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Graduated in Chemical Engineering

Integrated Wastewater Reuse System for Autonomy in Water Supply

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Abstract

Potable water is essential for all aspects of life and sustainable development. However, over 2 billion people live in countries experiencing high water stress. In addition, over 80% of the world's wastewater is released to the environment without treatment. To solve these problems Veolia proposes a Reuse pilot to transform wastewater into drinking water. The pilot is designed to be a closed loop that could provide complete water autonomy to any facility.

The main objectives of this project are to produce potable water from wastewater, to operate in a closed loop system, to ensure reliability and performance of the process and to demonstrate financial viability. The pilot consists of processes such as phytoremediation, micro-granular activated carbon adsorption assisted by ozonation, ultrafiltration and reverse osmosis.

We succeed in producing water with drinking quality according to french legislation. The system is not a closed loop yet but we achieved a reliable hydraulic balance control that allows us to close the system in the near future. The performance of the system is reliable, in one year and three months approximately 142,6 m³ of water have been treated and not even once the turbidity of UF permeate has reached 1NTU (legislation limit). The permeability of the membrane now is around 55 LMH/bar. In our best scenario the cost of treated water is 6,01 €/m³ while the average cost of water in france is 5 €/m³. We believe that a scale up of the system will decrease the cost per m³ of water produced. In addition, for places with water scarcity the autonomy of water supply is an important advantage.

Keywords: Direct Potable Reuse, Ultrafiltration, Phytoremediation, micro-granular activated carbon adsorption, reverse osmosis

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Abbreviations

AOPs	Advanced Oxygen Processes
AWT	Advanced Water Treatment
BAF	Biological Active Filtration
BAC	Biological Activated Carbon
CD	Chemical Dosing
COD	Chemical Oxygen Demand
CUR	Carbone Usage Rate
DAF	Dissolved Air Flotation
DPR	Direct Potable Reuse
EBCT	Empty Bed Contact Time
ECs	Emerging Contaminants
EU	European Union
GAC	Granular Activated Carbon
HRT	Hydraulic Retention Time
IPR	Indirect Potable Reuse
MF	Microfiltration
µGAC	Micro-granular Activated Carbon
NF	Nanofiltration
NGWRP	New Goreangab Water Reclamation Plant
OZ	Ozonation
PAC	Powdered Activated Carbon
POZ	Pre-ozonation
RO	Reverse Osmosis
RSF	Rapid Sand Filtration
TMP	Transmembrane Pressure
UN	United Nations
UF	Ultrafiltration
USEPA	United States Environmental Protection Agency
WHO	World Health Organization
WRP	Water Reclamation Plant
WTP	Water Treatment Plant
WWTP	Wastewater Treatment Plant

1 Introduction

1.2 Background and motivations

Potable water is essential for all aspects of life and sustainable development [1]. Currently over 2 billion people live in countries experiencing high water stress, and about 4 billion people experience severe water scarcity during at least one month of the year [2]. Considering the exponential growth of the world's population and the effects of climate change, it's expected that the water scarcity will increase in the following years. The World Water Development Report released by the United Nations (UN) in 2018 predicted that, by 2050, between 4.8 billion and 5.7 billion people will live in areas that are water-scarce for at least one month of the year [3].

Another consequence from the world's population growth is the increase in wastewater production. Over 80% of the world's wastewater is released to the environment without treatment. In some less developed countries this value can reach 95% [4]. Inadequate discharge of wastewater can cause damage to human health and to the environment, and can pollute freshwater supplies increasing the problem of water scarcity.

These problems were addressed in the 2030 Agenda for Sustainable Development, adopted by all UN member states in 2015. The agenda defines 17 sustainable development goals. Goal number 6 is to “ensure availability and sustainable management of water and sanitation for all” [5]. The Agenda also defines 8 targets to help achieving goal 6, of which 2 mention water reuse.

Target 6.3 is defined as “by 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally”. In addition, target 6.a is defined as “by 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programs, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies”[5].

Water reuse is a sustainable solution to reduce the gap between freshwater demand and availability. It not only treats wastewater protecting the environment and human health, but also increases the availability of water resources. Instead of a problem, wastewater can be a sustainable source of water, energy, nutrients and other recoverable by-products. Recovering, recycling, and reusing what is normally seen as waste can provide social, economic and environmental benefits [1].

