Layman's Report 2013/2016

aWARE

Innovative hybrid MBR systems to promote Water Reuse

http://www.life-aware.eu/

aWARE: Innovative hybrid MBR-PAC-NF systems to promote Water Reuse

CETAQUA CENTRO TECNOLÓGICO DEL AGUA

Aigües de Barcelona

LNEC

With the contribution of the Life financial instrument of the European Comission

LIFE11 ENV/ES/000606 aWARE

The project: consortium

The aWARE project that started in January 2013 and ended in November 2016 has a total budget of 2.6 million euros, and the financial contribution of the LIFE + programme of the European Commission (1.3 m€). The aWARE project is coordinated by **Cetaqua** Water Technology Center, and counts with **Aigües de Barcelona, Empresa Metropolitana de Gestió del Cicle Integral de l'Aigua (AB)** and **Laboratorio Nacional de Engenharia Civil (LNEC)** as project partners.

Project consortium

Cetaqua

Water technology center and coordinating beneficiary (Spain). Expertise in operation and design of water reclamation technologies, life cycle analysis and costing.

Aigües de Barcelona

Empresa Metropolitana de Gestió del Cicle Integral de l'Aigua (Spain). Experience in the management, operation and water quality control of wastewater treatment and reclamation plants as well as potable water works and distribution networks.

Laboratorio Nacional d'Engheneria Civil

National Laboratory of Civil Engineering (Portugal). LNEC brings its knowledge of activated carbon adsorption and of hybrid processes combining adsorption and membrane technology for controlling organic pollutants.

Stakeholders

aWARE stakeholders have played an important role in the development of the project, participating in technical workshops and visits to the demonstration and prototype site.

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01 Context

Water reclamation and reuse

In Europe water stress caused by freshwater scarcity is one of the major concerns that our society will have to face in the nearest future.

Water reclamation and reuse is considered as the most sustainable way to supply water for certain uses and appears as the best solution to complement water efficiency measures, in order to balance the increasing disparity between the available freshwater and the demand.

However, water reuse is still limited and below its maximum potential in most European areas due to technical, environmental, legal and social barriers.

Amongst them, the accumulation of priority and emerging pollutants is considered as a potential barrier for the implementation of water reuse in environmental or agricultural applications.

Benefits of integrating water reuse in resource management

01 Increase in quantity and temporal stability of available water resources, ensuring water supply.

02 Reduction of overexploitation of conventional water resources such as surface or groundwater by adapting the quality of water produced by reclamation systems to industries, agriculture, maintenance of natural ecosystems and development of green areas in cities.

03 Reduction of environmental or economic impact compared to seawater desalination, water transfers and damns, saving in energy and infrastructures.

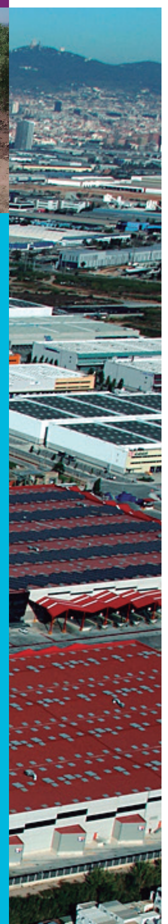


Figure 1 View of Llobregat river in drought and flooding period (top left and right respectively) and general view of Baix Llobregat water reclamation plants (bottom) in Barcelona (Spain).

Priority pollutants (PP) and emerging pollutants (EP) in the water cycle

The European Commission, through the **Water Framework Directive** (WFD 2000/60/EC) and the **Environmental Quality Standards Directive** (2008/105/EC) - EQS, and the 2013/39/EU Directive established a water policy strategy for control of priority pollutants (PP) and their maximum and annual average concentrations in natural water bodies. In order to achieve "good chemical status" and accomplish the EQS for the PPs (biocides-pesticides, heavy metals, detergents, dissolvent, polyaromatic hydrocarbons) member states should implement measures to control their emissions.

Emerging Pollutants (EP), which may be included in the PP list of updated versions of the WFD, are also being considered. In particular, pharmaceuticals, personal care products and hormones are groups of emerging contaminants that are receiving increasing attention because of their potential harmful effects for the environment and human health.

The main source of priority and emerging pollutants within the water cycle is the **wastewater of industrial, agricultural and urban origins (Figure 2)**. Because most of the wastewaters generated within the water cycle are treated in urban and industrial **WWTP** and these are not specifically designed to remove PP and EP, their effluents have been identified as the main point of source in the natural water bodies.

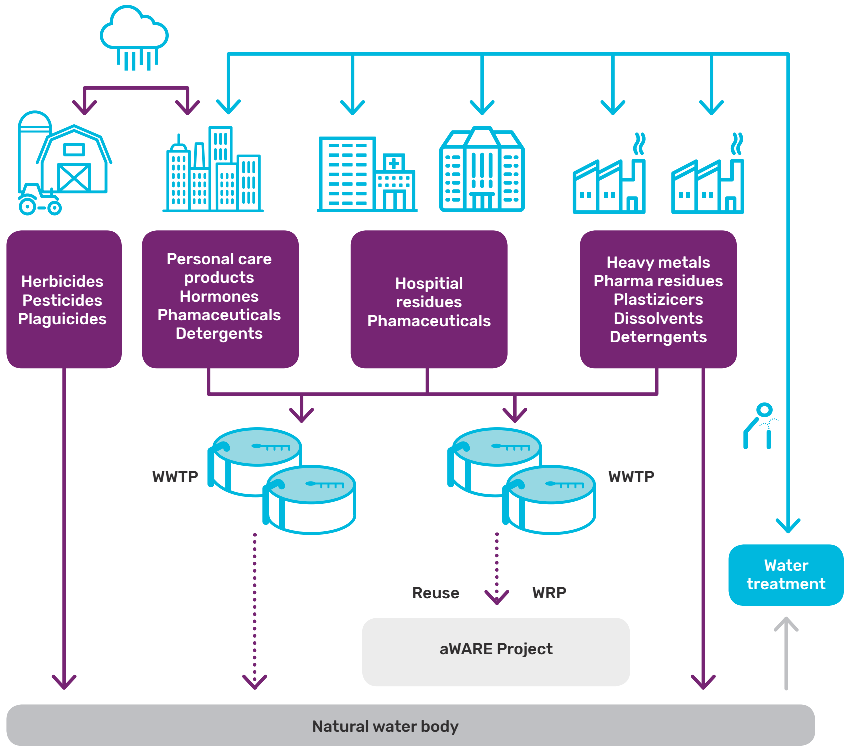


Figure 2 Urban water cycle with main sources of PP and EP to the environment.

aWARE Project: Advanced Water Reclamation for removal of PP and EP

Advanced water reclamation technologies and treatment schemes also need to be considered as an additional barrier of persistent priority and emerging pollutants within the water cycle in scenarios where their levels can compromise the environment, and public health.

02 aWARE concept

Water Reclamation for removal of priority and emerging pollutants

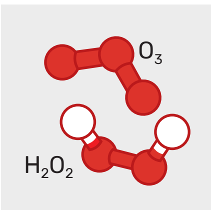
Conventional reclamation schemes enable to upgrade water quality to ensure safe use of water for the different applications. However, water reclamation schemes have not been specifically designed for the removal of priority and emerging pollutants that are persistent in WWTP. In the aWARE project, two main concepts have been tested as possible solutions for this purpose: **Advanced Oxidation Processes and Powdered Activated Carbon.**

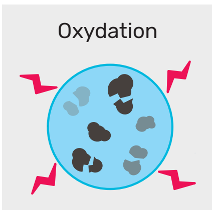
Revamped WRP with AOP

Innovative MBR-PAC-NF

Applied for conventional water reclamation plants revamping › **Advanced Oxidation Process (AOPs)** › **aWARE Technologies for removal of PP and EP** ‹ **Powdered Activated Carbon (PAC)** ‹ **Combined with membrane technology for water treatment and reuse in innovative treatment schemes**

Advanced Oxidation Processes (AOPs) are based on the generation of oxidants (ozone and hydroxyl radicals), which applied to treated effluents enable to oxidize (break up) organic micropollutants.



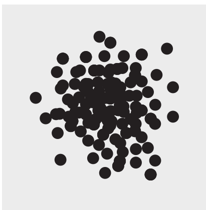


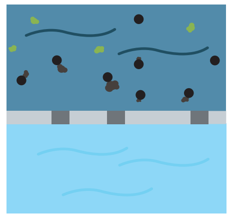
In the aWARE project different combinations of ozone, hydrogen peroxide and UV light have been implemented in conventional water reclamation schemes for enhancing the removal of PP and EP.

PP and EP

- **Acetaminophen**
- **Atenolol**
- **Atrazine**
- **Carb. Epoxide**
- **Carbamazepine**
- **Codeine**
- **Cotinine**
- **Diclofenac**
- **Diuron**
- **Erythromycin**
- **Isoproturon**
- **Nonylphenol**
- **Octylphenol**
- **Pentaclorophenol**
- **Simazine**
- **Sulfametoxazole**
- **Terbuthylazine**

Powdered activated carbon (PAC) is a material that applied to water enables removal of organic micropollutants and other contaminants through adsorption.





In the aWARE project PAC has been combined with two membrane based water reclamation technologies: membrane bioreactors (MBRs) and capillary nanofiltration (NF) in an innovative scheme (MBR-PAC-NF).

