perspective of a multi-municipal operator, Águas do Tejo Atlântico highlights that the applicability of treatment technologies in rural contexts depends critically on operational robustness, flexibility to variable influent quality and compatibility with limited human and financial resources. In low-density service areas, infrastructure constraints and seasonal variability require decentralised solutions that can operate autonomously, minimise chemical handling and simplify maintenance.

The modular treatment approaches tested within GestEAUr align closely with these operational realities. Their transportability, scalability and potential integration with renewable energy respond directly to the challenges faced by rural operators, particularly in dispersed settlements with limited access to specialised technical support.

Moreover, water reuse is a central element of integrated water cycle management in rural contexts, especially where water scarcity, agricultural demand and climate variability create pressure on conventional resources. Reuse can support irrigation, street cleaning, green areas, aquifer recharge and other non-potable applications, provided that treatment quality and risk management requirements are met.

At European level, reclaimed water for agricultural irrigation must comply with **Regulation (EU) 2020/741** on minimum requirements for water reuse. In Portugal, wastewater reuse systems must comply with **Decree-Law No. 119/2019** and obtain authorisation from the Portuguese Environment Agency. In Spain, testing linked to reuse must also take into account the applicable national framework, including **Royal Decree 1085/2024** on water reuse.

The treatment systems tested in GestEAUr respond to this regulatory framework through multi-barrier approaches. Membrane technologies such as nanofiltration, reverse osmosis and ultrafiltration provide physical separation of contaminants and microorganisms. Electrochemical oxidation supports disinfection and degradation of organic micropollutants. Constructed wetlands reduce organic matter and nutrients. Solar photoreactors support advanced detoxification and disinfection. Activated carbon contributes to the removal of organic compounds and disinfection by-product precursors. Together, these technologies create flexible treatment chains that can be adapted to the quality required for each reuse application.

Overall, the available treatments tested and analysed within GestEAUr show that rural water management in the SUDOE area can be strengthened through decentralised, scalable and technically robust solutions. These technologies make it possible to improve drinking water quality, treat wastewater more efficiently, enable safe reuse, reduce chemical and energy dependency, and support local operators in territories affected by low population density, seasonal demand fluctuations and increasing climate pressure.

CIRCULAR ECONOMY

Circular economy principles offer a strategic framework for improving the management of water resources in rural areas. Applied to the urban water cycle, circular economy means moving beyond the traditional linear model — abstraction, treatment, use, collection, treatment and discharge — towards a **system in which water, energy, nutrients and materials are kept in use for as long as possible**. This approach can reduce pressure on conventional water resources, improve resilience to droughts, limit pollution, reduce energy and chemical dependency, and create new synergies between municipalities, farmers, local industries and water operators.

In the SUDOE area, circular water management is particularly relevant because rural municipalities face a combination of structural pressures already discussed in the previous sections, which make it difficult to replicate conventional urban water models.

The GestEAUr pilots and diagnostic work show that circular economy in rural water management should not be understood only as wastewater reuse. It should also include leakage reduction, decentralised treatment, nature-based solutions, energy-efficient technologies, recovery of nutrients, use of renewable energy, valorisation of local waste streams, digital monitoring and cooperation between municipalities and productive sectors.

Circularity of water: main challenges and issues of urban water in rural contexts

The circularity of water in rural contexts is both a necessity and a challenge. It is necessary because rural territories are increasingly affected by water scarcity, lower summer flows, diffuse pollution, climate variability and competing uses between households, agriculture, livestock, industry, tourism and ecosystems. At the same time, it is challenging because the conditions required for conventional circular water infrastructure — large treatment plants, stable flows, specialised operators, high investment capacity and economies of scale — are often absent in small rural municipalities.

This difficulty is closely linked to the **territorial structure of rural settlements**. Many rural municipalities in the SUDOE area are characterised by low population density, dispersed households and small settlements. Long networks serve relatively few users, while small treatment plants often operate with variable flows and limited operational staff. As population size decreases, the unit cost of installation, operation and maintenance increases, making conventional depuration and reuse models less economically viable. In this context, circularity cannot be understood as the simple replication of urban systems in rural areas; it requires solutions that are scaled to local realities.

This is particularly visible in areas such as La Moraña, where many municipalities have very small populations and where the rural water cycle must be managed at small scale. It is also relevant in mountain and dispersed territories such as Béarn and Alto Minho, where rural areas coexist with more urbanised centres. These internal differences mean that circular economy solutions cannot be uniform. Some areas may require intermunicipal coordination and shared infrastructure, while others need decentralised treatment units, modular technologies or nature-based systems adapted to isolated settlements.

The **limited suitability of conventional treatment systems** reinforces this need for adaptation. Conventional water and wastewater treatment solutions are typically designed for urban environments, where population density, financial capacity and technical infrastructure justify large-scale, centralised systems. These systems often rely on continuous energy supply, skilled operators, complex maintenance routines, chemical supply chains and stable hydraulic loads. In small rural settlements, these conditions are not always guaranteed. As a result, replicating conventional urban depuration systems in rural areas may lead to underperformance, abandonment of facilities or excessive operational costs.

Seasonal variability adds another layer of complexity. Rural water systems must respond to fluctuating demands linked to tourism, second homes, agricultural labour peaks, irrigation periods, livestock needs and agro-industrial activity. These peaks often occur in summer, when water availability is lower, drought risk is higher and raw water quality may deteriorate. This creates a circularity paradox: reclaimed water and alternative resources are most needed during periods of water stress, but treatment systems may also face the greatest hydraulic and quality variability at the same time. Circular systems therefore need to be designed not only for average operating conditions, but also for seasonal peaks, drought episodes and changing water-quality profiles.

In addition to quantity, circularity depends on the capacity to **reuse water safely**. In rural agricultural territories, water resources may be affected by nitrates, pesticides, pathogens, organic matter or emerging contaminants. These pollutants can compromise drinking water quality and also limit the possible uses of reclaimed water. For this reason, circular water management must integrate treatment, monitoring and risk management from the outset. Reuse cannot be promoted simply as an additional water source; it must be linked to quality standards, health protection and environmental safeguards.

The **condition of existing infrastructure** is also decisive. Circular economy begins with efficiency. Before treated wastewater can become a reliable resource, rural municipalities need to reduce water losses, improve network performance, limit infiltration and parasitic inflows in sewer systems, and ensure that wastewater is adequately collected and treated. Ageing pipes, obsolete facilities, inefficient networks and insufficient monitoring weaken the ability of municipalities to close the water cycle. In this sense, leakage reduction and infrastructure renewal are themselves circular economy measures, because they prevent the unnecessary abstraction, treatment and loss of water.

These technical barriers are closely connected to **economic constraints.** Rural municipalities often have smaller tariff bases, limited public budgets and a high dependence on external funding. Even when circular measures generate long-term benefits — such as reduced abstraction, lower pollution, improved drought resilience or reduced fertiliser dependency — the initial investment can be difficult to absorb. This affects the feasibility of reuse networks, advanced treatment, storage tanks, quality monitoring, digital systems and maintenance. Therefore, circular economy strategies in rural areas must prioritise low-OPEX technologies, phased implementation, shared services and solutions that can be maintained locally.

Governance conditions further influence the success of circularity. Circular water management requires coordination between municipalities, water operators, farmers, industries, environmental agencies, river basin authorities and citizens. In many rural territories, responsibilities are divided between different levels: abstraction, drinking water production, distribution, wastewater collection, wastewater treatment and reuse authorisation may depend on different actors. Without clear roles, shared planning, cost-sharing mechanisms and regulatory guidance, circular economy measures risk remaining isolated pilots rather than becoming part of municipal water management.

Operational capacity is equally important. Circular water systems require monitoring, maintenance, quality control and reporting. However, rural operators may have limited technical staff and cannot depend on solutions requiring permanent calibration, complex SCADA operation or frequent intervention by external suppliers. This is why circularity in rural contexts must be based on robust, automated and transferable systems. The objective should not be to increase the burden on municipalities, but to provide solutions that can be operated with the resources and skills available locally.

Social acceptance is another condition for success. The reuse of treated wastewater can raise concerns among farmers, citizens and local businesses if the intended uses, safety conditions and benefits are not clearly communicated. In small rural communities, trust in local authorities and operators is decisive. Circularity therefore requires participatory planning, transparency, clear information on water quality and early involvement of end users. Farmers, in particular, should not be considered only as potential users of reclaimed water, but as strategic partners in defining acceptable uses, nutrient value, irrigation needs and operational requirements.