In accordance with the 2030 Agenda for Sustainable Development, Veolia proposes a Reuse pilot to transform wastewater into drinking water. With an eco-design approach, the pilot applies technologies such as ultrafiltration and reverse osmosis to avoid the use of chemicals. Following the principles of circular economy, the pilot is designed to be a closed loop that could provide complete water autonomy to any facility. Potable reuse is the future of drinking water production and we are ready to take the next step.

1.2 Objectives

1.2.1 To produce water with drinking quality in accordance with French legislation

Water designated for human consumption must be free of microbial and chemical hazards otherwise it will cause damage to human health in a short or long term. In wastewater reuse the feed of the system is more contaminated with chemicals and microorganisms than the feed in conventional water treatment. Therefore, it's harder to obtain potable water quality and advanced water treatment is necessary.

One of the biggest challenges for potable reuse is the public opinion. Many people are not willing to drink water produced from wastewater and this stance is based on a lack of confidence in the quality of the water produced [6]. Ensuring the quality of drinking water according to the legislation is essential for the success of the project, not only to protect human health, but also to convince public opinion that reuse is a safe option.

1.2.2 To design and operate a closed loop system

The traditional linear economic model, which is based on a take-make-consume-throw away pattern, relies on large quantities of cheap, easily accessible materials and energy [7]. As explained in the background section, this is not the case of potable water for billions of people. It's necessary to change and adopt a circular economy model based on reducing waste, recycling and reuse.

With the closed loop the water treated in the reuse pilot will be sent back to the facility where the water will be consumed and the wastewater created will feed the reuse pilot again. This will provide complete water autonomy to the facility. However, to achieve this goal it's necessary to have a precise control of the hydraulic balance in the system.

1.2.3 To ensure reliability and performance of the process

When dealing with drinking water it's necessary to ensure the quality of water all the time. One incident can result in damage to human health or to the environment and turn public opinion against the project. To ensure this, the process must be reliable and have a stable performance.

For the purpose of this thesis I will focus on the performance of the membranes where the biggest challenge is dealing with fouling. To overcome this challenge we focus on the membrane permeability and the frequency of cleaning. As we have a multi barrier approach, if we ensure the membrane performance, we guarantee the water quality.

1.2.4 To demonstrate financial viability of the project

Wastewater reuse is not the only option to produce potable water. For investors to choose this project instead of traditional water treatment or even seawater desalination, it must be financially attractive. It's a challenge demonstrating financial viability in small scale in a complex pilot with many process units such as this one.

2 Literature Review

2.1 Potable Reuse

The reuse of water, both intentional and unintentional, has grown in recent decades. When a wastewater treatment plant (WWTP) discharges effluent into a river or reservoir that supplies a drinking water treatment plant (WTP) unintentionally, we have *de facto* reuse [8]. In this dissertation we are interested in planned potable reuse, a more controlled and safer process that can produce better quality drinking water.

Potable reuse can be classified as direct or indirect. In Indirect Potable Reuse (IPR), reclaimed water is discharged into an environmental buffer (such as a river, lake, aquifer or reservoir) before arriving at the intake of a water treatment plant. In Direct Potable Reuse (DPR) the environmental buffer is not necessary. Although IPR is more commonly applied, the potential advantages of DPR over IPR include reduced energy requirements, reduced construction and operational costs, higher control of the water and the possibility to reuse water even if a suitable environmental buffer is not available [9]. However, without the environmental buffer DPR has a decrease in response time to incidents when compared to IPR. Therefore, the level of monitoring must be higher and the multi-barrier approach is essential. The pilot studied in this dissertation is a DPR.

2.2 Hazards in reuse water source

Even after conventional wastewater treatment, wastewater can contain microbial pathogens and a wide range of industrial, commercial and domestic chemicals. These are hazards to human health. To achieve a successful DPR system it is necessary to identify the risks associated with the water source and build a multi-barrier process to eliminate them.