03 Objectives

The overall aim of the aWARE project is to promote water reuse by consolidating knowledge about a wide range of water reclamation technologies and identifying key issues regarding the production and distribution of reclaimed water. The two main objectives include:

01

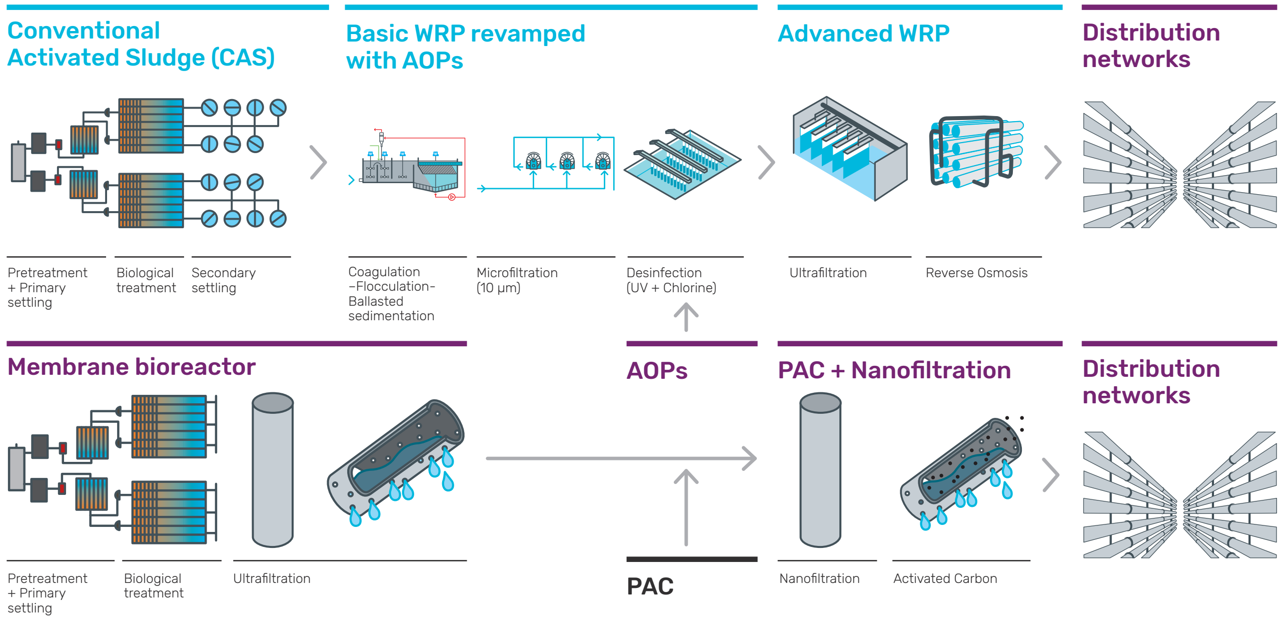
To compare the technical, economic and environmental feasibility and impact of implementing advanced oxidation processes and an innovative MBR-PAC-NF treatment scheme as a means for preventing the emission of persistent priority and emerging pollutants within the water cycle.

02

To identify the main factors that influence the development of biofilm in distribution networks of reclaimed water in order to contribute to management strategies that guarantee water quality in the point of use.

Water reclamation treatment schemes for removal of PP and EP

Distribution



In order to accomplish the project objectives an MBR-PAC-NF and AOPs demonstration plants as well as the distribution network prototype have been designed, constructed and operated in Baix Llobregat Water Reclamation Plant during a period of almost two years.

Barcelona Water Reuse Scheme and Baix Llobregat Water Reclamation plant represent a unique show case study and demonstration site for boosting water reuse acceptance across Europe.

▲

Figure 3 Schematic representation of aWARE scope: 1- Comparison of water reclamation schemes focused on the removal of PP and EP. 2- Distribution networks of reclaimed water.

Barcelona's Metropolitan Area Water Reuse Scheme

In the **Barcelona Metropolitan Area** conventional water resources have been unable to satisfy water demand in periods of prolonged drought. In order to avoid overexploitation of groundwater resources, which led to saline intrusion to the aquifer, and to overcome ecological water deficits of surface water, water reclamation and reuse was found to be the most feasible solution to provide alternative water resources.

The Barcelona water reuse scheme (**Figure 4**) has been in operation for several years and is key for the supply of water, especially in periods of severe drought. In order to guarantee reclaimed water supply, 4 water reclamation plants with capacities ranging from 6 to 100 Hm³/year were constructed. More than 66 km distribution network enable to transport reclaimed water for industrial, agricultural, recreational, environmental and urban uses.

1. Green areas irrigation
   Industrial reuse
2. Seawater instrusion barrier
3. Wetlands maintenance
4. River flow maintenance
5. Agricultural irrigation
6. Recreational irrigation (golf courses)

Water reclamation plants
03

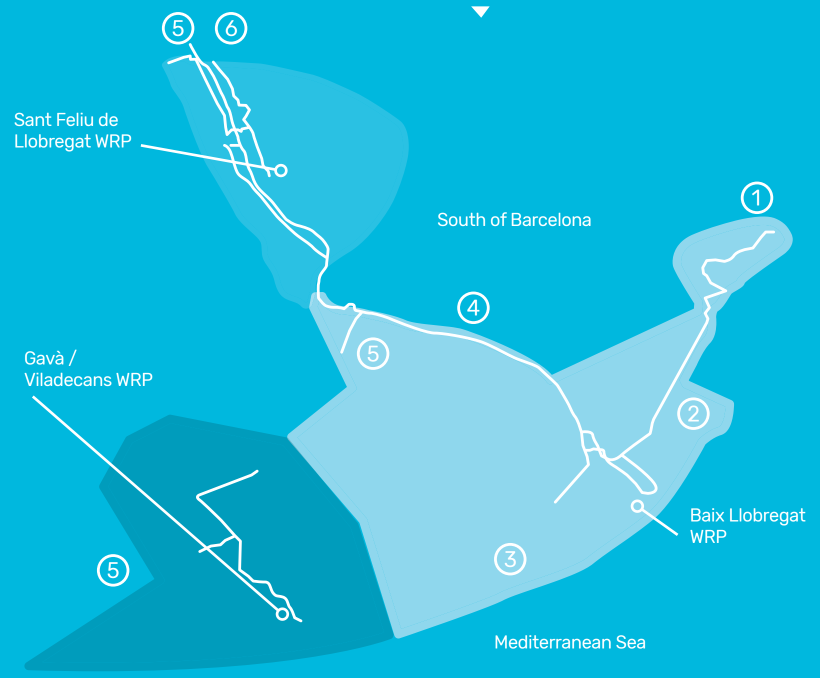
Total Capacity
398.400 m³/day

Supply area
Centre and South of Baix Llobregat, South West Barcelonés

Total Km. of distribution network
66,3 km

Uses
Urban, Environmental Industrial, Agriculture and Recreational

Figure 4 South Barcelona's Metropolitan area reuse scheme.



Demonstration site: Baix Llobregat Water Reclamation Plant

The demonstrative actions of the aWARE project took place in the Water Reclamation Plant of Baix Llobregat (Barcelona). This Water Reclamation Plant (WRP) represents one of the largest facilities of water reuse in Europe and is a key piece for ensuring the sustainability and management of the urban water cycle in the Barcelona's water reuse scheme.

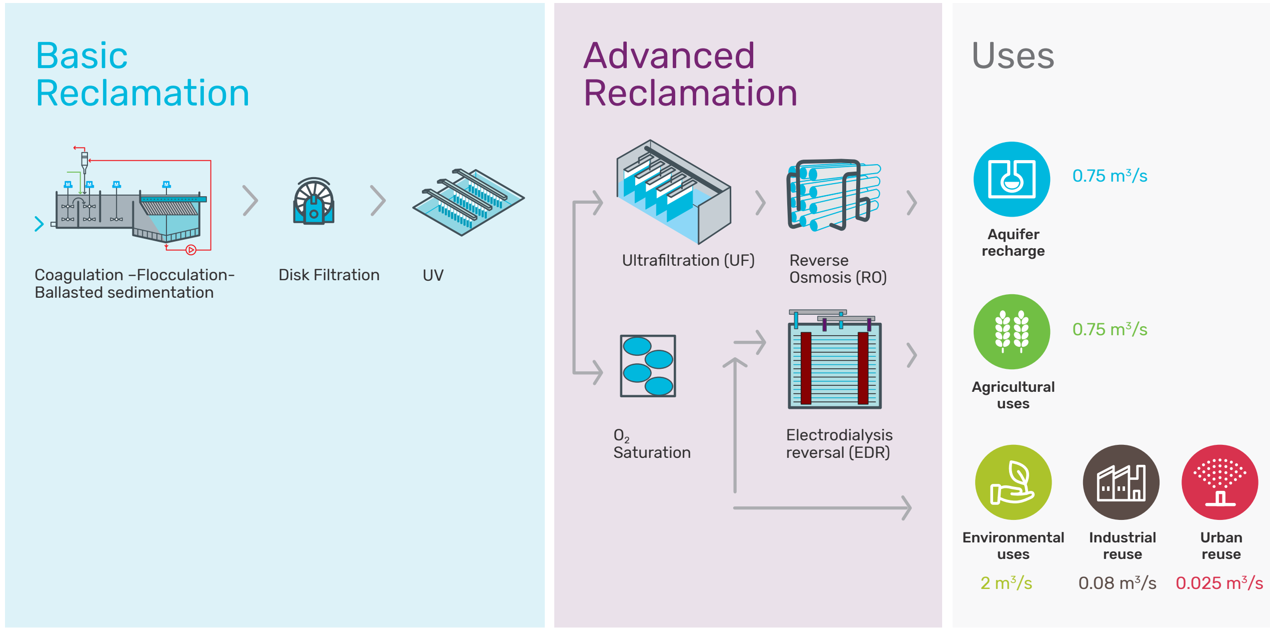
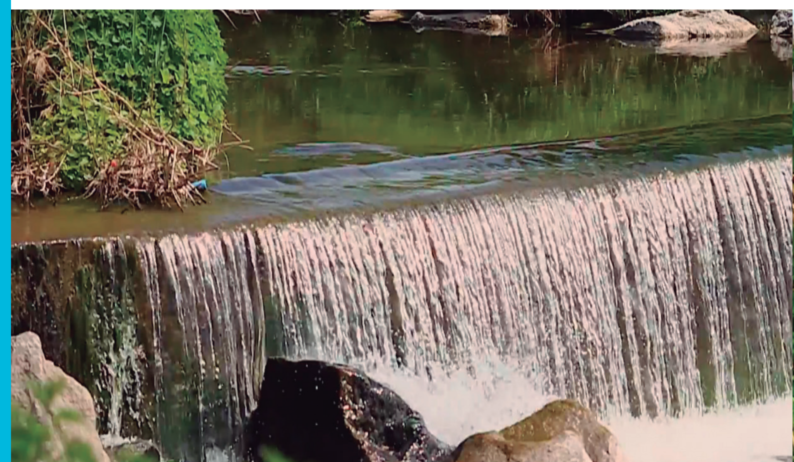


Figure 5 Baix Llobregat basic and advanced water reclamation plants scheme.