The five GestEAUr areas show that these issues vary according to local conditions. In La Moraña and Guadiana, circularity is closely linked to agricultural pressure, water scarcity, drinking water quality and the need for cost-effective treatment and reuse. In Alto Minho, the priority is to integrate circularity into a dispersed and multilevel governance system, aligning water management with climate adaptation, biodiversity protection and local planning. In Portugal Oeste – Torres Vedras, the existence of wastewater treatment infrastructure and agricultural, agro-industrial and tourism pressures create opportunities for reclaimed water, but also requires regulatory compliance, financing and user confidence. In Béarn, circularity must respond to a highly heterogeneous territory, combining urban centres, rural valleys, mountain zones, agriculture, industry, tourism, ageing wastewater infrastructure, emerging pollutants and climate-driven increases in irrigation demand.

Municipal circular economy in rural contexts of the SUDOE area

To integrate circular economy approaches into the management of water in rural municipalities, the GestEAUr strategy promotes a decentralised municipal model based on fit-for-purpose treatment, reuse of local resources, low-maintenance technologies, digital support and cooperation with local productive sectors. The aim is not to transfer complex urban systems to small municipalities, but to **design circular solutions adapted to rural realities.**

A central element of this model is the **transition towards decentralised and modular treatment systems**. Rural municipalities need treatment units that can be scaled to local population size, seasonal demand and available operational capacity. Modular systems make it possible to treat water or wastewater close to the point of use, reduce the need for large infrastructure, and adapt treatment intensity to the actual risk and final use. This approach is particularly relevant for small settlements, isolated facilities, dispersed households and municipalities with limited budgets.

The GestEAUr pilots show the value of this decentralised approach. Electrochemical systems, mobile membrane units, constructed wetlands and solar-based treatment technologies can be deployed in specific locations according to local needs. Their modularity makes them easier to replicate in municipalities with similar characteristics, while their lower operational complexity makes them more compatible with rural management capacities.

Within this decentralised model, Nature-Based Solutions play a particularly important role. Constructed wetlands offer a low-OPEX alternative to conventional wastewater treatment plants and are especially suitable for small rural communities where land availability is higher and technical resources are limited. They require less energy, fewer chemical reagents and less specialised labour than conventional systems, while also providing co-benefits such as biodiversity enhancement, landscape integration, carbon reduction and improved resilience to variable hydraulic loads.

GestEAUr Pilot Action 2 demonstrates this approach through electro-stimulated wetlands and conventional wetlands. In Portugal, at the Valada Wastewater Treatment Plant in Cartaxo, two vertical-flow constructed wetlands — one electro-stimulated and one conventional — are being implemented to treat effluent from an existing activated sludge system. The wetlands are followed by ultrafiltration and disinfection, enabling the reclaimed water to be used for applications such as irrigation or street cleaning. In Ávila, the wetland system is complemented by recharge ponds, allowing treated water to infiltrate into the aquifer as indirect reuse. These solutions show that nature-based treatment can support both wastewater depuration and circular water reuse in rural municipalities.

Circularity can also be strengthened by **connecting the urban water cycle with local productive activities.** Rural municipalities often host agri-food activities that generate organic by-products, such as fruit stones, husks or other lignocellulosic residues. Instead of treating these materials only as waste, they can be repurposed as bio-adsorbents or functional media within water treatment systems. This creates a local circular economy loop: agro-industrial waste becomes a resource for wastewater depuration, while municipalities reduce treatment costs and local SMEs reduce waste-management burdens.

This is one of the most relevant circular innovations tested in GestEAUr. Bio-remediation curtains derived from agro-industrial waste have been designed to remove heavy metals and organic loads, in combination with other solutions such as the electro-stimulated wetland system. This approach links the urban water cycle with the local productive fabric and demonstrates how rural circularity can be built around territorial resources rather than imported materials.

Another key component is the **use of fit-for-purpose reuse protocols**. Not all reclaimed water needs to reach drinking-water standards. Circular management requires matching treatment intensity with the final use: agricultural irrigation, street cleaning, green-area irrigation, industrial uses, aquifer recharge or environmental flows may require different quality levels and monitoring requirements. This prevents municipalities from investing in unnecessary purification levels while ensuring compliance with safety standards.

Regulation (EU) 2020/741 provides a common framework for the safe use of reclaimed water in agricultural irrigation, based on minimum water-quality and monitoring requirements and risk management. In Spain, reuse must also be aligned with Royal Decree 1085/2024, while in Portugal reuse systems must comply with Decree-Law No. 119/2019 and obtain authorisation from the Portuguese Environment Agency. For rural municipalities, the practical implication is clear: reuse should be planned according to the intended use, the required quality class, the local treatment capacity and the potential users.

In this framework, **treated wastewater** becomes a strategic resource for agriculture and municipal services. It can provide a reliable, climate-independent water source in rural SUDOE municipalities, especially where drought frequency is increasing. By reclaiming wastewater at municipal level, rural communities can reduce dependence on scarce freshwater abstractions, maintain agricultural activity during dry periods and increase resilience to climate variability. Reclaimed water can be used for irrigation, street cleaning, green areas, industrial cleaning or other non-potable applications, depending on local demand and regulatory conditions.

The project pilots demonstrate different pathways for this. In Cartaxo, treated wastewater is regenerated through constructed wetlands, ultrafiltration and disinfection, making it suitable for reuse in irrigation or street cleaning. In Ávila, treated wastewater can contribute to aquifer recharge through infiltration ponds. In Béarn, the solar photoreactor pilot in Lescar explores tertiary treatment and polishing to remove emerging contaminants and support potential reuse applications. These examples show that reuse can be adapted to different rural contexts, from agricultural plains to peri-urban and mountain territories.

The circular value of treated wastewater is not limited to water quantity. It should also be considered as a **potential nutrient bank.** In agricultural areas, reclaimed water may contain nitrogen and phosphorus that can support crop growth and reduce reliance on mineral fertilisers, if quality and application conditions are properly managed. This is particularly relevant in rural municipalities where agriculture is a central economic activity and where circularity can connect wastewater treatment with local food production.

This approach requires careful monitoring and communication with farmers. Nutrient content should be known, stable and integrated into fertilisation planning to avoid over-application or pollution risks. When properly managed, nutrient reuse can reduce fertiliser costs, lower the environmental footprint of agricultural production and reinforce the link between municipal water management and local circular economy.

Circular water management also benefits from treatment systems that **reduce dependency on external inputs**. A central barrier in rural areas is the cost and logistical burden of procuring, transporting, storing and handling chemical disinfectants. The electrochemical technologies tested in Pilot Action 1 address this barrier by generating oxidants such as ozone and hydrogen peroxide on site from water and electricity. When the electricity is supplied by photovoltaic panels, the treatment system becomes more autonomous and circular.

This model has several circular economy benefits. It reduces the carbon footprint associated with chemical transport, lowers dependence on external suppliers, uses renewable energy for water treatment, and avoids part of the secondary pollution associated with conventional chlorination, such as the formation of trihalomethanes and haloacetic acids. It also increases the autonomy of rural operators, which is particularly important in remote or low-density municipalities.

The Pilot 1 technology developed by UCLM demonstrates this potential. Electrochemical disinfection with ozone and/or hydrogen peroxide has shown the capacity to reduce microbiological contamination in urban wastewater and support compliance with water reuse requirements. The system is modular, transportable and compatible with photovoltaic energy, making it suitable for decentralised rural applications.

Circular economy is also **linked to materials, maintenance and local technical capacity.** The 3D printing fabrication route developed for the electrochemical reactors introduces an additional circular dimension because reactor components can be manufactured and repaired more locally, reducing dependence on specialised industrial supply chains and keeping technical knowledge within the territory.

Within GestEAUr, UCLM developed two ozone production units, each composed of four reactors, and two hydrogen peroxide production units, each composed of two reactors. These designs are optimised for simple assembly, long electrode service life and medium-to-low maintenance requirements. For rural municipalities, this is important because treatment technologies are more likely to be sustained over time when repair, spare parts and technical knowledge are accessible.

Digitalisation reinforces this circular model by helping municipalities understand and manage the flows they are trying to close. Circular water management requires information: how much water is abstracted, treated, lost, reused and discharged; what quality it has; which uses are possible; and how demand may change under climate or seasonal conditions. SID_AQUARURAL can support municipalities by monitoring the quantity and quality of water and reclaimed water, modelling uncertainty, anticipating seasonal pressure and helping operators choose the appropriate treatment and reuse pathway.