2.2.1 Microbial Hazards

The first type of hazard that can be found in wastewater is pathogenic microorganisms. These microorganisms include bacteria, viruses, protozoa and helminths that can cause diseases. Any negative effect on human health caused directly or indirectly by the condition, or changes in the quantity or quality of water can be considered a water-related disease [10].

Figure 1 presents the number of outbreaks of water-related diseases in pan-European region from 2000 to 2013. Pan-European region refers to the Member States in the World Health Organization European Region and Liechtenstein [10]. France is included in Western Europe.

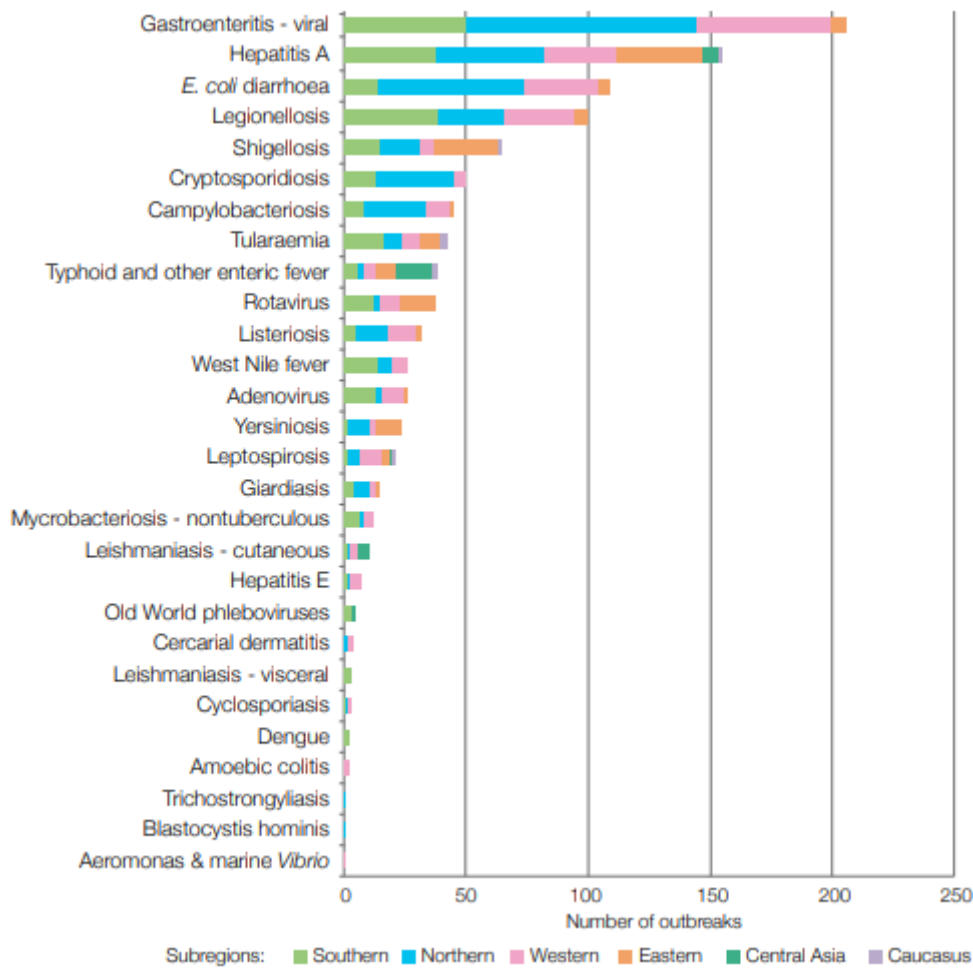


Figure 1: number of outbreaks of water-related diseases in pan-European region. Source [10]

The greatest risk from exposure to wastewater is gastrointestinal disease following ingestion of enteric pathogens [11]. Among the most common outbreaks we have 2 viral and 2 bacterial diseases. Viral gastroenteritis can be caused by a variety of viruses such as Adenoviruses, Astroviruses, Noroviruses, etc. Hepatitis A is a liver disease caused by the hepatitis A virus (HAV). The virus is spread when a person ingests food or water that is contaminated with the feces of an infected person [12]. The bacteria *Escherichia Coli* can also cause gastroenteritis while the bacteria *Legionella* can cause a serious respiratory disease.