Baix Llobregat Water Reclamation Plant produces two different water qualities (Figure 5):

The **basic WRP** produces over 300 000 m³/d of reclaimed water with the quality standards set by existing legislation (RD 1620/2007) for reuse in agricultural, industrial, municipal and environmental applications.

The **advanced WRP** produces 15000 m³/d of low salinity effluent by means of a combined Ultrafiltration and Reverse Osmosis treatment. The water produced in the advanced reclamation is distributed along the coastline and injected into the aquifer as seawater intrusion barrier.



05 Innovative treatments and reclamation schemes: MBR-PAC-NF

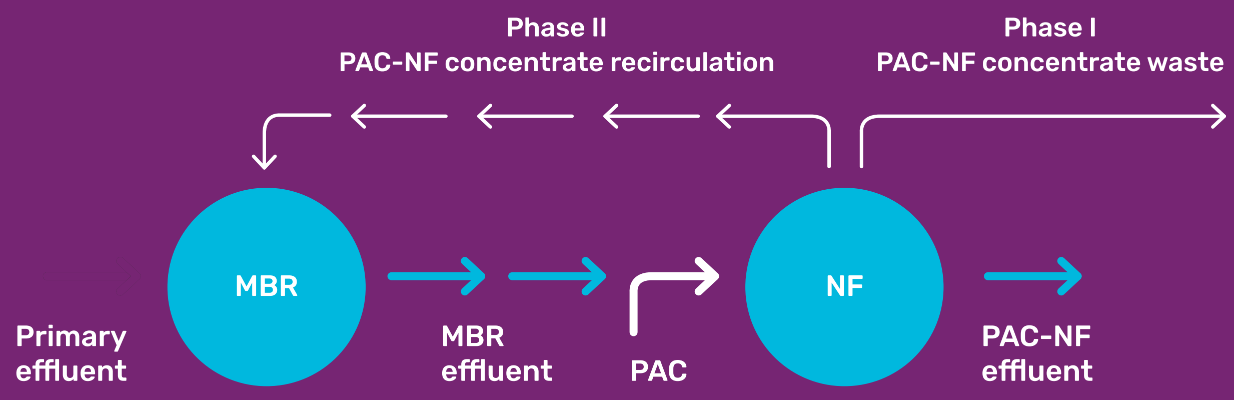


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Figure 6 Schematic representation of the MBR-PAC-NF treatment scheme and phases of operation.

Technical program

The Membrane bioreactor followed by powdered activated carbon and nanofiltration (MBR-PAC-NF) treatment plant has been operated and optimized during almost two years (January 2015 to September 2016) with the primary effluent wastewater in Baix Llobregat WRP (Spain). The operation and optimization was divided in two phases (Figure 6), with and without PAC recirculation form the NF concentrate to the MBR (Phase I and Phase II respectively) with the objective of evaluating the influence of PAC on membrane performance as well as priority and emerging pollutants removal.

Membrane performance, productivity, chemicals and energy consumption were monitored in order to evaluate whether the potential benefits of the use of PAC represent a reduction in membrane operational and investment costs. The MBR-PAC-NF treatment scheme has been compared in technical, environmental and economic terms, either to the basic WRP revamped with AOPs or to the advanced WRP based on membrane technology.

	Phase I (12 months)	Phase II (9 months)
MBR	**Optimization for the identification of baseline performance of the MBR without PAC addition** • Biological and membrane operation. • Evaluation of water quality for reuse and removal of PP and EP.	**Operation of the MBR with three different PAC doses (25, 50 and 100 mg/L)** from the spent PAC of the NF concentrate **for performances comparison of the MBR** in phase I.
PAC-NF	**Optimization of PAC doses (25, 50 and 100 mg/L) in the PAC-NF for:** • Identification of membrane operational conditions, energy and cleaning requirements for each dose. • Evaluation of the impact on water reuse parameters and removal of PP and EP.	**Long term tests during 9 months at each PAC dose for the validation of:** • Sustainable membrane operational conditions. • Water quality results obtained in phase I.

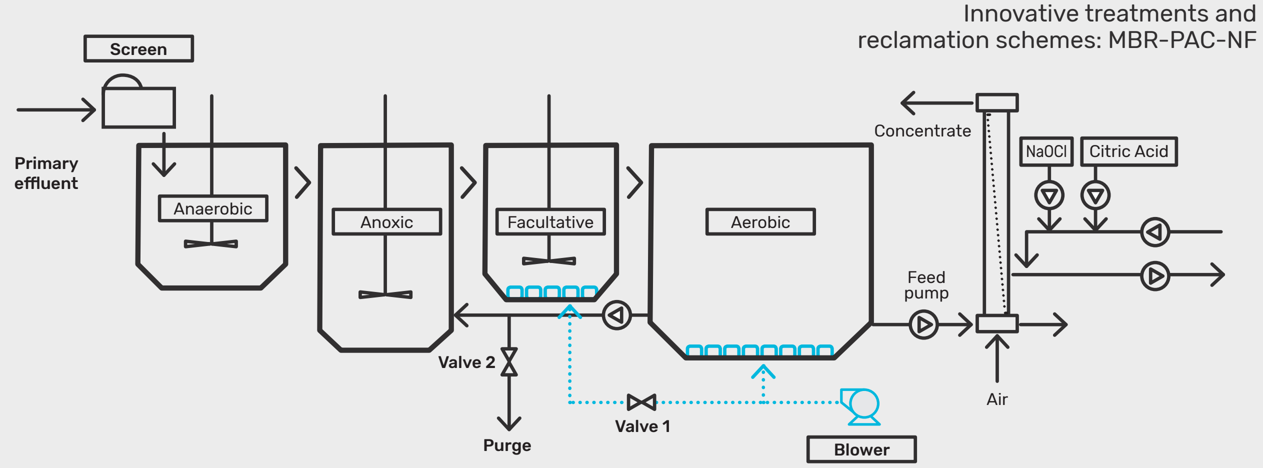

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Figure 7 Schematic representation of the aWARE MBR prototype.

MBR plant characteristics

Membrane bioreactors (MBRs) integrate biological treatment and membrane filtration for the production of reclaimed water in a single step. Main advantages of MBRs in comparison to conventional water reclamation systems include the production of an effluent free of solids, low turbidity and disinfection requirements, which can be employed for most reuse applications, as well as a reduction on footprint and the ease to retrofit existing treatment plants.

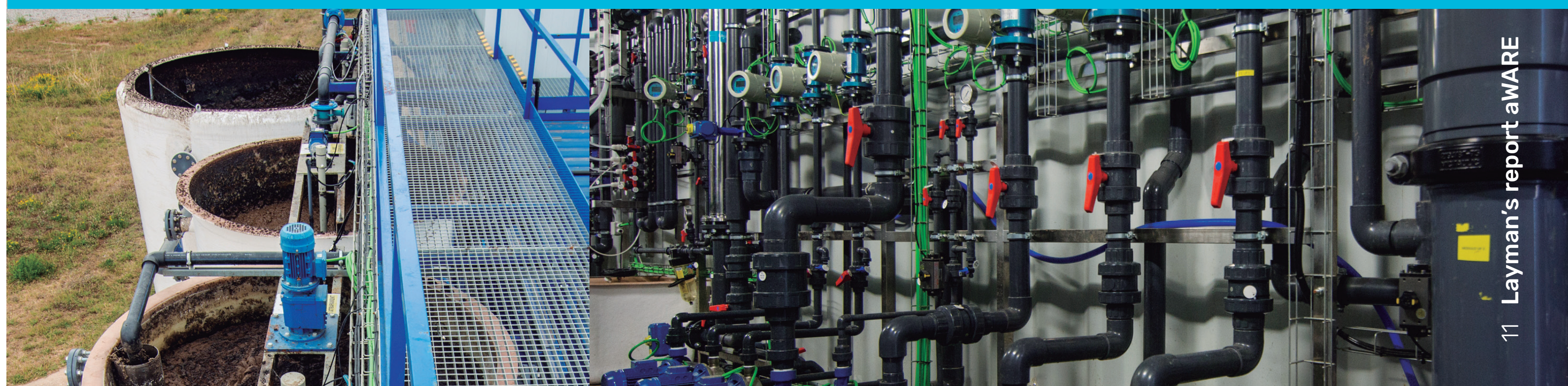
Figure 8 MBR prototype: Biological tanks (left) and sides tream airlift modules and pumping equipment (right).
▼

The pilot plant has been designed with a high degree of instrumentation and operated in continuous mode under real environmental conditions that full scale treatment plants have to face.

Each plant was equipped with commercially available membranes modules employed in full scale installations in order to obtain representative performance values and avoid scaling up risks for implementation of the technology.

MBR - Characteristics

Containerized 40 feet, automatic operation 24h / 7d	
Treatment capacity	50-60 m^3/d
Biological treatment	20 m^3 for biological COD and TN removal
Membrane configuration	Multitubular airlift UF Inside-out filtration
Membrane area	33 m^2/module
Tube internal diameter	5.2 mm
MWCO	20 nm
Material	PVDF
Standard production	1,4- 2 m^3/h/module



NF plant characteristics

The capillary NF membranes enable the rejection of organics and present low removal of salts that conventional NF and RO membranes achieve. Main advantages of the capillary NF membrane in comparison to spiral wound NF-RO include the higher operational flexibility of the membranes due to the possibility of performing chemical and physical (backwashes) cleanings and the possibility of treating influent streams with higher solids and turbidity without further pretreatment requirements.

The NF plant was equipped with two commercial capillary NF modules, one of which was operated directly with the MBR effluent, while the other has been operated with PAC in order to compare membrane performance and water quality (Figure 10).

In order to achieve sustainable membrane operation the capillary NF with PAC has been optimized with the internal recirculation flow and physical cleaning cycles.

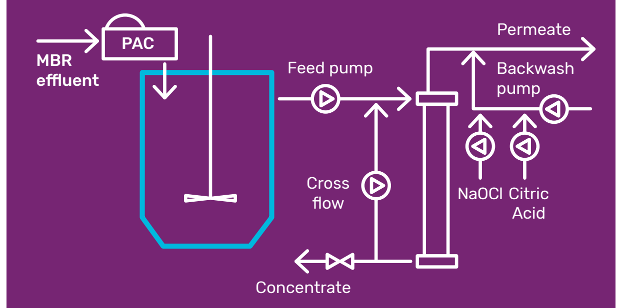


Figure 9 Schematic representation of the aWARE PAC-NF plant.