For rural municipalities, the value of digitalisation lies in simplicity and decision support. Operators need tools that are accessible, visual and adapted to limited staff capacity. By integrating monitoring, probabilistic assessment and treatment information, SID_AQUARURAL can help build confidence among local authorities, farmers and citizens. This is essential for a safe and transparent transition towards circular water management.

Finally, **municipal cooperation and shared services** are essential to make these approaches viable. Many rural municipalities are too small to implement circular economy measures individually. Intermunicipal cooperation can help share technical staff, monitoring equipment, treatment units, maintenance services, funding applications and reuse planning. This is especially relevant in territories such as Alto Minho and Béarn, where governance is multilevel and where water resources, infrastructure and demand patterns cross administrative boundaries. Circular economy should therefore be integrated into intermunicipal water planning, climate adaptation plans and rural development strategies.

The benefits of adopting these circular economy approaches are multiple. Environmentally, they reduce pressure on rivers, aquifers and reservoirs; decrease pollutant loads; improve treatment performance; and support climate adaptation. Economically, they lower long-term dependency on external water resources, chemicals and fertilisers; reduce operational costs where low-maintenance technologies are used; and create local synergies with agriculture and agro-industry. Socially, they improve water security, strengthen the resilience of rural services and create opportunities for cooperation between municipalities, operators and local users.

These different circular economy approaches will be further considered in the definition of the long-term objectives and strategic directions of the GestEAUr strategy.

WATER DIGITALIZATION AND ARTIFICIAL INTELLIGENCE

In territories characterised by low population density, dispersed settlements, limited technical capacity, ageing infrastructure, seasonal demand peaks and increasing climate uncertainty, services are often not able to collect and manage data properly to help them in operating their water services and anticipate future challenges. Digital tools can help convert fragmented information into actionable knowledge. Their value lies not only in collecting data, but in supporting better decisions on abstraction, treatment, reuse, maintenance, risk prevention and long-term planning.

At EU level, digitalisation is increasingly recognised as a necessary component of water resilience. The European Water Resilience Strategy identifies the need to reduce water consumption, improve efficiency, reduce leaks and modernise water infrastructure through digital solutions. In parallel, the European Commission is preparing an EU-wide Digital Action Plan for the water sector, aimed at modernising water management through data-driven innovation, including smart metering and digital tools. In this context, SID_AQUARURAL is aligned with a broader European transition towards smarter, more resilient and more transparent water governance.

Recap of existing artificial intelligence (AI) techniques and lessons learned during the design and execution of the SID_AQUARURAL digital tool

The integration of digital layers into water systems represents a shift from reactive management to proactive, data-driven optimisation. Traditional rural water management often reacts to problems once they have already occurred: shortages, pipe failures, poor-quality raw water, treatment non-compliance or pollution incidents. Digitalisation makes it possible to move towards **early warning, predictive maintenance, adaptive treatment and scenario-based planning**.

This transformation is underpinned by the increasing availability of the Internet of Things, remote sensing, smart metering, geographic information systems, data platforms and artificial intelligence. These technologies allow high-frequency data to be collected, transmitted, analysed and translated into operational recommendations. In rural water systems, where information is often incomplete, irregular or dispersed across different institutions, this is particularly relevant.

Technology Component	Primary Function	Strategic Impact
IoT Sensors	Real-time monitoring of flow, pressure, and chemical composition.	Immediate detection of leaks, anomalies, and quality deviations.
Smart Water Meters	Automated consumption tracking and demand profiling.	Enhanced demand forecasting and reduction of non-revenue water.
SCADA Systems	Centralized control and data acquisition for operational oversight.	Streamlined plant operations and remote management capability.

GIS Integration	Spatial mapping of infrastructure and environmental variables.	Optimized asset management and spatial risk assessment.
5G/NB-IoT	High-speed, low-latency data transmission.	Enables massive sensor density and real-time feedback loops.

Artificial intelligence adds value by **processing large and heterogeneous datasets** to identify patterns, detect anomalies, predict future states and support decision-making under uncertainty. Unlike purely deterministic models, which may struggle with the non-linear and non-stationary behaviour of climate-affected hydrological systems, **AI-based approaches can learn from historical discrepancies, integrate new data and adapt progressively to changing conditions.**

In hydrology and water management, AI techniques have evolved from deterministic process-driven models towards data-driven and hybrid approaches. Artificial Neural Networks, Support Vector Machines and Bayesian methods are among the most widely used techniques for prediction, classification and decision support. Artificial Neural Networks are especially useful for modelling non-linear relationships, although their performance may be limited in highly variable semi-arid systems or when long lead-times are required. Support Vector Machines can be effective for short-term prediction, particularly where overfitting must be minimised. Bayesian methods are particularly relevant when uncertainty must be made explicit, because they provide probabilistic outputs rather than a single deterministic value.

For rural water management, this is a crucial distinction. Local operators and municipalities do not only need a prediction; they need to understand the confidence of that prediction, the risk range and the possible consequences of acting or not acting. For this reason, **probabilistic approaches are especially useful** in contexts affected by droughts, seasonal demand peaks, diffuse pollution and climate uncertainty.

To overcome the fragmentation of individual modelling methods, the project adopts a **Meta-Water-Modelling approach.** The Meta-WaM framework operates as a stochastic framework using Object-Oriented Bayesian Networks to integrate several key challenges of rural water systems: spatiotemporal continuity, rainfall-runoff delay, predictive uncertainty, computational cost reduction, previous soil conditions, infrastructure influence and solid-flow fraction. By using hyperparameters as surrogate models, this approach enables quasi-real-time simulation without the excessive computational costs associated with traditional numerical models.

SID_AQUARURAL represents the practical application of this research within GestEAUr. The project defines SID_AQUARURAL as a digital tool based on artificial intelligence that will allow the quality and quantity of water to be controlled across the different stages of the integrated water cycle. It is conceived as a **simple and visual digital twin,** designed to facilitate decision-making by the authorities responsible for rural water management. The tool is developed from existing information, the results of previous projects and data obtained during the GestEAUr pilots.

The tool is structured around the main stages of the rural water cycle. According to the project design, SID_AQUARURAL includes modules for high-level supply and potabilisation, low-level sanitation and depuration, reclaimed water and aquifer recharge. These modules are intended to be integrated so that information can be propagated across the whole water cycle, rather than remaining isolated in separate operational silos.

In this sense, SID_AQUARURAL can be understood as a lightweight, modular digital twin specifically designed for rural associations, municipalities and operators. Unlike conventional management software, it is not conceived only as a data repository or a complex SCADA system. It functions as a knowledge-based decision-support system that hybridises historical records, real-time sensor data from project pilots and expert knowledge into a unified operational platform.

The **High-Supply Module** focuses on potabilisation. It monitors and predicts the quality and quantity of water at the extraction or treatment point. This module can incorporate parameters from advanced treatment technologies and specific contaminants such as nitrates and arsenic, which are particularly relevant in rural agricultural territories and are being addressed through Pilot Action 1.

The **Low-Sanitation Module** focuses on wastewater depuration. It can reproduce and monitor the performance of treatment systems such as nature-based solutions and electro-stimulated wetlands. Through stochastic indicators, it can help predict how seasonal load peaks, rainfall events or changes in influent quality may affect effluent quality.

The **Reclaimed Water Module** focuses on resource recovery and reuse. Its purpose is to assess whether treated water is suitable for agricultural or urban reuse according to fit-for-purpose quality standards. This is particularly relevant in relation to Regulation (EU) 2020/741, which establishes minimum requirements for water quality, monitoring and risk management for the safe use of reclaimed water in agricultural irrigation.

The **Aquifer Recharge Module** is especially relevant in rural territories where groundwater depletion, seasonal scarcity or overexploitation of aquifers are strategic concerns. By integrating water quality, treated-water availability, soil and hydrogeological information, this module can support decisions on whether indirect reuse or managed aquifer recharge is technically and environmentally appropriate.

A key feature of SID_AQUARURAL is its capacity for omnidirectional information propagation. By providing evidence to one node of the system, the tool can calculate the a posteriori probability of other related processes in the water cycle. This makes it possible to assess how a change in one part of the system — for example, a decline in raw water quality, a nitrate spike, a reduced river flow, a treatment failure or a seasonal demand peak — may affect other processes such as drinking water treatment, wastewater quality, reclaimed water availability or aquifer recharge.