2.2.2 Chemical Hazards

Chemicals can be harmful to human health and to the environment. The chemical hazards in wastewater include chemicals used in households, industrial chemicals, chemicals excreted by people, and chemicals used or formed during wastewater treatment processes [11]. The composition of chemicals in wastewater can vary depending on location, industrial activity, seasonality, etc. Table 1 shows the chemicals more likely to be present in wastewater or produced during treatment.

Table 1: Chemicals possibly present in wastewater or produced during treatment. Source [11]

Type of chemical	Examples	Potential sources
Heavy metals	Cadmium, copper, chromium, lead, mercury, nickel, silver, arsenic (metalloid)	Industrial discharges, natural sources, water/wastewater, pipes and fittings
Inorganic chemicals	Fluoride, nitrate, nitrite, ammonia	Mains water, natural sources, human waste
Synthetic industrial chemicals	Plasticizers, biocides, epoxy resins, degreasers, dyes, chelating agents, polymers, polyaromatic hydrocarbons, polychlorinated biphenyls, phthalates	Widespread commercial use, industrial discharges
Volatile organic compounds	Petrochemical products, industrial solvents, halogenated DBPs	Industrial discharges, mains water (e.g. trihalomethanes)
Pesticides	Household, garden and agricultural pesticides	Domestic, agricultural and industrial discharges
Pharmaceuticals	Non-steroidal anti-inflammatories, antibiotics, anti-hypertensives, statins, veterinary pharmaceuticals	Pharmaceuticals and metabolites excreted by people and animals, domestic disposal of unused pharmaceuticals, discharges from manufacturing sites
Steroidal hormones (estrogenic and androgenic)	Estradiol, estrone, estradiols, testosterone	Human and animal waste (particularly from feedlots); can include excretion of natural hormones and contraceptive medication
Personal care products	Fragrances, cosmetics, antiperspirants, moisturizers, soaps, creams, whitening agents, dyes and shampoos	Human waste
Antiseptics	Triclosan, triclocarban	Household use and commercial use
Per- and polyfluoroalkyl substances	Perfluorooctanoic acid, perfluorooctane sulfonate	Household products (e.g. water and stain resistant compounds including furnishings and non-stick coatings for cookware), firefighting foams
Flame retardants	Brominated flame retardants, ftyrol FR 2 (tri(dichloroisopropyl) phosphate), tris(2-chloroethyl) phosphate	Household products, e.g. furnishings, clothing, electrical devices
Dioxins and polychlorinated biphenyls	Octachlorodibenzo-p-dioxin, 2,3',4,4',5-pentachlorobiphenyl	Industrial discharges
Nanomaterials	Silver, titanium oxide, zinc oxides	Used in consumer products, e.g. personal care products, food storage containers, cleaning supplies, bandages, clothing and detergents
Cyanobacterial toxins	Microcystin, cylindrospermopsin, anatoxins, saxitoxins	Growth of cyanobacteria in wastewater treatment plants, wastewater lagoons and surface waters used as environmental buffers
Disinfection by-products	Trihalomethanes, haloacetic acids, bromate, chlorate, chlorite, N-nitrosodimethylamine	Reaction between disinfectants and organic material in wastewater and drinking-water; types produced dependant on source water and nature of disinfectant

It is estimated that around 30000 different chemicals can be found in products intended for households [13]. Chemicals excreted by people can include pharmaceuticals and their metabolites and natural steroidal hormones. Usually the concentration of pharmaceuticals is some orders of magnitude below the acceptable daily intake [14].

Industrial discharges can be a source of heavy metals, synthetic industrial chemicals, manufactured pesticides and pharmaceuticals, volatile organic carbons, dioxins and polychlorinated biphenyls [11]. Particularly, the heavy metals such as chromium, nickel and copper are potential causes of hazardous impact on human health and adverse effect on aquatic biota [15]. Chemicals used or formed during wastewater treatment may include toxins produced by the microorganisms responsible for biodegradation, disinfectants, products of chemicals degradation, etc.