PAC-NF CHARACTERSITICS AND OPERATION

Containerized 40 feet, automatic 24h / 7d	
Treatment capacity	40-50 m³/d
PAC	Contact time: 30 min – 2h
	Dose: 25-50-100 mg/l
Membrane configuration	Capillary inside-out filtration
Membrane area	40 m²/module
Fibre internal diameter	0,8 mm
MWCO	1000 Da
Material	PES
Standard production	0,8- 1 m³/h/module

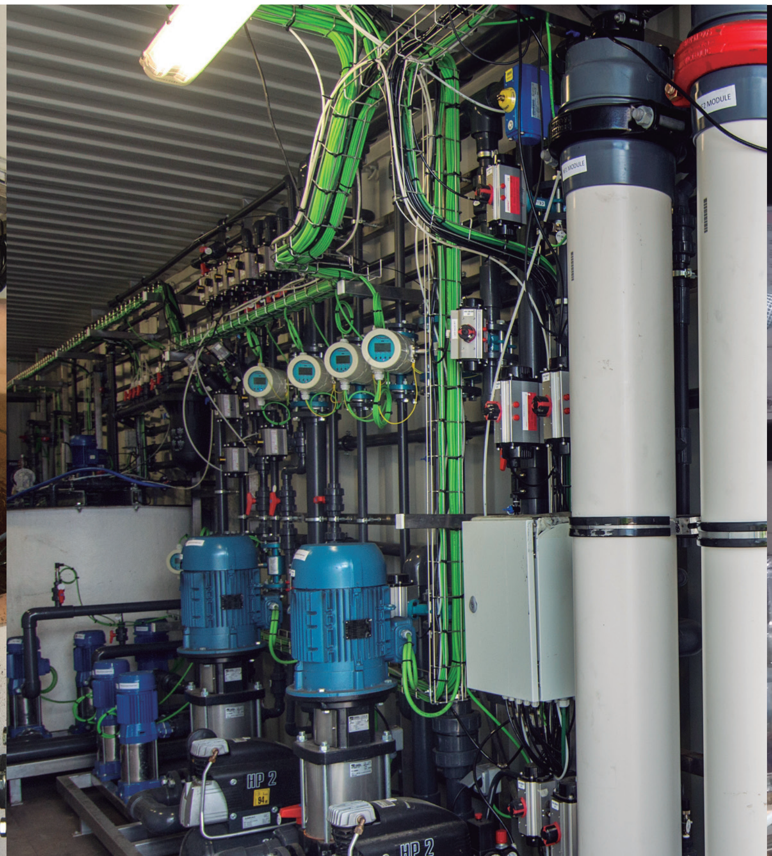
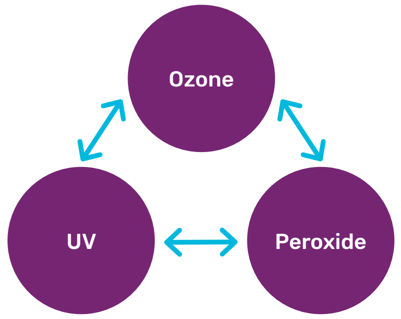


Figure 10 PAC-NF Prototype: PAC contact tank (left) and two NF modules operated in parallel with and without PAC

06 Advanced Oxidation Process for revamping basic water reclamation plants (WRP)



Technical program

Advanced Oxidation Processes combining ozone, ultraviolet (UV) and hydrogen peroxide have been applied at pilot scale to the disk filter effluent of Baix Llobregat WRP in substitution of the conventional UV disinfection in order to evaluate improvements in removal of organic matter removal and character, disinfection, PP and EP removal as well as to evaluate the influence on membrane fouling on subsequent UF-RO membranes of the advanced WRP.

	Phase I (12 months) AOP selection	Phase II (3 months) Optimization of selected AOP
Objetive	**Testing different combinations and doses of ozone, UV and hydrogen peroxide**	**Testing the selected AOP in the range of doses for optimization:**
Parameters evaluated on the use AOPs for revamping basic WRP	Evaluation of removal of organic matter and disinfection performance: • Ozone dose range: 3-50 mg/L • Peroxide doses range: <1-15 mg/L • UV doses: 80-160 mJ/cm²	**Removal of organic PP and EP** Ozone doses: 3-9 mg/L UV doses: 80-160 mJ/cm²
Parameters evaluated on the Effect of AOP in subsequent Advanced WRP	• Fouling • Permeate water quality	Validation of **fouling amelioration** in **UF and RO membranes at long term**

Figure 11 AOP pilot plant.

AOP plant characteristics

Advanced oxidation plant

Ozone Generator	
Treatment capacity	1 m³/h
Ozone production capacity	10-40 g/h
Ozone concentration	40-120 g/Nm³
Applied Ozone doses	3-50 mg/L
UV reactor	
Treatment capacity	1 m³/h
Lamp power	25 W
Applied UV doses	80-160 mJ/cm²
Applied peroxide doses	0,8-15 mg/L

07 Distribution of reclaimed water

Technical program

A distribution network prototype has been designed, constructed and operated with Baix Llobregat basic WRP, in order to simulate the operational conditions of a distribution network. Factors that have been evaluated include those related to the production of reclaimed water, the demand and the distribution network itself (Figure 12):

In each of the three branches new, aged and antimicrobial PE pipes were installed and biofilm analyzed for bacterial groups (Total Coliforms, E.Coli. P. aeruginosa, L. pneumophila) and biofilm characteristics (Total cell count, Cell viability, Exopolymeric substances, Biofilm thickness).

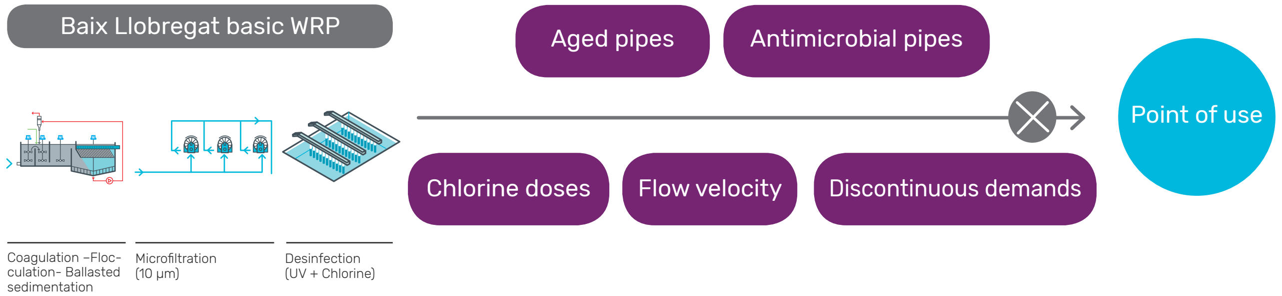


Figure 12 Schematic representation of the different factors studied in the distribution network prototype.

Distribution network plant characteristics

The distribution network prototype consisted of a series of 3 branches each one operated under different velocities and either with continuous or discontinuous circulation of basic WRP effluent (Table 1).

Distribution network prototype operation

	DN 110 Tube	DN 32 Tube
Branch 1 (3d ON: 4d OFF)	5,5 m^3/h (0,2 m/s)	4,3 m^3/h (1,5 m/s)
Branch 2 (Continuous)	5,5 m^3/h (0,2 m/s)	4,3 m^3/h (1,5 m/s)
Branch 3 (Continuous)	21 m^3/h (0,8 m/s)	14 m^3/h (4,8 m/s)

Table 1 Operational conditions applied in the distribution network plant.

Figure 13 The distribution network prototype operated in Baix Llobregat WRP.

08 Results obtained for reclamation schemes with removal of priority pollutants (PP) and emerging pollutants (EP)

Advanced oxidation processes for revamping reclamation plants

Table 2 Summary results obtained during the selection trials of AOPs applied to the basic WRP.

Results from the different combinations of AOP (Table 2) showed that:

01 None of the AOPs applied in the range of doses tested enabled a significant reduction in organic matter content.

02 Ozone based AOPs (ozone + UV and ozone + peroxide) enabled significant reduction in aromatic character of the organics (UV254) and reduced UF fouling in comparison to no AOP treatment.

03 Peroxide based AOPs (ozone + peroxide and UV + peroxide) showed a negative influence on fouling of RO membranes.

AOP combination

Parameter (Unit)	Ozone + UV	Ozone + Peroxide	UV + Peroxide
Doc Removal	4-10%	2-3%	2-14%
UV_{254} Reduction	46-68%	27-68%	5-19%
UF Performance (relative to no AOP)	18-90% Improvement with increasing UV and O_3 doses	69-98% Improvement with increasing H_2O_2/O_3 ratio from 0 to 1	No significant effect
RO Performance (relative to no AOP)	No significant effect	2-9 x higher fouling Peroxide negative influence in comparison to only O_3	3-10 x higher fouling With peroxide in comparison to only UV

Selected AOP conditions for revamping basic WRP

Ozone: 3-9 mg/L + UV: 80-160 mJ/cm²

Parameter	Log reduction
E.Coli	2.3-3.6
Total Coliforms	2.5-4
Clostridium perfringens	1-2
Clostridium perfringens	1.9-2.6
Aerobic bacteria	2-3.5

Table 3 Disinfection of disk filtered effluent obtained by selected AOP conditions.

Disinfection and membrane results with selected AOP conditions:

- The application of combination ozone + UV to disk filtered effluent showed to be efficient for a complete disinfection (Table 3).
- In terms of membrane performance of subsequent advanced WRP, long term tests showed that UF fouling rates could be reduced by 30 % in comparison to no AOP treatment.