The design and execution of SID_AQUARURAL generated several **important lessons for rural water digitalisation.** One of the most relevant is that digital complexity can easily become a barrier rather than a solution. Traditional SCADA systems and advanced digital platforms are often too complex for small municipalities or rural operators with limited specialised IT staff. For this reason, digital tools for rural territories must prioritise simple visual interfaces, guided interpretation and participatory modelling. The objective should be to make complex information usable, not to increase the technical burden on local teams.

The experience also confirmed the **value of uncertainty as a decision-making resource**. Stakeholders expressed a preference for probabilistic outcomes rather than apparently precise deterministic figures. In rural water management, uncertainty is unavoidable: climate variability, rainfall-runoff delays, seasonal population changes, diffuse agricultural pollution and infrastructure limitations all affect the reliability of predictions. Bayesian causal reasoning is therefore particularly useful because it provides range-based predictions and risk levels for variables such as aquifer levels, water quality or treatment performance.

Another key lesson is the **need to connect climate information with water quality and operational management.** The diagnoses show that rural water management cannot be separated from climate change, agricultural activity and seasonal demand. Digital tools must therefore be able to link long-term climate scenarios with immediate operational questions, such as the quality of raw water entering the treatment cycle, nitrate peaks after rainfall, drought-related concentration of pollutants, or reduced dilution capacity in receiving water bodies.

Beyond operational control, SID_AQUARURAL also shows that **digital tools should support learning and governance**. Participatory modelling is essential in rural contexts, where local authorities, operators, farmers and citizens need to understand the water cycle, the reasons behind treatment decisions and the consequences of different management options. In this sense, SID_AQUARURAL can also act as a pedagogical platform that builds capacity, transparency and trust.

Finally, the development process highlighted that **digitalisation must be affordable and transferable**. The project explicitly differentiates SID_AQUARURAL from more complex tools through its lighter computational requirements and lower expected cost, making it more accessible for entities with limited resources. This is a critical lesson for rural SUDOE areas: digital tools will only be adopted if they match the financial, technical and organisational capacity of municipalities and operators.

The **potential benefits of SID_AQUARURAL** are therefore significant. It can improve resilience by helping communities anticipate droughts, pollution incidents or seasonal demand surges. It can improve resource efficiency by optimising treatment processes, such as membrane filtration, ozone dosing, wetland operation or reclaimed-water quality control. It can strengthen operational autonomy by providing small municipalities with automated insights and decision support. It can also support circularity by facilitating the monitoring of wastewater regeneration, reuse and aquifer recharge.

Recommendations for improving water management through digitalization

To maximise the impact of digitalisation in the SUDOE area, future efforts should focus on expanding digital tools in ways that are technically robust but operationally realistic for rural municipalities. Digital transformation should not be understood as the simple introduction of sensors or software. It should be conceived as a gradual process that improves monitoring, supports decision-making, reduces waste, increases transparency and strengthens the capacity of local operators. In this sense, GestEAUr proposes 10 recommendations for improving water management through digitalization:

1. Develop **modular AI frameworks for rural decentralisation**. Rural water systems are heterogeneous: some municipalities manage very small networks, others depend on intermunicipal operators, and others combine drinking water, wastewater, reuse and irrigation-related needs. Digital systems should therefore be modular, allowing each municipality or operator to activate the components that respond to its actual needs. Hierarchical input decomposition and adaptive data augmentation can help monitor small-scale nature-based solutions, decentralised treatment systems and dispersed infrastructure where continuous centralised monitoring is not available.
2. Promote **dynamic treatment optimisation**. AI algorithms should be used to adjust treatment processes in real time according to influent quality, hydraulic load, reuse requirements and energy availability. This is particularly relevant for reagent dosing, ozone or hydrogen peroxide generation, membrane filtration, aeration control and the operation of constructed wetlands. Predictive systems can help anticipate quality fluctuations and adjust treatment intensity before non-compliance occurs. This would support both resource efficiency and regulatory compliance.
3. Move from monitoring to **smart operations and predictive maintenance**. Many rural systems suffer from leaks, pressure problems, obsolete pipes, undetected failures and high non-revenue water. Digitalisation should therefore support early detection of leaks, irregular pressure patterns, abnormal flows, pump inefficiencies and potential asset failures. Advanced algorithms using pressure, flow, acoustic, vibration or consumption data can identify anomalies before they become major failures. This can reduce water losses, maintenance costs and emergency interventions.
4. Integrate **Earth Observation data and climate information** into water decision-support systems. Satellite imagery, including Copernicus services, can support the monitoring of drought risk, soil moisture, vegetation stress, irrigation needs, land use and catchment conditions. When combined with IoT sensors and local monitoring, Earth Observation can provide rural managers with better visibility over water availability and demand. This is particularly useful for strategic crop planning, rainwater harvesting, drought preparedness and prioritisation of reuse.
5. Strengthen **digital support for water reuse and circular economy**. Digital tools should help municipalities determine when reclaimed water is available, what quality it has, which uses are permitted, what treatment is required and what risks must be managed. This is essential for fit-for-purpose reuse, aquifer recharge, agricultural irrigation, street cleaning, green areas and industrial non-potable uses. SID_AQUARURAL can support this by connecting treatment performance, reclaimed-water quality, regulatory thresholds and local demand.
6. Ensure **interoperability with existing operational systems**. From the perspective of a regional water utility, Águas do Tejo Atlântico underlines that digital solutions must strike a balance between analytical sophistication and operational usability. Tools such as SID_AQUARURAL represent a significant advancement because they prioritise decision support over simple data

accumulation. However, long-term adoption will depend on their ability to connect with existing operational systems, databases, sensors, SCADA platforms, GIS layers and reporting procedures. Interoperability should therefore be considered a core design requirement.

7. Apply a **gradual adoption pathway**. Rural municipalities should not be expected to implement advanced digitalisation all at once. A realistic sequence could begin with basic mapping of assets, flow and pressure monitoring, and digital records of incidents. The next stage could include smart meters, water-quality sensors and GIS integration. A more advanced stage could then introduce predictive algorithms, digital twins, treatment optimisation and probabilistic decision support. This staged approach reduces risk and allows local teams to build confidence progressively.
8. Invest in **upskilling and trust-building**. Digital transformation proceeds at the speed of trust. Operators, municipal technicians, farmers and decision-makers need to understand how digital tools work, what data they use, what their limitations are and how their outputs should be interpreted. Training should therefore be embedded into digitalisation strategies. The creation of a European Water Academy or similar transnational training mechanism could help upskill rural operators, exchange good practices and support the long-term adoption of tools such as SID_AQUARURAL.
9. Involve users directly in the **product development lifecycle**. Digital tools for rural water management should be co-designed with the people who will use them: municipal technicians, operators, river basin authorities, farmers, wastewater managers and regional administrations. This ensures that the interface, indicators, alerts and outputs respond to real decision needs. It also increases trust and reduces the risk of developing tools that are technically advanced but poorly used.
10. Use digitalisation to improve **investment planning and communication with regulators**. Predictive tools can help operators justify investments by showing expected risks, avoided losses, quality improvements or climate impacts. They can also support more transparent communication with municipalities, regulators and citizens by providing verifiable data on water quality, treatment performance, reuse suitability and infrastructure needs. This is particularly relevant in rural areas where investment capacity is limited, and decisions must be clearly prioritised.

In operational terms, SID_AQUARURAL should become a bridge between data, treatment and governance. It should help municipalities answer practical questions: where are the main losses? When will demand peak? Which treatment option is most suitable? Is reclaimed water safe for the intended use? What happens if drought conditions persist? Which infrastructure investment should be prioritised? How could climate change affect water quality and availability?

For the GestEAUr strategy, digitalisation and artificial intelligence should therefore be considered not as isolated technological objectives, but as transversal tools supporting the long-term objectives of the project.

LONG TERM OBJECTIVES AND STRATEGIC DIRECTIONS

The long-term strategic framework of GestEAUr is based on the diagnosis of the five project areas — La Moraña, Guadiana, Alto Minho, Portugal Oeste – Torres Vedras and Béarn — and on the lessons learned from the project's work on water uses and demands, treatment technologies, circular economy, digitalisation and artificial intelligence.