2.2.3 Micropollutants

Although they are also a type of chemical hazard, we decided to focus on micropollutants on this topic. Also called Emerging Contaminants (ECs), they can be natural or anthropogenic substances,

such as pesticides, industrial compounds, pharmaceuticals, personal care products, steroid hormones, drugs of abuse, endocrine disruptors and others. They are called micropollutants because of their low concentration in water (usually from 0.001 to 1 µg/L in treated wastewater). Sources of ECs include: industrial wastewater; runoff from agriculture, livestock and aquaculture, landfill leachates and domestic and hospital effluents [16].

Because of their low concentration we currently don't have a limit established in french legislation for the concentration of most of the micropollutants in treated wastewater. In fact, the effectiveness of removal of ECs by traditional wastewater treatment techniques such as sedimentation, flocculation, and active sludge treatment is low [17]. Common activated sludge technique cannot remove all micropollutants efficiently and entirely, e.g. diclofenac and carbamazepine that are resistant to biodegradation. Moreover, various processes like biological and chemical degradation and photolysis may transform ECs into forms that can be more toxic than their parent compound [18].

However, the continued release of micropollutants with wastewater effluent is believed to cause long-term hazards, as the contaminants are bioaccumulating and even forming new mixtures in an aquatic environment ("Cocktail effect"). The exact effects are not fully known, but the presence of micropollutants in the environment also has been linked to toxic biological effects, including estrogenicity, mutagenicity and genotoxicity [18].

The processes effective for ECs removal are : Chemical oxidation processes (such as ozonation, with or without the addition of hydrogen peroxide, and UV radiation combined with ozone, H₂O₂ or titanium oxide), activated carbon adsorption and membrane processes (such as nanofiltration and reverse osmosis) [19].

2.3 Treatment Process

For direct potable reuse the conventional wastewater treatment is not enough. In order to improve the quality of water an advanced water treatment (AWT) is necessary. Advanced water treatment processes have four main objectives. The first is the removal of suspended solids that carry over from conventional wastewater treatment such as fine particles, colloidal material and microorganisms. This step increases the performance of next steps in AWT. The second objective is the reduction of concentration of dissolved substances, such as salts, organic molecules and residual nutrients [20].

The third objective is disinfection. This may include not only elimination of pathogenic microorganisms but also generation of a residual disinfectant to maintain water quality in the final water delivery pipeline. Some disinfection processes can also degrade chemical contaminants through oxidation. The final objective is the stabilization of water by restoring alkalinity, hardness and pH. Reverse Osmosis (RO), and to a lesser degree also Nanofiltration (NF), remove minerals such as calcium and magnesium from water. This may result in an extremely corrosive permeate water that can cause damage to metal piping or concrete tanks. In these cases, it is typically necessary to stabilize

the water by remineralization techniques [21]. Table 2 presents the technologies most commonly used in AWT for each objective.

Table 2: Unit processes used in potable reuse for each objective. Modified from [21]

Treatment Objective	Process
Suspended solids removal	Coagulation Flocculation Sedimentation Media filtration Microfiltration (MF) Ultrafiltration (UF)
Reduction of dissolved chemicals concentration	Reverse Osmosis (RO) Nano Filtration (NF) Electrodialysis Activated Carbon Adsorption Ion exchange Biological Active Filtration (BAF) Advanced Oxygen Processes (AOPs)
Disinfection and removal of trace organic compounds	Ultraviolet (UV) Chlorine Peracetic acid Pasteurization Ozone Advanced Oxygen Processes (AOPs) MF/UF/NF/RO
Stabilization	Sodium hydroxide Lime stabilization Calcium chloride Blending

2.4 Examples of planned potable reuse plants and the multi-barrier approach

Many examples of planned potable reuse projects in operation, such as Toreele Reuse Plant (Belgium, 2002), NEWater (Singapore, 2003), Orange County GWRS (USA, 2014) and Beenyup AWRP (Australia, 2016), use Ultrafiltration (UF) followed by Reverse Osmosis (RO) and the final disinfection is done by Ultraviolet (UV) or Advanced Oxygen Processes (AOPs) [21]. However, these are examples of IPR plants.