Water quality in innovative PAC-MBR vs revamped basic WRP with ozone: basic water quality

Summary Results:

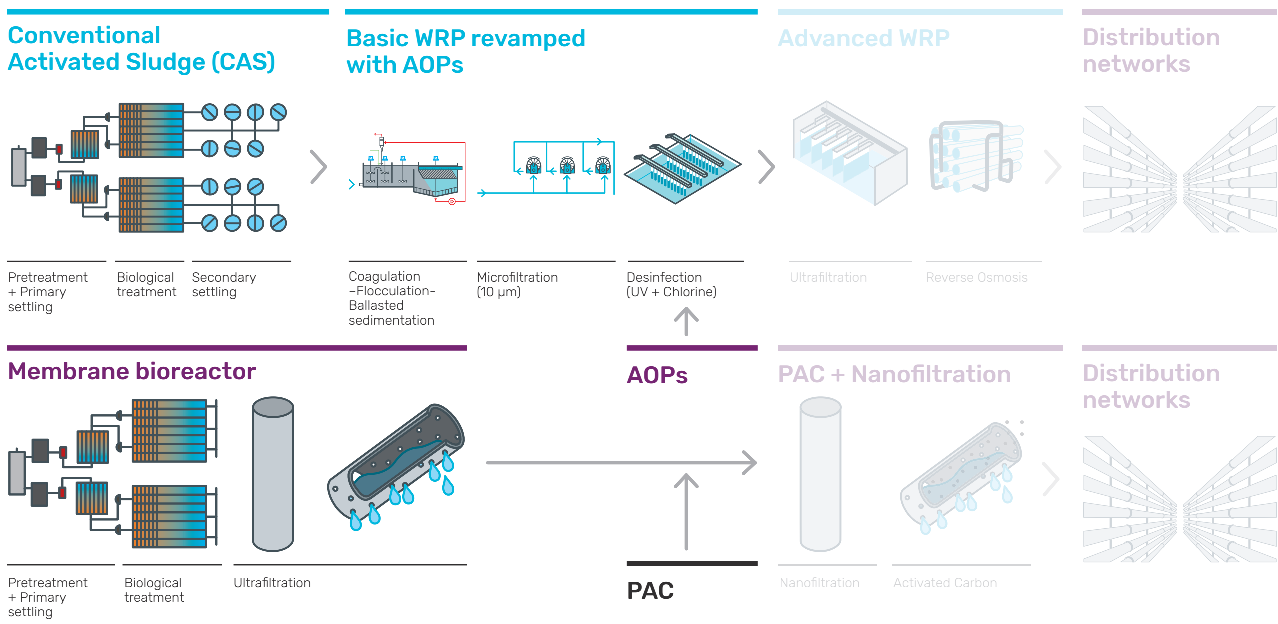
01 In comparison to the basic WRP, the MBR provided better quality in terms of SS and turbidity with absence of solids in the UF permeate and turbidities ranging between 0.5-0.7 NTU.

02 The addition of PAC to the MBR or ozone to the basic WRP provided only marginal improvements in terms of organic matter and no improvement for turbidity or suspended solids.

03 Both MBR (with and without PAC) as well as basic WRP (with and without ozone) showed complete removal of microbiological parameters, with over 90% of the samples analyzed below the detection limit for E.Coli and Legionella.

Table 4 Summary results of water quality for reuse obtained in the MBR, PAC-MBR and Basic WRP with and without ozonation.

Parameter (Unit)	Influent to MBR	MBR	PAC-MBR	Basic WRP	Revamped basic WRP O_3
COD (mg-O_2/L)	375-545	22 - 28	24- 28	27-32	22-39
BOD5 (mg-O_2/L)	187-369	< 1- 1.4	< 1- 2.4	2-3	-
TN (mg-N/L)	55-84	11-15	9- 12	7-9	5.1-8.3
TP (mg TP/L)	8-12	-	0.3-1.5	1-1.9	-
SS (mg/L)	107-216	<1	<1	1-4	1-2,5
Turbidity (NTU)	120-215	0.5-0.8	0.5 – 0.7	1-2	1.7-3
E.Coli (CFU/100 mL)	1-9.7 • 10^6	<1	<1	<1	<1
Legionella (CFU/L)	-	<100	<100	<100	-



Results obtained for reclamation schemes with removal of priority pollutants (PP) and emerging pollutants (EP)

Water quality in innovative PAC-MBR vs revamped basic WRP with ozone: Priority and emerging pollutants

MBR vs basic WRP

Basic WRP contributes marginally to removal of organic PP and EP with maximum enhancement for Diclofenac (+30%), Codeine (+20%) and Octylphenol (+14%).

Removal efficiencies in the MBR and CAS + basic WRP correlated well for most organic PP and EP. (Figure 13).

The MBR showed significantly higher removals for Eritromicine (+50%) and Diclofenac (+20%) in comparison to the basic WRP effluent.

Persistent organic PP and EP in both MBR and basic WRP:

- Low removal (< 50%): Carbide Epoxide , Carbamazepine and Diuron (Eritromicine in the basic WRP).
- Medium removal (50-60%): Diclofenac, Sulfametoxazol and Codeine.

MBR (PAC) vs basic WRP (ozone)

From the persistent organic PP and EP that presented low or medium removal in the MBR, PAC addition showed to increase their removal above 80% depending on the dose applied (Figure 12)

- With 25 mg/L Diuron increased from below 20% to 92% and Codeine from 74% to 95%.
- With 50 mg/L Sulfametoxazol and Carbamazepine removal increased to 76 and 81% respectively.
- The basic WRP with ozone appeared to be more effective than PAC for removal of persistent PP and EP:
- With 3 mg/L O_3 removals exceeding 80% for Codeine (90%), Carbamazepine (83%) and Diclofenac (96%).
- With doses of 6-9 mg/L O_3, atenolol , Diuron and Sulfametoxazol increased to 80-87%, 79-83% and 92-96% respectively.

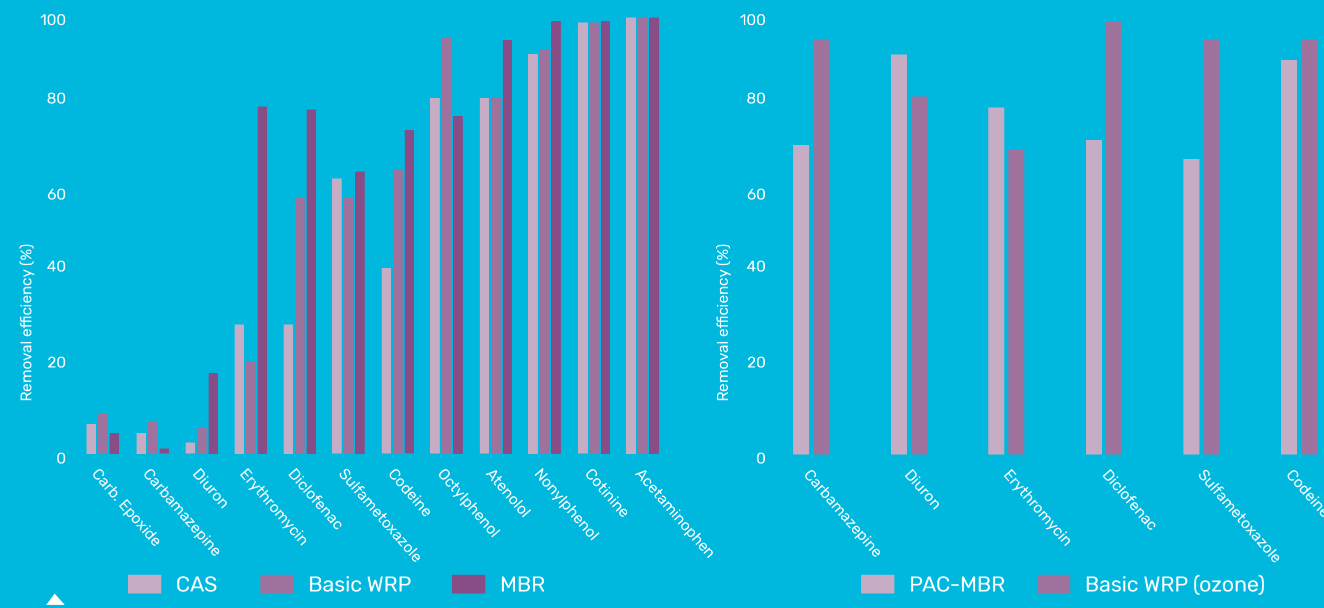


Figure 14 Removal efficiencies of the conventional activated sludge (CAS), basic WRP and MBR (left). Removal efficiencies of persistent PP and EP in the conventional treatment with PAC in the MBR and ozone in the basic WRP (right).

Water quality in innovative PAC-NF vs advanced WRP based on membrane treatment: basic water quality

Summary Results:

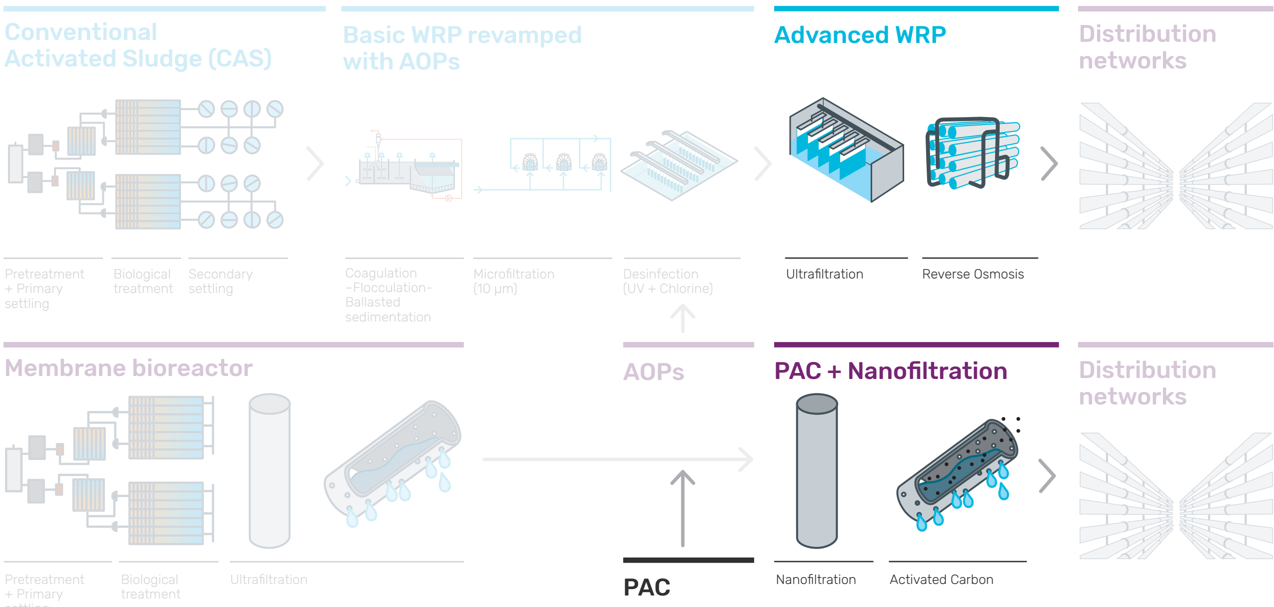
The capillary NF provides levels of organic matter and turbidity comparable to the advanced WRP (50% blend of UF-RO) with removal efficiencies reaching 50-60% from the MBR-UF effluent (Table 5).