The framework is designed to be adopted by at least one organisation in each participating country before January 2028. To ensure clarity and facilitate adoption by different types of organisations, the GestEAUr strategy is structured around **eight long-term strategic objectives**, each translated into a corresponding **strategic direction**. The objectives define the desired long-term changes for rural water management in the SUDOE area, while the strategic directions indicate the broad pathways through which these changes can be progressively achieved. The flexibility of this structure allows it to be adapted to different rural contexts in Spain, Portugal and France. The strategic objectives presented below should therefore be interpreted flexibly and implemented through measures adapted to each territory. Depending on local conditions, implementation may build upon existing regional and national planning instruments, ongoing investment programmes and previously identified priority projects, complemented where appropriate by technological investments, governance improvements, capacity-building actions or other initiatives that contribute to achieving the same strategic objectives. The proposed strategic lines of action should not be understood as a closed list of technical measures to be fully implemented in two years. Rather, they define the main priorities that adopting organisations may progressively integrate into their planning, investment decisions, governance arrangements and future projects.

Long-term strategic objective	Strategic direction
Objective 1. Guarantee safe and resilient water supply under climate change conditions	Move towards climate-risk-based water security planning.
Objective 2. Deploy sustainable treatment technologies adapted to rural contexts	Promote modular, decentralised and fit-for-purpose treatment systems.
Objective 3. Improve water efficiency and reduce losses in rural water systems	Prioritise water-saving infrastructure, leakage reduction and predictive maintenance.
Objective 4. Optimise water use and manage seasonal and productive demand	Develop demand management models adapted to rural uses and seasonal variability.
Objective 5. Integrate circular economy principles into municipal water management	Promote safe reuse, resource recovery and circular synergies between water, agriculture and local industry.
Objective 6. Strengthen data knowledge and digital readiness of rural water services	Build reliable data foundations and use SID_AQUARURAL and other digital tools to support monitoring, prediction and decision-making
Objective 7. Reinforce cooperation, capacity-building and governance	Build intermunicipal and multi-actor governance models for resilient rural water management.
Objective 8. Enable realistic investment and financing pathways	Support phased, cost-effective and fundable implementation models for small rural systems

Objective 1. Guarantee safe and resilient water supply under climate change conditions. Strategic direction: Move towards climate-risk-based water security planning.

Rural areas of the SUDOE space are increasingly exposed to droughts, low-flow periods, raw water quality deterioration and seasonal pressure on water resources. The first strategic objective is therefore to ensure that rural populations have access to safe, sufficient and reliable water under present and future climate conditions.

This requires moving from reactive management to preventive planning, where water security is assessed not only under normal conditions, but also under drought, contamination episodes, extreme rainfall events, flooding and long-term climate scenarios.

Strategic lines of action:

- Integrate climate risk and water security considerations into rural water planning.
- Prioritise the protection of drinking water sources and the prevention of raw water quality deterioration.
- Promote preparedness mechanisms for droughts, floods and flood-risk management (including update of Potentially Significant Flood Risk Areas), contamination events and seasonal supply stress.

Objective 2. Deploy sustainable treatment technologies adapted to rural contexts. Strategic direction: Promote modular, decentralised and fit-for-purpose treatment systems.

Conventional urban treatment systems are often difficult to replicate in small rural municipalities because they require high investment, stable flows, specialised staff, continuous chemical supply and complex maintenance. Rural water systems need technologies that are robust, affordable, scalable, energy-efficient and easy to operate.

GestEAUr has tested and analysed several solutions that respond to this need, including membrane technologies, electrochemical oxidant generation, nature-based solutions, electro-stimulated wetlands, ultrafiltration, activated carbon, solar photoreactors and reuse-oriented treatment chains.

Strategic lines of action:

- Encourage the selection of treatment technologies according to local rural conditions, operational capacity and water-quality risks.
- Promote modular and decentralised solutions where conventional centralised systems are not technically or economically suitable.
- Support the future replication of GestEAUr-tested technologies in territories with comparable needs.

Objective 3. Improve water efficiency and reduce losses in rural water systems. Strategic direction: Strengthen efficiency-oriented management of water infrastructure and services.

In a climate change context, improving efficiency is one of the most immediate ways to increase water availability. Rural systems often face ageing infrastructure, long networks, limited monitoring and high maintenance costs per inhabitant. Reducing avoidable losses is therefore both an environmental and economic priority.

This objective focuses on improving the knowledge, performance and management of rural water infrastructure, recognising that efficiency is a prerequisite for resilience and circularity.

Strategic lines of action:

- Promote a progressive improvement in the knowledge and monitoring of rural water networks.
- Prioritise efficiency and loss reduction as core principles in infrastructure planning and maintenance.
- Encourage preventive and predictive approaches to infrastructure management where feasible.

Objective 4. Optimise water use and manage seasonal and productive demand. Strategic direction: Promote adaptive demand management adapted to rural seasonality and productive uses.

Rural water demand is hybrid. It includes permanent domestic consumption, public services, tourism, second homes, agricultural labour peaks, livestock, agro-industrial activity, municipal irrigation and other non-household uses. These demands often increase during the same periods in which water availability decreases.

The objective is not to restrict rural development, but to promote a more adaptive management of demand so that domestic, productive and environmental needs can coexist under increasing climate pressure.

Strategic lines of action:

- Incorporate seasonal and productive demand patterns into rural water planning.
- Promote more efficient water use across municipal, domestic, agricultural, tourism and industrial contexts.
- Strengthen dialogue with key water users to anticipate and manage periods of higher pressure.

Objective 5. Integrate circular economy principles into municipal water management. Strategic direction: Advance towards circular use of water, nutrients, energy and local resources.

Circular economy is essential for rural water resilience. It allows municipalities to reduce pressure on conventional resources, recover value from wastewater, reduce waste and create links between water services, agriculture and local industries.

In rural municipalities, circular economy should be understood broadly: not only as water reuse, but also as leakage reduction, energy efficiency, nutrient recovery, nature-based treatment, renewable energy integration and the use of local by-products in water treatment.

Strategic lines of action:

- Promote safe and fit-for-purpose reuse of treated wastewater where technically, legally and socially feasible.
- Encourage circular synergies between municipal water services, agriculture, local industry and renewable energy.
- Integrate resource recovery and nature-based solutions into future rural water planning.

Objective 6. Support the water authorities in knowing better their services Strategic direction: Build reliable data foundations and use SID_AQUARURAL and other digital tools to support monitoring, prediction and decision-making.

Rural water authorities may face significant difficulties in managing the operational data of their services. Due to limited technical skills, financial resources and staff capacity, the collection, organisation and analysis of data are often not prioritised in day-to-day service management. This lack of structured information makes it more difficult for rural operators and municipalities to understand the real performance of their systems, identify risks, prioritise interventions and make informed decisions on future investments. Improving knowledge of water services should therefore be recognised as a strategic priority.

In addition to strengthening this data foundation, digitalisation and artificial intelligence can help rural municipalities move from reactive management to more anticipatory governance. However, digital tools must be adapted to rural capacities. They should be simple, interoperable, modular, affordable and decision-oriented, supporting operators in monitoring, prediction and decision-making without increasing the technical burden on local services.

SID_AQUARURAL provides a strategic opportunity to support rural water management through a lightweight digital twin that integrates data, expert knowledge and probabilistic modelling across the water cycle.

Strategic lines of action:

- Encourage the water authorities to manage and compile operational data of their services.
- Promote the use of SID_AQUARURAL or equivalent tools as decision-support instruments for rural water management.
- Use digitalisation to improve anticipation of risks related to quality, scarcity, demand and treatment performance.
- Ensure that digital tools remain accessible, interoperable and useful for rural operators and municipalities.

Objective 7. Reinforce cooperation, capacity-building and governance. Strategic direction: Consolidate multi-actor and intermunicipal governance for rural water resilience.

Water management in rural areas depends not only on technology, but also on cooperation. Many rural municipalities are too small to address complex water challenges alone. Intermunicipal coordination, shared services and cooperation with farmers, operators, river basin authorities and regional administrations, and other competent public bodies are therefore essential.

This objective aims to ensure that water resilience is embedded in governance structures, not only in technical solutions.

Strategic lines of action:

- Strengthen cooperation between municipalities, operators, authorities and local water users.
- Promote intermunicipal approaches to technical support, planning, monitoring and future investment.

- Support capacity-building and knowledge exchange on rural water resilience, circularity and digitalisation.

Objective 8. Enable realistic investment and financing pathways. Strategic direction: Guide future investments through phased, fundable and context-adapted planning.