Since 1968, DPR has been a reality in Windhoek (Namibia). In 2002 the New Goreangab Water Reclamation Plant (NGWRP) replaced the old plant and until today potable reclamation is a fixed part of the water supply in Windhoek. Considering that Namibia is one of the most arid countries in Sub-Saharan Africa, wastewater has become an indispensable resource for the survival and continued growth of the city [22].

At NGWRP, reclaimed water is blended with other potable sources (treated Von Bach Dam water and borehole water, maximum 35% reclaimed water) before the AWT. Then, the following unit

process are responsible for producing a high quality drinking water: powdered activated carbon dosing (PAC), pre-ozonation (POZ), enhanced coagulation and flocculation obtained by chemical dosing (CD), dissolved air flotation (DAF), dual media rapid sand filtration (RSF), main ozonation (OZ), biological activated carbon (BAC) filtration, granular activated carbon (GAC) adsorption, ultrafiltration (UF), disinfection with chlorine and stabilization with caustic soda (NaOH) [23]. Figure 2 shows a diagram of NGWRP with the operational units where Mix is mixture, Poly is polymer, BPCL2 is break point chlorination, CT is contact chamber and PS is high lift pumps.

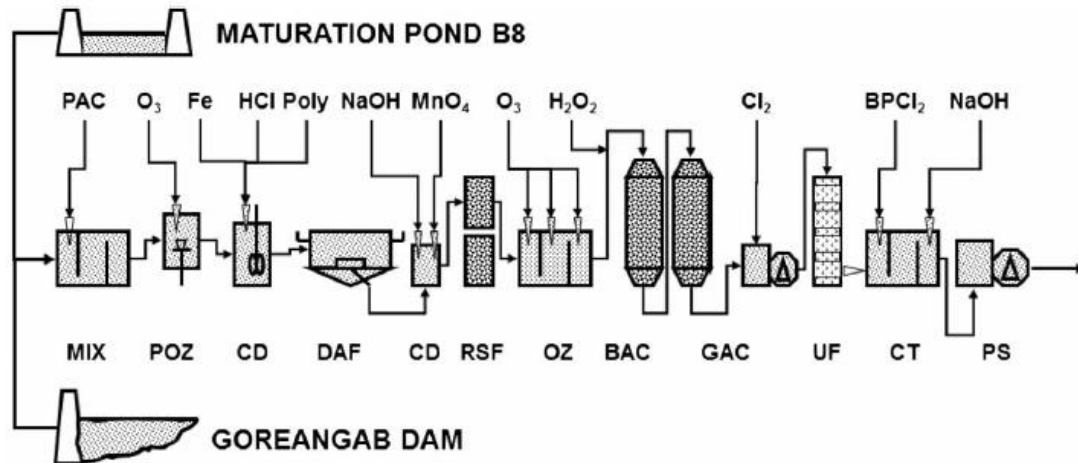


Figure 2: Diagram of NGWRP with the operational units. Source [22]

NGWRP is an example of a multi-barrier approach. The multi-barrier approach is an integrated system of procedures, processes and tools that collectively prevent the contamination of drinking water to reduce risks to public health [24]. In this approach the system must be redundant (multiple processes can eliminate the same contaminant, so if a unit process fails, there will be no risk to water quality), robust (covers a broad range of contaminants) and resilient (monitoring, protocols and strategies are in place to identify and fix failures). Table 3 shows the redundancy in the NGWRP system.

Table 3: Multi-barrier approach at NGWRP. C: complete barrier; P: partial barrier. Source [12]

	Barrier 1	Barrier 2	Barrier 3	Barrier 4
New Plant				
Physical and organoleptic	CD/DAF/RSF: C	UF: C	GAC: P	
Microbiological: bacteria and viruses	POZ: P	OZ: C	UF: C	BPCl ₂ : C
Biological: <i>Giardia</i> , <i>Cryptosporidium</i>	CD/DAF/RSF: C	OZ: P	UF: C	BPCl ₂ : P
Organics and DBPs	POZ: P	CD/DAF/RSF: P	OZ: P	BAC-GAC: P
Macro elements: Fe, Mn	POZ: P	CD/DAF/RSF: P	OZ: P	BAC-GAC: P
Stability	CD (NaOH): C			

The successful case of DPR in Windhoek inspired other projects around the globe. Table 4 provides an overview of the major DPR projects and includes information about the type of water reclamation plant (WRP) inlet (source water), reclamation plant capacity, reclamation unit processes, blending with other water sources and the additional treatment of the blended water [23]. Considering the

number of significant projects currently operational it is clear that DPR's potential has not yet been explored. This shows the importance of research projects in this topic.