The capillary NF showed no removal of salinity and nutrients (total nitrogen and total phosphorus), limiting its applicability as treatment for reuse in aquifer recharge according to existing legislation (RD1620/2007).

PAC addition showed only marginal improvements in terms of organic matter and turbidity in comparison to the NF treatment without PAC.

Table 5 Summary results of water quality for reuse obtained in the NF, PAC-NF and the Advanced WRP (50% blend UF-RO).

Parameter (Unit)	Influent to NF and PAC-NF	NF1	PAC-NF1	Influent to advanced WRP	Advanced WRP UF+RO
COD (mg-O_2/L)	22-28	15-20	14-19	27-32	11-18
BOD5 (mg-O_2/L)	< 1-1.4	<1-1.3	<1-1.1	2-3	<1-2
TOC (mg-C/L)	6.6-11.3	5.0-6.0	4.5-5.6	-	4.5-7.2
TN (mg-N/L)	11-15	10-14	9.9-13.5	7-9	4.4-6.6
NO_3- (mg-NO_3/L)	39-53	44-52	40-50	8.4-24.3	4.2-9.4
TP	0.3-1.5	0.3-1.5	0.3-1.5	1.2-2.5	0.3-1.1
SS (mg/L)	<1	<1	<1	<1	<1
Turbidity (NTU)	0.5-0.8	0.24-0.47	0.28-0.45	1-2	0.2-1
E.Coli (CFU/100 mL)	<1	<1	<1	<1	<1
Legionella (CFU/L)	<100	<100	<100	<100	<100



Water quality in innovative PAC-NF vs advanced WRP based on membrane treatment: Priority and emerging pollutants

Main conclusions drawn from the monitoring program of organic PP and EP can be summarized as (Figure 15):

01 Low contribution of NF and UF (< 20%) to removal of organic PP and EP due to their larger pore size in comparison to the size of these organics (200-300 Da).

02 In the RO effluent all the organic micropollutants were found below the limit of detection with removal efficiencies in most cases in the range of 81-98%.

03 PAC addition provided low-medium removal for the lowest dose of 10-25 mg/L (27-79%). Increasing PAC dose to 47-52 mg/L resulted in medium removal for most of organic PP and EP (53-86%) and a maximum increase of removal of 26% in comparison to lower doses.

RO
UF
Removal NF
PAC-NF (10-26 mg/L)
PAC-NF (47-52 mg/L)

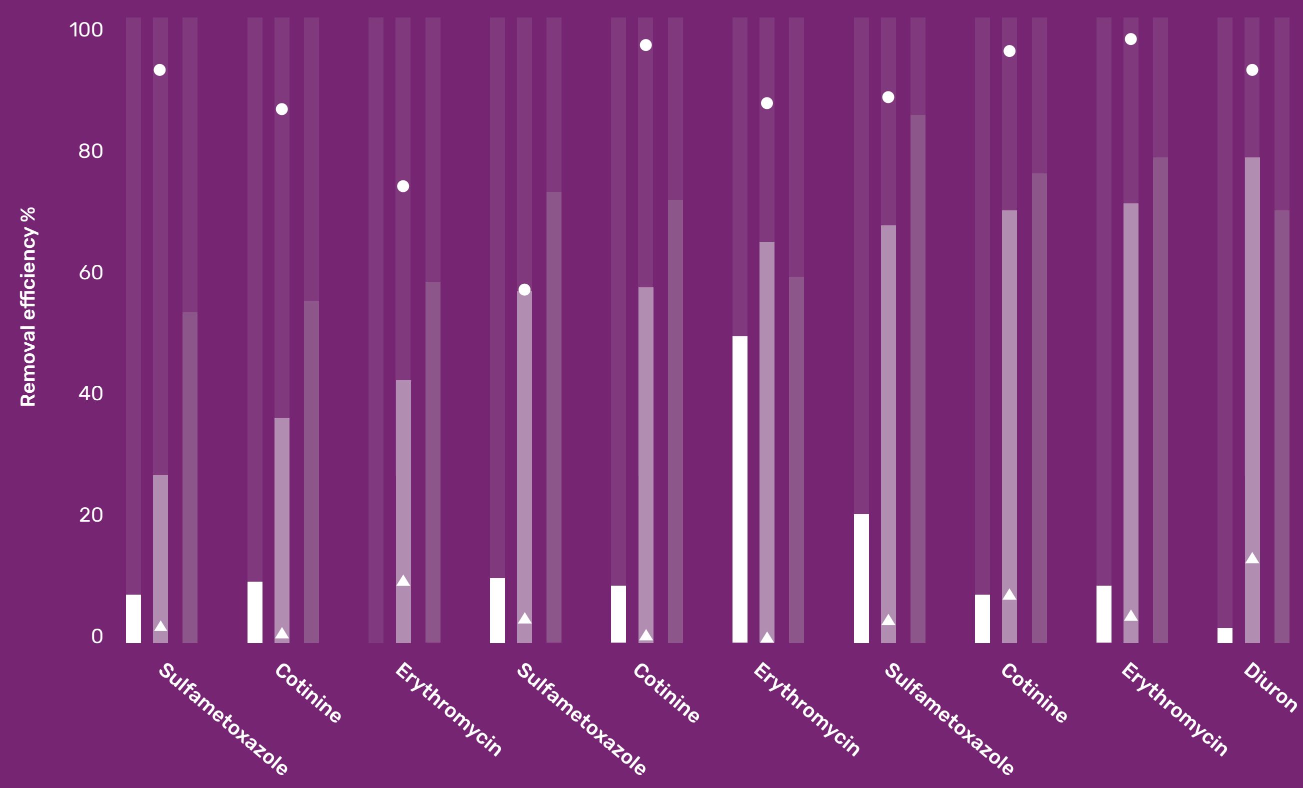
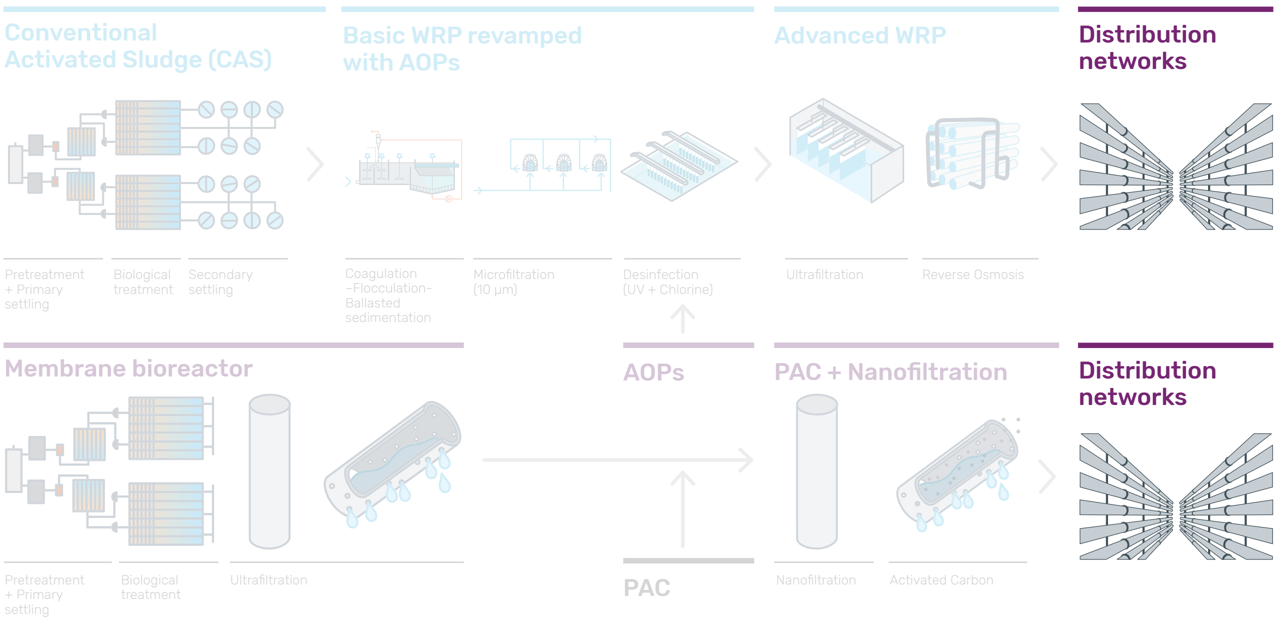


Figure 15 Comparison of removal of organic PP-EP with NF and PAC-NF (aWARE) with UF and RO (advanced WRP).

09 Factors affecting biofilm development in distribution networks of reclaimed water



Reclaimed water and distribution network operational parameters:

- For most parameters, no clear trends were found between chlorine doses (2-10 ppm) and biofilm characteristics.
- Between 1 and 3 log units higher bacterial counts found at the velocity of 0,8 m/s in comparison to lower (0,2 m/s) and higher velocities (1,5 m/s).
- Between 1 and 3 log units higher bacterial counts found with discontinuous operation in comparison to continuous.