Rural municipalities often face limited budgets, low tariff bases and high infrastructure costs per inhabitant. For this reason, the strategy must support financially realistic implementation. The objective is to guide future investment decisions towards measures that are technically necessary, economically viable and aligned with available funding opportunities.

Investment should not focus only on large infrastructure. It should also include maintenance, digitalisation, training, monitoring, renewable energy integration, pilot replication and governance support.

Strategic lines of action:

- Promote phased implementation pathways adapted to the financial and operational capacity of rural organisations.
- Use diagnosis results, pilot evidence and digital simulations to support future investment prioritisation.
- Align rural water resilience priorities with regional, national and European funding opportunities.

WATER SERVICES FINANCING IN RURAL URBAN CONTEXTS

The financing of rural water services must be understood as a combination of sources. The OECD "3Ts" framework — **tariffs, taxes and transfers** — remains useful to describe the basic structure of water financing: tariffs paid by users, public funding from taxation, and transfers from external sources such as national or European funds. In sparse and dispersed rural areas, however, transfers and public co-financing are often indispensable, because full cost recovery through tariffs alone may create affordability problems or remain insufficient to cover the investment required.

The GestEAUr strategy should therefore promote a mixed financing approach. Local resources and tariffs can support operation, maintenance and small improvements, while regional, national and European funds should be mobilised for infrastructure renewal, sustainable treatment technologies, reuse systems, digital tools, climate adaptation, circular economy and intermunicipal cooperation. Loans and blended finance can also play a role for larger operators or regional entities with sufficient repayment capacity, especially where investments generate measurable efficiency gains or reduce long-term operating costs.

Actual and potential financing for water systems in rural areas, particularly those with sparse and dispersed populations

Existing and potential financing sources for rural water systems can be grouped into several categories: European structural funds, territorial cooperation programmes, national recovery and resilience instruments, sectoral environmental and agricultural funds, research and innovation programmes, public loans, regional mechanisms and complementary internal or private instruments.

The first and most relevant source for infrastructure remains **Cohesion Policy, especially the European Regional Development Fund.** In the 2021–2027 period, EU Cohesion Policy includes specific investment categories for access to water and sustainable water management, with wastewater collection and treatment representing the highest planned allocation among those water-related categories. For rural municipalities, ERDF support is particularly relevant for water supply systems, wastewater treatment, network renewal, water efficiency, climate adaptation and environmental compliance.

For the SUDOE area, **Interreg programmes are especially relevant** because they finance cooperation, testing, transfer and governance rather than only infrastructure. The Interreg SUDOE programme supports transnational cooperation projects co-financed up to 75% by the ERDF and has an ERDF budget of EUR 125 million for 2021–2027. This makes it particularly suitable for scaling and transferring GestEAUr results, developing common methodologies, strengthening governance and preparing joint action plans. POCTEP and POCTEFA are also relevant for cross-border territories. POCTEP 2021–2027 is the largest Spain–Portugal cross-border cooperation programme, with a total budget of EUR 475 million, including EUR 356 million from the ERDF, while POCTEFA supports sustainable development in the Spain–France–Andorra border area.

A second important source is the R**ecovery and Resilience Facility,** channelled through national recovery plans. In Spain, the PERTE for the digitalisation of the water cycle is particularly relevant because it supports projects to improve the efficiency and digitalisation of urban water management, including in small rural municipalities. The RRF-supported line includes more than EUR 200 million for improving the digitalisation of the urban water cycle and supports measures such as metering, monitoring, control systems and efficiency improvements. Although the Recovery and Resilience Facility is time-limited, its logic remains important for the GestEAUr strategy: digitalisation, efficiency and climate resilience can be financed when projects are sufficiently mature and aligned with national priorities.

A third financing route is the **Common Agricultural Policy**, particularly where rural water management intersects with farming, irrigation, water retention, nutrient management and pollution prevention. CAP Strategic Plans allow Member States to address local and regional challenges related to agricultural water use, while contributing to wider EU goals on safe water and environmental sustainability. This is highly relevant for GestEAUr territories where agricultural and livestock activities affect both water demand and water quality.

The **LIFE Programme** is another important funding source, particularly for nature-based solutions, circular economy, water reuse, climate adaptation, biodiversity and demonstration of innovative environmental technologies. LIFE supports the transition towards a sustainable, circular and resilient economy, and is therefore well aligned with GestEAUr solutions such as constructed wetlands, reuse-oriented treatment chains, circular resource recovery and nature-based depuration.

For research, innovation and demonstration, **Horizon Europe, PRIMA and Water4All** are particularly relevant. Horizon Europe can support advanced research and innovation on resilient water systems, purification technologies, digital monitoring, decision-support tools and climate adaptation. PRIMA is especially relevant for Mediterranean territories because it funds research and innovation in water management, farming systems and food value chains, and has integrated the Water–Energy–Food–Ecosystems Nexus approach into its calls. Water4All is a European Partnership that funds scientific research and innovation in freshwater and water security, with joint transnational calls that can support research, demonstration, monitoring, governance and treatment solutions relevant to rural water systems.

In terms of repayable finance, the **European Investment Bank** is increasingly relevant for water resilience. The EIB has committed to increasing investment in water to EUR 15 billion between 2025 and 2027, including major infrastructure, pipelines, treatment plants, reduction of water losses and pollution control. For rural areas, EIB loans may be most suitable when projects are aggregated at regional, intermunicipal or operator level, since individual small municipalities may lack the financial capacity to borrow directly.

The **Council of Europe Development Bank** can also support water and wastewater investments where they contribute to social cohesion and resilient living environments. A relevant example is the CEB's financing for water treatment in rural areas of Castilla y León, including a EUR 50 million loan to improve drinking water supply and wastewater treatment, and an additional EUR 40 million financing facility to partially finance 118 additional wastewater treatment plants. This type of financing is especially relevant for rural areas where water infrastructure is linked to quality of life, territorial cohesion, seasonal pressure and the fight against depopulation.

At **national and regional level,** several instruments can complement European funds. In Portugal, the Fundo Ambiental is the main financing instrument for environmental and climate policy and also acts as an intermediary for several components of the Recovery and Resilience Plan related to climate action.

In Spain, regional water agencies and public infrastructure entities can play an important role. For example, the Agencia del Agua de Castilla-La Mancha and Infraestructuras del Agua de Castilla-La Mancha support planning, supply, depuration and hydraulic infrastructure, complementing national and European financing sources. Similar regional or basin-level mechanisms in France, Spain and Portugal can be essential for translating strategic priorities into fundable projects.

Complementary mechanisms should also be considered. In France, the 1% solidarity mechanism created by the Oudin-Santini law allows local authorities, water agencies and water or sanitation services to allocate up to 1% of their water and sanitation budget to international solidarity actions in the water and sanitation sector. While this mechanism is not primarily designed for local infrastructure financing, it is relevant for cooperation, knowledge transfer and solidarity-based water projects.

Finally, **private and internal mechanisms** can support specific elements of the strategy. These may include public-private partnerships for digital tools or energy-efficiency investments, pay-per-use or licensing models for decision-support platforms such as SID_AQUARURAL, payment for ecosystem services schemes, and agreements with agricultural or agro-industrial users that benefit from reclaimed water, nutrient recovery or watershed protection. The European Water Resilience Strategy also foresees a Water Resilience Investment Accelerator to support innovative cases related to natural water retention and water efficiency, bringing together investors, solution providers and problem holders.

Although several of the funding instruments currently available are linked to the 2021–2027 programming period, the financing approach of the GestEAUr strategy should not be limited to this timeframe. The strategy is conceived as a long-term framework that can guide investment, cooperation and project development beyond 2027, including during the next EU programming period. The **future 2028–2034 Multiannual Financial Framework,** together with the **evolution of Cohesion Policy**, territorial cooperation, LIFE, Horizon Europe successor programmes, agricultural funding, water resilience initiatives and national/regional instruments, should therefore be considered as part of the medium- and long-term financing horizon for rural water resilience.

Summary of financing opportunities

The financing opportunities available for rural water systems can be summarised into five main categories, each suited to a different type of need and implementation stage of the GestEAUr strategy.