Table 4: Overview of the major DPR projects. Source [23].

DPR project	WRP inlet	WRP Q (m ³ /d)	Water reclamation process	Blending – reclaimed water/ 'natural water' (%)	Additional treatment
Windhoek, Namibia, NGWRP (2002)	Secondary domestic effluent ^a	21,000	Pre-O ₃ , coagulation, DAF, DMF, main-O ₃ , BAC, GAC, UF, Cl ₂ , NaOH	25/75 ^b (treated dam water [70] + groundwater [5]); Pipe-to-pipe blending in the distribution network	None
Beaufort West, South Africa (2011)	Secondary municipal effluent	2,000	Cl ₂ , sedimentation, Cl ₂ , SF, UF, RO, AOP (H ₂ O ₂ + UV), Cl ₂	20/80 (treated dam water + ground water); max. 30% of reclaimed water; blending in a storage tank	None
Big Spring, TX, USA (2013)	Disinfected tertiary municipal effluent	7,600	De-chlorination, MF, RO, AOP (H ₂ O ₂ + UV)	15/85 (untreated lake and dam water); blending in raw water pipeline	Conventional WTP
Wichita Falls ^c , TX, USA (2014–2015)	Secondary municipal effluent	19,000	Cl ₂ , NH ₃ , coagulation, sedimentation, MF, RO, UV; lagoon	50/50 (untreated lake water); blending in a splitter box	Conventional WTP
Cloudcroft, NM, USA	Secondary effluent from MBR	379	RO, AOP (H ₂ O ₂ + UV), Cl ₂	49/51 (spring/well water); blending in an engineered storage buffer	Advanced WTP (UF, UV, GAC, NaOCl)
Brownwood ^d TX, USA	Tertiary municipal effluent	5,700	Cl ₂ , UF, UV, NH ₃ , de-chlorination, RO, GAC, UV, NH ₃ , Cl ₂	Blending in the distribution system with treated lake water	None
El Paso ^e , TX, USA	Tertiary municipal effluent	27,300	MF, NF or RO, AOP	Primary goal: blending in the distribution system	None

AOP, advanced oxidation process; BAC, biological activated carbon filter; DAF, dissolved air flotation; DMF, dual media filtration; DPR, direct potable reuse; GAC, granular activated carbon filter; IPR, indirect potable reuse; MF, micro-filtration; NF, nano-filtration; RO, reverse osmosis; SF, sand filtration; UF, ultra-filtration; WRP, water reclamation plant; WTP, water treatment plant.

^aPolished in maturation ponds.

^bAverage ratio, maximum permitted portion of reclaimed water is 35%; however, in the current emergency situation the reclaimed water portion could rise to 40%.

^cDPR decommissioned in July 2015, conversion to IPR.

^dProject put on indefinite hold.

^ePilot testing.

2.5 Potable Reuse Regulation

Potable reuse regulation is important to ensure production and delivery of safe drinking-water to consumers. This type of regulation should include [15]:

- Responsibilities of drinking-water providers, wastewater management entities, regulatory agencies and other stakeholders;
- Requirements for water safety plans and sanitation safety plans;
- Water quality standards;
- Monitoring and testing requirements;
- Reporting requirements during normal operation and in response to incidents and emergencies; and
- Surveillance.

According to the potable reuse guide for producing safe water from the World Health Organization (WHO) [15], the water quality standards can be listed in regulations or incorporated by reference to a separate document, such as a set of national drinking-water guidelines or standards based on the “Guidelines for Drinking-water Quality” from WHO [25].

As France does not have specific regulation for potable reuse water, we follow the Decree of January 11, 2007 relating to the limits and quality references of raw water and water intended for human

consumption mentioned in articles R. 1321-2, R. 1321-3, R. 1321-7 and R. 1321-38 of the public health code (code de la santé publique) [26]. Annex 1 presents the limits and references of water quality intended for human consumption, excluding conditioned water, extracted from this Decree (and amended by Decree of August 4, 2017 - art. 3 [27]).