Microbiology of biofilm:

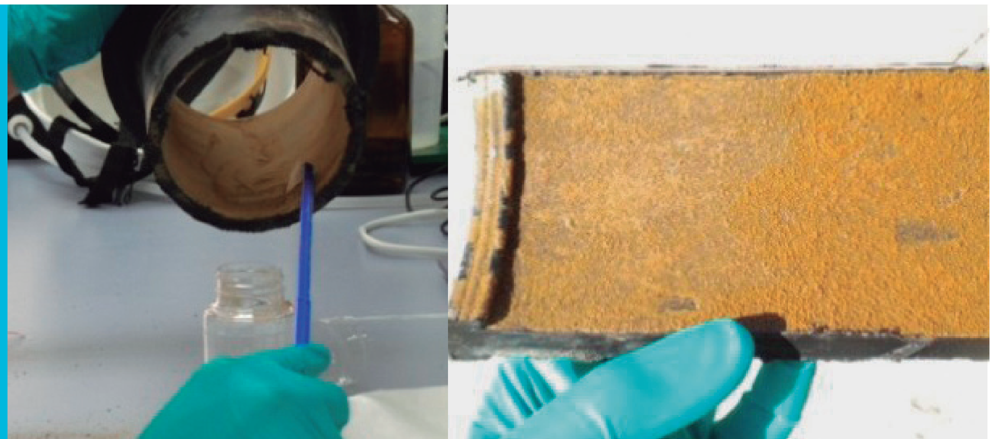
- Across the different conditions and elements tested (24 in total) Legionella pneumophila was not found colonizing biofilm.
- E.Coli was found in 20% of the samples and between one and two orders of magnitude lower abundance than total coliforms and P. Aerugionosa. At the highest chlorine doses applied no E.Coli quantified above detection limit (<0.1 CFU/cm^2) whilst for the lower doses average values of 15 CFU/cm^2 were found.

Distribution network pipe elements:

- No clear trends for aged pipes in comparison to new or antimicrobial pipes. Antimicrobial pipes generated thinner biofilms, with higher cell viability and lower EPS content.

Results suggest that factors related to demand (flow velocity and discontinuous operation) enhance more biofilm development in comparison to the factors related to the distribution system itself. Microbial parameters indicated in reuse Spanish legislation (RD 1620/2007), such as Legionella do not tend to develop in biofilms formed in distribution network pipes of reclaimed water whilst E.Coli could not be detected for the highest dose of chlorine of 10 ppm applied in the study.

Figure 16 Sampling from pipes of the distribution network prototype for microbiological analyses (left). Pipe with biofilm employed for confocal laser scanning microscopy analyses and result example (right).



10 Technical, economic and environmental comparison of reclamation systems

Technical comparison of innovative PAC-MBR vs revamped basic WRP with ozone

The data obtained during the two years of prototypes operation has enabled to obtain the design parameters in order to scale-up the MBR and a full scale ozonation plant to the case of basic WRP of Baix Llobregat with a total production of 3,8 m^3/s. The MBR and the WRP schemes with PAC and ozonation have been compared in terms of energy and reagents consumptions as well as water losses and sludge production taking into account both water and sludge treatment lines.

From the scale-up of the water reclamation schemes summarized in Table 6, it can be concluded that:

- The MBR presents 50% reduction in footprint in comparison to basic WRP.
- Both MBR and CAS + WRP present similar sludge production in solid basis, but a 50% reduction in volumen basis.
- 20% higher chemicals required in the MBR due to membrane cleaning. When removal of organic PP and EP is considered, the MBR with PAC (25 mg/L) employs 30% lower chemicals in comparison to the basic WRP with ozone 6 mg O_3/L).
- The MBR presents 40% increase in energy demands in comparison to basic WRP mainly due to membrane operation. The additional energy demands of ozonation reduces this difference to 24% when considering the flowseets for removal of PP and EP.

Table 6 Technical comparison of the MBR (with and without PAC) with the basic WRP (conventional and revamped with ozone).

PROJECTIONS	MBR	Conventional activated sludge + basic WRP
Produced Flow (m³/d)	330000	
Footprint (m²)	60500	113000
Sludge production	0,18	0,2
(g SS/ g COD removed)	(6,4)	(12,5)
[L WAS /g COD removed]		
Coagulant dosing- (ppm)	50-70	80
P-removal < 1-2 ppm-TP	($FeCl_3$)	(PAX)
Total reagents needed (Tn/year)	5400	4400
	8411 with PAC	12123 with ozone
Electricity consumption	0,68 water line	0,41 water line
(kWh/m³ treated eff.)	Similar with PAC	0,52 water line with ozone

Economic and environmental comparison of innovative PAC-MBR vs revamped basic WRP with ozone

An economic and environmental comparative assessment (based on Life Cycle Assessment) including operation and infrastructures for the state of the art reclamation technologies with those focused on removal of PP and EP and considered in the aWARE project was conducted taking into account the scale-up projections and the results obtained from the prototypes. The quantification of the environmental and economic impact of the wastewater and sludge treatment lines were included together with the MBR and the basic WRP.

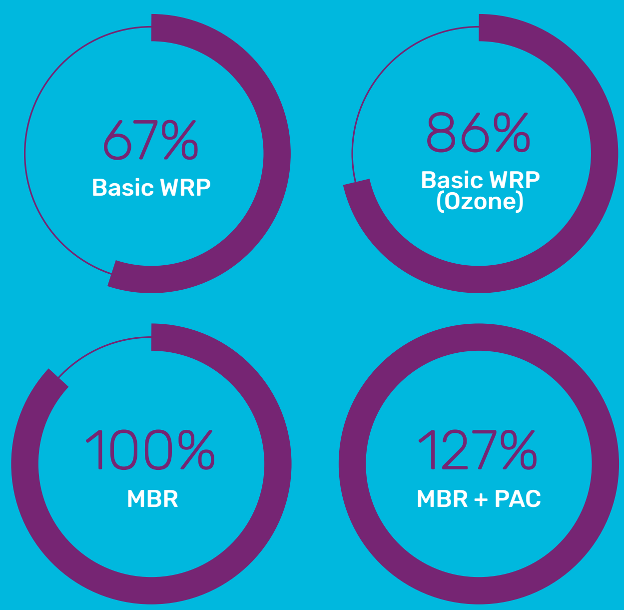
Summary results from the economic and environmental assessment (Figure 16 and Table 7) are:

- The MBR treatment represents 30% higher costs and environmental impact than the basic WRP. Costs increase in the MBR in comparison to the basic WRP are mainly related to energy and membrane replacement.
- Considering the application of ozonation, increases costs by less than 20% and the environmental impacts by 30% in comparison to the conventional basic WRP. Ozonation combined with the basic WRP present 14% lower costs than the MBR and comparable environmental impact.
- The combination of MBR and PAC represent a 27% increase in total costs and 75% in environmental impact in comparison to only MBR treatment.

Table 7 Comparison of environmental impact for the MBR, PAC-MBR and Basic WRP with and without ozonation.

Basic WRP 0.21 $KgCO_2/m^3$	**MBR** 0.28 $KgCO_2/m^3$
Basic WRP + ozone (6 mg/L) 0.28 $KgCO_2/m^3$	**MBR + PAC (25 mg/L)** 0.81 $KgCO_2/m^3$

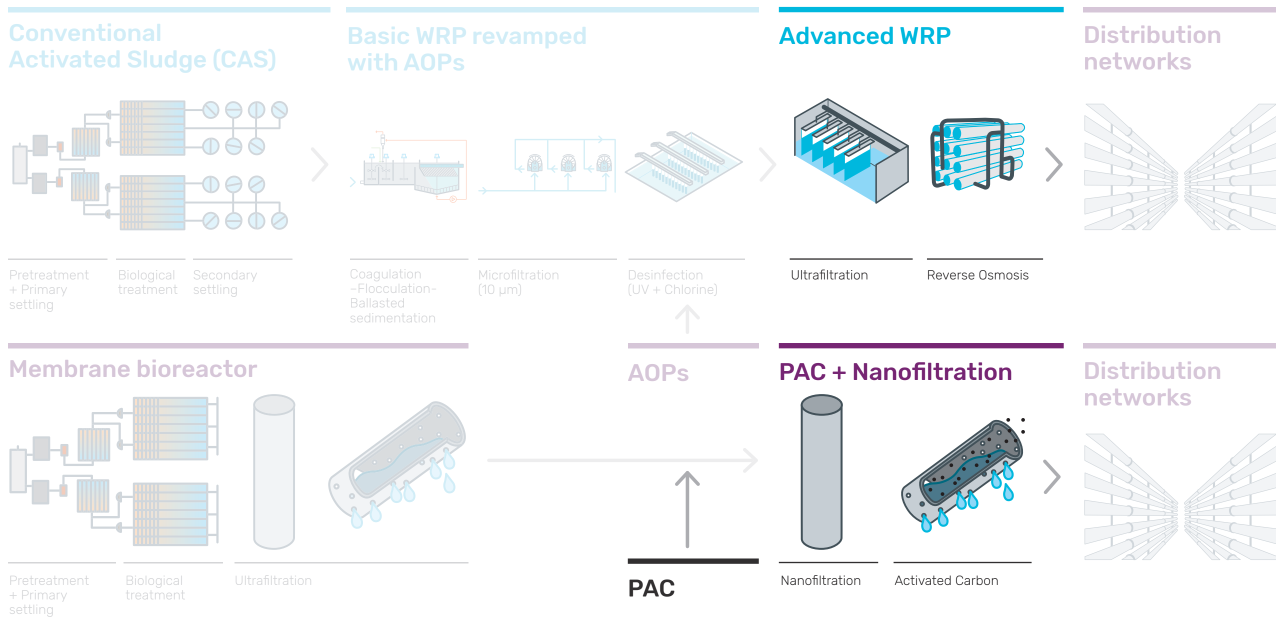
Figure 16 Cost difference relative to the MBR of the PAC-MBR, basic WRP and revamped basic WRP with ozone.



Technical comparison of innovative PAC-NF vs advanced WRP based on membrane treatment

From the scale-up of the PAC-NF, summarized in Table 08, it can be concluded that:

- The PAC-NF presents a reduction in energy demands of 50% in comparison to the advanced basic WRP (UF-RO).
- The PAC-NF (one stage) present a reduction of 30% in membrane area installed in comparison to the combination of UF-RO.
- Water yields in the PAC-NF are comparable to the ones shown by the UF-RO (5% lower).
- However the PAC-NF concentrate, can be recycled back to a biological stage without adverse effects on treatment performance.
- 85% increase in chemicals usage due to PAC dosing.