Financing category	Main instruments	Most suitable uses in the GestEAUr strategy
Infrastructure grants and public subsidies	ERDF, Cohesion Policy, national and regional water infrastructure programmes, recovery plans	Network renewal, water supply, wastewater treatment, depuration, leakage reduction, climate adaptation
Territorial cooperation funds	Interreg SUDOE, POCTEP, POCTEFA	Transnational cooperation, cross-border planning, transfer of GestEAUr results, governance, shared methodologies, pilot replication
Research, innovation and demonstration grants	LIFE, Horizon Europe, PRIMA, Water4All	Innovative treatment technologies, nature-based solutions, circular economy, reuse, digital tools, AI, demonstration pilots
Loans and blended finance	EIB, CEB, national or regional public banks	Larger infrastructure packages, network modernisation, treatment plants, loss reduction, regional or intermunicipal investment programmes
Internal, private and complementary mechanisms	Tariffs, local budgets, pay-per-use models, public-private cooperation, payment for ecosystem services, 1% solidarity mechanisms	Operation and maintenance, small improvements, digital services, ecosystem protection, knowledge transfer, co-financing

The most immediate opportunities for the GestEAUr strategy lie in **grants for cooperation, innovation and resilience**. Interreg SUDOE remains particularly relevant for consolidating the governance, transfer and action-planning dimension of the strategy. LIFE can support the replication of nature-based solutions, circular economy approaches and demonstration of low-energy treatment systems. Horizon

Europe, PRIMA and Water4All can support the further development and validation of electrochemical treatment, solar photoreactors, membrane systems, SID_AQUARURAL and advanced digital monitoring.

For **infrastructure modernisation**, ERDF, national programmes and regional water agencies are likely to be the most relevant sources. These funds can support the upgrading of rural water supply systems, wastewater treatment facilities, leakage reduction, metering, energy efficiency and climate adaptation measures. In Spain, the experience of the PERTE for the digitalisation of the water cycle is particularly relevant for projects linked to monitoring, smart metering, efficiency and digital governance.

For **larger investment packages**, loans from the EIB or CEB may be appropriate, especially when projects are aggregated through regional authorities, public companies, intermunicipal entities or operators with sufficient financial capacity. These instruments are particularly relevant for network renewal, wastewater treatment plants, pollution control and loss reduction. The use of digital tools such as SID_AQUARURAL can strengthen the investment case by providing data on risks, expected benefits, performance monitoring and prioritisation.

For **agriculture-related circular economy measures**, CAP Strategic Plans, PRIMA and Water4All may provide opportunities to finance efficient irrigation, water retention, reuse, nutrient management, nature-based solutions and the Water–Energy–Food–Ecosystems Nexus. These instruments are especially relevant where rural water management is closely connected to agricultural activity and where reclaimed water or nutrient recovery can reduce pressure on conventional resources.

For **digitalisation and artificial intelligence**, funding opportunities should focus on decision-support tools, monitoring systems, smart meters, data interoperability, predictive maintenance and capacity-building. SID_AQUARURAL can be positioned as a practical tool for improving eligibility and readiness for financing, because it supports diagnosis, planning, monitoring and justification of investments. It can also help rural operators move from fragmented data to evidence-based decision-making.

Private and internal mechanisms should be treated as complementary rather than substitutive. In sparse rural areas, private investment will generally be more feasible when linked to specific revenue-generating or cost-saving components, such as renewable energy, digital services, reuse agreements, performance contracts or agro-industrial synergies. Tariffs and local budgets remain necessary for operation and maintenance but should be designed carefully to avoid affordability problems.

To move from demonstration to full-scale adoption, each GestEAUr partner territory should identify a realistic financing mix adapted to its institutional and territorial context. A small municipality may focus on regional subsidies, Interreg cooperation, LIFE demonstration and basic local co-financing. An intermunicipal operator may be able to combine ERDF, national funds, EIB or CEB loans, and internal investment planning. A regional authority may use the strategy to structure larger programmes for rural water resilience, digitalisation and circular economy.

The financing approach should therefore follow a staged logic:

1. **Prepare the investment case** using diagnosis results, pilot evidence and SID_AQUARURAL outputs.
2. **Match the need with the right funding source**, distinguishing between infrastructure, innovation, digitalisation, circular economy, governance and training.
3. **Aggregate demand where possible**, so that small municipalities can access larger funding opportunities through intermunicipal or regional structures.
4. **Combine grants, loans and own resources**, avoiding overdependence on a single source.
5. **Include operation, maintenance and monitoring costs**, not only initial capital expenditure.
6. **Use GestEAUr-tested solutions as replicable models**, especially where they reduce energy use, chemical dependency, water losses or pressure on conventional resources.

ADOPTION AND IMPLEMENTATION PATHWAY

To support adoption by at least one organisation in each participating country before January 2028, the strategy is presented as a common framework with flexible local implementation. Each adopting organisation should be able to endorse the general objectives and strategic directions while selecting the priorities most relevant to its mandate, territory and resources.

A practical adoption pathway could include:

1. Formal endorsement of the GestEAUr strategic framework by a municipality, intermunicipal body, water operator, regional authority or another competent organisation.
2. Identification of the objectives and strategic directions most relevant to the adopting territory.
3. Integration of the selected priorities into existing water, climate adaptation, circular economy, infrastructure or rural development plans.
4. Definition of a light implementation roadmap for 2028–2030, indicating broad priorities, responsible actors and possible funding routes.
5. Participation in transnational exchanges between Spain, Portugal and France to support learning and replication.

The adoption mechanism should remain simple and realistic. Organisations should not be required to implement all objectives immediately. Instead, they should commit to the strategic principles and progressively align their planning, cooperation and investment decisions with the GestEAUr framework.

INDICATIVE MONITORING FRAMEWORK

Strategic objective	**Possible strategic indicators**
Safe and resilient water supply	Water security and climate risk considered in planning; priority risks identified; preparedness measures defined
Sustainable treatment technologies	Rural treatment needs identified; suitable GestEAUr-tested solutions considered; replication potential assessed
Water efficiency and loss reduction	Efficiency recognised as a planning priority; network knowledge improved; loss-reduction needs identified
Demand management	Seasonal and productive demand pressures considered; demand-management principles integrated into planning
Circular economy	Reuse and circularity opportunities identified; circular economy principles included in municipal water planning
Data collection and management (with Digitalisation and AI)	Data management systems are defined; SID_AQUARURAL or equivalent tools considered; digital data needs identified; staff awareness improved
Governance and capacity-building	Relevant stakeholders involved; cooperation mechanisms reinforced; knowledge-exchange activities promoted
Financing and implementation	Priority investment areas identified; funding opportunities explored; implementation roadmap prepared

CONCLUSIONS

The GestEAUr strategy establishes a transformative framework for improving water resource management and increasing climate resilience in rural areas of the SUDOE space. Based on the diagnosis of the five project areas — La Moraña, Guadiana, Alto Minho, Portugal Oeste – Torres Vedras, and Béarn — the strategy responds to a set of shared challenges affecting rural water systems: water scarcity, seasonal demand peaks, diffuse agricultural and livestock pressures, ageing infrastructure, low population density, limited technical and financial capacity, and the need to guarantee safe water supply under increasingly uncertain climate conditions.

The strategy confirms that the future of rural water security depends on the convergence of **decentralised technical solutions**, **circular economy principles** and **advanced digital intelligence**. Rural territories cannot rely only on conventional urban water models, which are often based on large-scale centralised infrastructure, economies of scale, continuous technical supervision and high investment capacity. Instead, sparsely populated and dispersed areas require solutions that are modular, robust, low-maintenance, affordable and adapted to local operational capacities.

A core message of the strategy is the need to move from reactive, high-cost infrastructure responses towards a more proactive and holistic governance model. This model prioritises prevention, climate-risk planning, water efficiency, demand management, safe reuse, Nature-Based Solutions, circular resource use and digital decision-support. In this sense, GestEAUr provides a scalable roadmap for territorial rebalancing across the SUDOE space, addressing the systemic underinvestment and operational vulnerability that often affect rural water infrastructures.

The analysis of urban water uses and demands shows that rural water systems serve much more than domestic consumption. They support public services, agriculture, livestock, agro-industrial activity, tourism, municipal uses and environmental protection. This hybrid demand profile requires systems able to respond to seasonal peaks, variable water quality, drought periods and competing uses. The strategy therefore recommends moving towards climate-risk-based planning, adaptive demand management and stronger coordination between municipalities, operators, farmers, industries and public authorities.