The optimization of the PAC-NF during the two years of prototypes operation have enabled to identify the optimal operational conditions. The full scale projection of the PAC-NF is based on the production capacity of the advanced WRP (50% blend of UF-RO) and PAC dosing of 25 mg/L (contact times of 30 min). These conditions enable the capillary NF to operate with a similar water yield of over 70% in comparison to the advanced UF-RO, but with a single stage configuration.

Main outcomes have shown that although no salinity reduction or removal of nutrients can be achieved in the capillary NF, similar level of effluent organic matter and removal of organic PP and EP is possible in comparison to the advanced UF-RO.

PROJECTIONS	PAC-NF	Advanced Reclamation
Produced Flow (m^3/d)	15000	
Footprint (m^2)	~2000	~2000
Overall Water Yield (%)	71,4	76,5
Brine Generation (m^3/d)	6000 (head works)	4471 (UF+ RO) (marine disposal)
Membrane area installed (m^2)	33 600 (1 stage NF)	48408 (UF+ RO)
Electricity consumption (kWh/m^3)	0.35	0,70
Total reagents needed (Tn/year)	191	103

▲ **Table 8** Technical comparison of the PAC-NF with the advanced WRP (50% blend UF-RO).

Economic and environmental comparison of innovative PAC-NF vs advanced WRP based on membrane treatment

A life cycle assessment (LCA) focused on global warming impact (Table 8) as well as the economic analysis (Figure 17) was performed using the data obtained from the operation and optimization of the PAC-NF plant and from the scale-up projection.

From the economic and environmental assessment (Figure 17 and Table 8 respectively) of the PAC-NF and the UF-RO it can be concluded that:

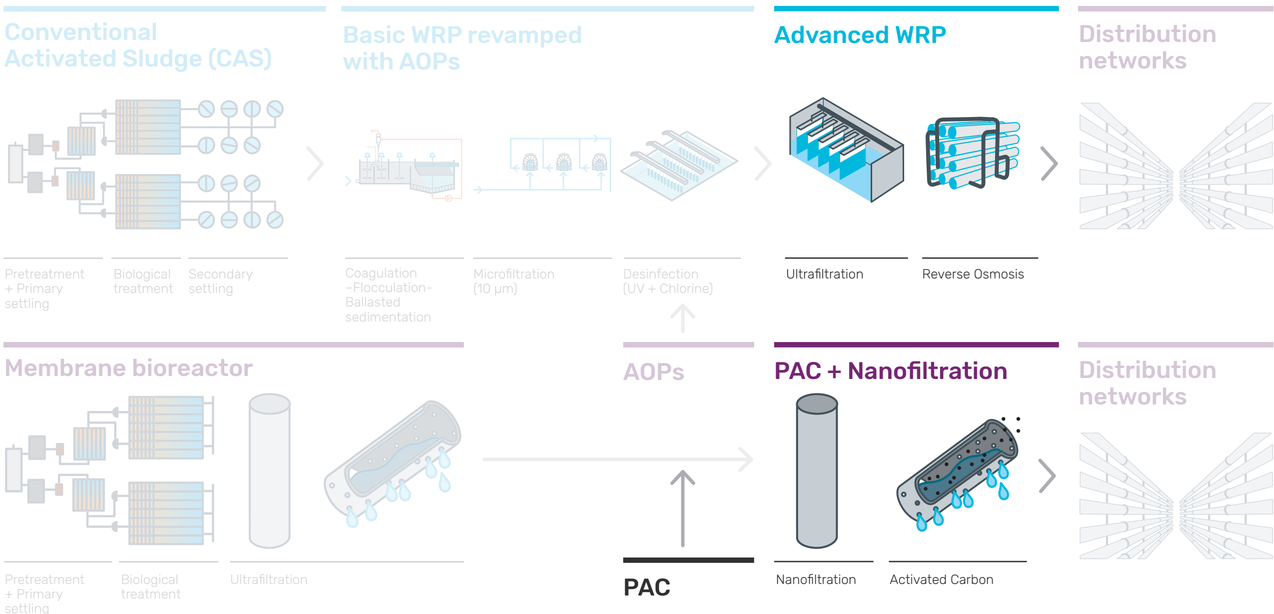
01 Despite the reduction in membrane area installed and energy demands of the PAC-NF in comparison to the UF-RO, the former presents 16% higher overall costs mainly due to the membrane replacements and activated carbon addition.

02 The PAC-NF also presents higher environmental impact than the advanced UF-RO mainly due to the chemical usage of PAC.

Table 9 Comparison of environmental impact between Advanced WRP (UF-RO 50% blend) and PAC-NF.

Advanced WRP (50 % UF-RO blend)	PAC-NF (25 mg/L)
0.24 $KgCO_2/m^3$	0.72 $KgCO_2/m^3$

Figure 17 Economic comparison of PAC-NF with the advanced WRP (50% blend UF- RO).



11 Conclusions

The aWARE project has evaluated innovative hybrid water reclamation technologies from a technical, economic and environmental perspective, in order to quantify the impact of implementing advanced water reclamation schemes as additional barrier for persistent priority and emerging pollutants within the water cycle. Furthermore, reclaimed water distribution networks behavior in terms of biofilm formation were also studied.

The aWARE project evaluated an **innovative MBR-PAC-NF hybrid water reclamation scheme for removal of PP and EP**, which was compared against state of the art systems. Main conclusions show that for the production of water quality for reuse, state of the art water reclamation schemes appear to deliver comparable water quality as the MBR and PAC-NF advanced treatments at a lower cost and environmental impact (Tables 7 and 9 and Figures 16 and 17). Conventional water reclamation without the use of adsorbents such as PAC or oxidation processes such as ozone, provide only marginal removal for priority and emerging pollutants that are persistent to the biological processes (from 12-60% removal for the compounds studied). In case additional removal of PP and EP is required two different scenarios have been identified:

01 For basic WRP (reuse without salinity reduction), the application of ozonation represents removal of 80-95% PP and PEP which are persistent to conventional treatment with less than 20% additional overall costs and approximately 30% in environmental impact in comparison with conventional treatments.

02 For advanced WRP (reuse with partial reduction in salinity) the PAC-MBR as pretreatment of RO , enables 90-95% removal of PP and PP which are persistent to conventional treatment with comparable overall cost and less than 20% of the environmental impact.

Basic water reclamation quality with removal of PP and EP

Scheme n°	% Removal (CAR, DIU)	% Removal (DIC, SMX, COD)	Cost difference with Basic WRP	Environmental Footprint (Kg CO_2/m^3 relcaimed WW)
Basic WRP	12	60	-	0.21
MBR	15	70	+30%	0.28
Basic WRP revamped with O_3	80	95	+19%	0.28
PAC-MBR (25 mg/L virgin PAC)	80	75	+60%	0.81

Advanced water Reclamation quality with removal of PP and CEC (50 % RO)

RO pretreatment	% Removal (CAR, DIU)	% Removal (DIC, SMX, COD)	Cost difference with Basic WRP+UF-RO	Environmental Footprint (Kg CO_2/m^3 relcaimed WW)
Basic WRP + UF	60	80	-	0.63
Basic WRP revamped with O_3 + UF	90	100	+7%	0.70
PAC-UF-RO (Based on PAC-NF)	80	90	+11%	1.23
PAC-MBR	90	95	0%	1.23

The feasibility of the use of PAC combined MBR and membrane processes (UF or loose NF) offers technical advantages also for applications in other sectors such as industries and hospitals where space limitation favors the use of compact technologies to control the emission of PP and EP.

Main conclusion from the work conducted in the **distribution network of reclaimed water** can be summarized as:

- Factors related to demand (flow velocity and discontinuous operation) are the ones that have largest impact on biofilm development in distribution networks of reclaimed water in comparison to the factors related to the distribution system itself.
- Microbiological parameters that are currently present in reuse legislation (RD1620/2007) such as Legionella do not tend to develop within distribution network of reclaimed water independently of operational conditions whilst E.Coli was controlled below detection limits with appropriate disinfection doses.

12 Communications activities

Numerous communication and networking activities were carried out during the entire project, aiming to disseminate the project's results and enhance the transferability of the knowledge stakeholders, other entities and interested groups.

Dissemination and publications

16 Oral and Poster presentations at conferences

04 Organized events

Networking and stakeholders

01 Notice Board located next to the pilot

02 Informative posters at the El Prat WWTP offices and conferences room

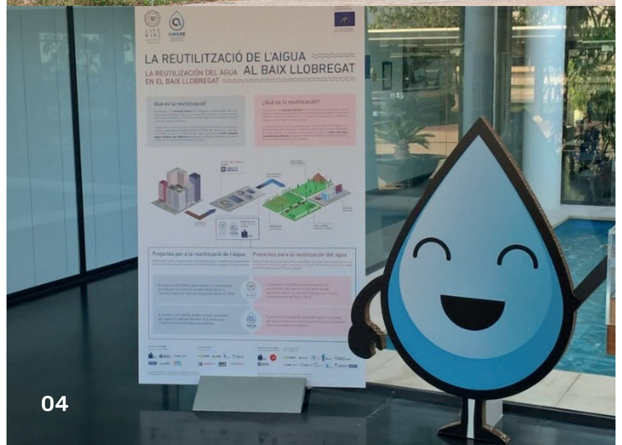
01 Website. Translated into Spanish, English and Portuguese **(www.life-aware.eu)**

+8500 Visits to the website


01


02


03



04

01 | aWARE Lisbon workshop. Organized by LNEC June 3rd, Lisbon.
02 | aWARE final workshop. Organized by Cetaqua and Aigües de Barcelona. November 9th and 10th, Barcelona.
03 | Technical Notice Board.
04 | Informative poster explaining the project and water reuse.

05

06.1

06.2

06.3

07

05 | Brochure with the project results.
06 | Cetaqua, LNEC and Aigües de Barcelona explaining their role in the project in the final video.
07 | La Vanguardia mentions the project on the World Environment Day.

Networking and stakeholders

02 Brochures (presentation and results)

09 Networking events

01 Newsletter

01 Video

In the video, the three partners of the project exposed their role in the aWARE.

+200 People visited the pilot

News & Press

01 Press Release

14 Articles in General and Local Media

Social networking

+75 Tweets and mentions about the project

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