A central recommendation is **the deployment of sustainable treatment technologies adapted to rural contexts.** The solutions tested and analysed by GestEAUr — including membrane technologies, reverse osmosis, nanofiltration, activated carbon, electrochemical oxidant generation, constructed wetlands, electro-stimulated wetlands, ultrafiltration, solar photoreactors and reuse-oriented treatment chains — demonstrate that rural water systems can be strengthened through technologies that are scalable, robust and compatible with limited operational capacity. These solutions are **not proposed as a single model, but as a portfolio** that territories can adapt according to their water quality problems, population size, available land, reuse potential and financial resources.

The strategy also reinforces the role of circular economy in rural water management. Water reuse, nutrient recovery, renewable-energy-based treatment, nature-based solutions, agro-industrial waste valorisation and managed aquifer recharge can reduce pressure on conventional resources and create new synergies between municipalities, agriculture and local industries. Future planning should promote "fit-for-purpose" reuse approaches, ensuring that treatment quality is adapted to the final use while complying with the applicable regulatory framework, including Regulation (EU) 2020/741 on minimum requirements for water reuse.

Data knowledge of the services with digitalisation and artificial intelligence issues are identified as transversal enablers of better rural water governance. **SID_AQUARURAL represents one of the key outputs of the project**, providing a lightweight digital twin and decision-support tool adapted to rural contexts. Its value lies in helping municipalities and operators anticipate risks, monitor water quantity and quality, support treatment decisions, assess reuse potential and communicate information more transparently. The strategy therefore recommends institutionalising the use of accessible digital tools such as SID_AQUARURAL, not as complex systems that add operational burden, but as practical instruments for predictive management, investment prioritisation and transparent governance.

The collaborative process underlying the strategy has been essential to its relevance and applicability. GestEAUr reflects a "Triple Helix" model of transnational cooperation, bringing together academic institutions such as USAL, UCLM and CNRS; water operators, including Aqualia, Aqualia Portugal and Aguas de Tejo Atlantico; and regional and territorial public authorities such as Diputación de Ávila, Pays de Béarn and CIM Alto Minho. This interdisciplinary approach ensured that technological innovations, such as electro-stimulated wetlands, electrochemical oxidant generation and solar photoreactors, were not developed in isolation, but in response to the practical demands of rural municipalities and water operators.

The synthesis of these experiences into the E1.2.1 Catalogue of Cost-Effective and Sustainable Solutions and the SID_AQUARURAL tool represents a significant step in bridging the gap between scientific modelling, technological demonstration and municipal policy formulation. The strategy therefore does not only gather technical results; it translates them into strategic directions that can guide future planning, investment and cooperation across different rural contexts.

The long-term strategic framework is structured around eight objectives and corresponding strategic directions: ensuring safe and resilient water supply; deploying sustainable treatment technologies; improving efficiency and reducing losses; optimising water use and demand management; integrating circular economy principles; strengthening digitalisation and artificial intelligence; reinforcing cooperation and governance; and enabling realistic financing pathways. These objectives provide a common direction for rural water resilience while allowing each adopting organisation to adapt the strategy to its own territory, responsibilities and resources.

The next phase of implementation should focus on the formal adoption of the strategy and its translation into realistic territorial action. Adoption should not require the immediate implementation of all objectives. Instead, each organisation should endorse the common framework, identify the strategic directions most relevant to its territory, and integrate them progressively into existing water, climate adaptation, circular economy, infrastructure or rural development planning.

The implementation process should be phased. In the short term, adopting organisations should prioritise strategic alignment, self-assessment, identification of priority risks, governance coordination, selection of relevant measures and preparation of fundable project pipelines. In the medium and long term, the strategy can support broader investments in sustainable treatment, infrastructure renewal, safe reuse, digitalisation, circular economy and capacity-building, including through current and future European, national and regional funding opportunities beyond 2027.

The expected impact of the strategy is environmental, socio-economic and institutional. From an environmental perspective, it can help safeguard natural capital by reducing pressure on water bodies and aquifers, limiting nutrient leaching, improving wastewater treatment and reducing the discharge of emerging contaminants. From a socio-economic perspective, it can support rural vitality by improving the reliability and quality of water services, reducing operational vulnerabilities and helping rural populations access water services closer to urban standards. From an institutional perspective, it can strengthen cooperation, improve decision-making and position the SUDOE area as a reference territory for decentralised, circular and digitalised rural water governance.

Ultimately, GestEAUr provides the scientific, technological and governance basis needed to treat water as a sustainable common good for the next generation of rural citizens. Its added value lies in translating project results into a practical, adaptable and forward-looking framework that can guide future decisions, investments and cooperation. Through this strategy, rural territories in the SUDOE space can move towards a water management model that is more secure, more efficient, more circular, more digital and better prepared for the climate challenges ahead.

REFERENCES

- Cheng, Y.-M., Horng, M.-F., & Chung, C.-C. (2024). ICT Innovation to Promote Sustainable Development Goals: Implementation of Smart Water Pipeline Monitoring System Based on Narrowband Internet of Things. *Sustainability*, 16(22), 9683. https://doi.org/10.3390/su16229683
- Council of Europe Development Bank (CEB). (2024, August 27). Water for all: A case for investing in water and sanitation in Europe. https://coebank.org/en/news-and-publications/blog/water-for-all-a-case-for-investing-in-water-and-sanitation-in-europe/
- Elcano Royal Institute. (2025). The European Water Resilience Strategy: A key lever to secure climate mitigation and adaptation. https://www.realinstitutoelcano.org/en/analyses/the-european-water-resilience-strategy-a-key-lever-to-secure-climate-mitigation-and-adaptation/
- European Investment Bank (EIB). (2024). Joint Annual MDB Water Security Financing Report 2024.(https://coebank.org/media/documents/Water_Security_Financing_Report_2024.pdf)
- European Parliament. (2024). Sustainable water management in recovery and resilience plans. European Parliamentary Research Service (EPRS).(https://www.europarl.europa.eu/RegData/etudes/BRIE/2024/762375/EPRS_BRI(2024)762375_EN.pdf)

- Hamitouche, M., & Molina, J.-L. (2022). A review of AI methods for the prediction of high-flow extremal hydrology. Water Resources Management, 36(10), 3859-3876. https://doi.org/10.1007/s11269-022-03240-y
- Idrica. (2025). Water technology trends 2025: Operational intelligence and AI. https://www.idrica.com/wp-content/uploads/2025/02/202501_XV_trends-2025_EN.pdf
- Molina, J.-L., & García-Aróstegui, J.-L. (2023). Water table prediction through causal reasoning modelling. Science of the Total Environment, 867, 161492. https://doi.org/10.1016/j.scitotenv.2023.161492
- Molina, J.-L., Zazo, S., & Espejo, F. (2025). Meta-water-modelling (Meta-WaM): A new framework for increasing applicability of digital water modelling. Knowledge-Based Systems, 318, 113543. https://doi.org/10.1016/j.knosys.2025.113543
- OECD. (2025, April 15). The circular economy in cities and regions of the European Union. https://www.oecd.org/en/publications/the-circular-economy-in-cities-and-regions-of-the-european-union_e09c21e2-en.html
- TYPSA. (2024). Strategy and Investments for Water Efficiency and Resilience in Spain. Report for SEOPAN. https://www.typsa.com/en/water-and-the-future-roadmap-for-water-resilience-in-spain/
- UNESCO. (2025). Applications of artificial intelligence for water management. UNESCO Chair on Water-related Disaster Risk Reduction. https://unesdoc.unesco.org/ark:/48223/pf0000393243
- Water Europe. (2024). Charting the pathways towards society's better use, valorisation and stewardship of our water resources.(https://watereurope.eu/wp-content/uploads/2024/10/Water-Europe_Final-Report_15102024-1.pdf)
- World Bank. (2021). Water in circular economy and resilience (WICER). https://www.worldbank.org/en/topic/water/publication/wicer
- World Economic Forum. (2025). Harnessing digital technologies for smarter water management in agriculture.(https://reports.weforum.org/docs/WEF_Harnessing_Digital_Technologies_for_Smarter_Water_Management_in_Agriculture_2025.pdf)
- López-Campos, B. ; Sanz-Alonso, R. ; Granados-Fernández, R. ; Fernández-Mena, I. ; Sáez, C. ; Rodrigo, M.A. ; Lacasa, E. 3D-printed electrochemical reactor for integrated ozone generation and gas-liquid separation via PEM technology. Journal of Environmental Chemical Engineering 14 (2026) 122613. (https://doi.org/10.1016/j.jece.2026.122613)