The Decree of August 2, 2010 of the French public health code talks about reusing water coming from public wastewater treatment plants in the irrigation of crops or green spaces. However, there are no specifications or technical requirements regarding human consumption [28].

Besides the guide from WHO, the United States Environmental Protection Agency (USEPA) also publishes guidelines for water reuse. The guidelines were published in 1980, 1992, 2004 and 2012.

European Union (EU) legislation has two directives that allow and encourage water reuse. The Urban Wastewater Treatment Directive states that 'treated wastewater shall be reused whenever appropriate'. The Water Framework Directive includes water reuse in the programs of measures for each river basin. In May 2018, the European Commission put forward a proposal for a regulation setting EU-wide standards that reclaimed water would need to meet in order to be used for agricultural irrigation. Currently *it returned to the Parliament for final adoption at second reading [29]. However, EU legislation does not specify conditions for potable water reuse.

Currently the RO permeate is drained from the system. However, the next step is to remineralise the permeate and send it back to be used in the toilets on site.

3.1.1 Phytoremediation

The constructed wetlands represent the first water treatment step in the ReUse pilot. It is a natural wastewater treatment system that reproduces the self-purification processes typical of aquatic environments. The aquatic plants metabolize some pollutants, filter the water and provide a suitable environment for the proliferation of microorganisms that digest pollutants present in wastewater [30]. Phytoremediation is considered a green technology due to the low energy consumption and low use of chemicals. It is an efficient process to treat nitrogen pollution (mainly ammonium, nitrites, nitrates and ureia) [31].

The water contained in the underground dilution tank is sent through a pump to two phytoremediation PVC basins that work in parallel, one of 8,6 m² and the other of 9 m². The roots of emerging macrophytes are supported by an inert permeable substrate (media). In the same substrate, we have the proliferation of the bacterial film (biofilm). The dimensions of the two basins are shown in Figure 5 (the measures are expressed in mm).

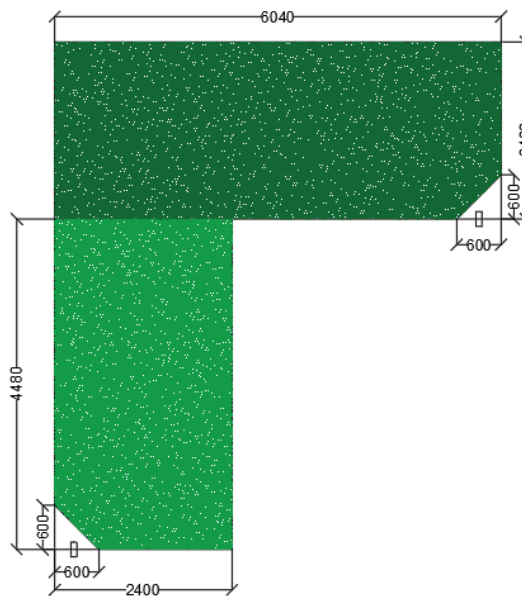


Figure 5: Phytoremediation basins dimensions. Source: Veolia

The basins are located on offices and laboratory roofs, 4 meters above the ground, as shown in Figure 6. The inert filling material consists of expanded clay balls having a diameter between 0,5 and 1 cm. Expanded clay balls also help filter and drain feed water. The height of the two tanks is 50 cm while that of the clay balls is 35 cm.



Figure 6: Phytoremediation basins view

The wastewater is fed to the smaller phytoremediation basin with a flow rate of $1,3 \text{ m}^3/\text{h}$, while the bigger phytoremediation basin is fed with a flow rate of $1,5 \text{ m}^3/\text{h}$; the feeding of the two basins is discontinuous. Stopping the feeding of the tanks allows the water level in the basins not to exceed that of the balls layer. The cycles of high and low water level in the basins are essential to bacteria oxygenation avoiding anoxic areas and the proliferation of insects. Figure 7 presents a schematic of filling and emptying the phytoremediation basins.

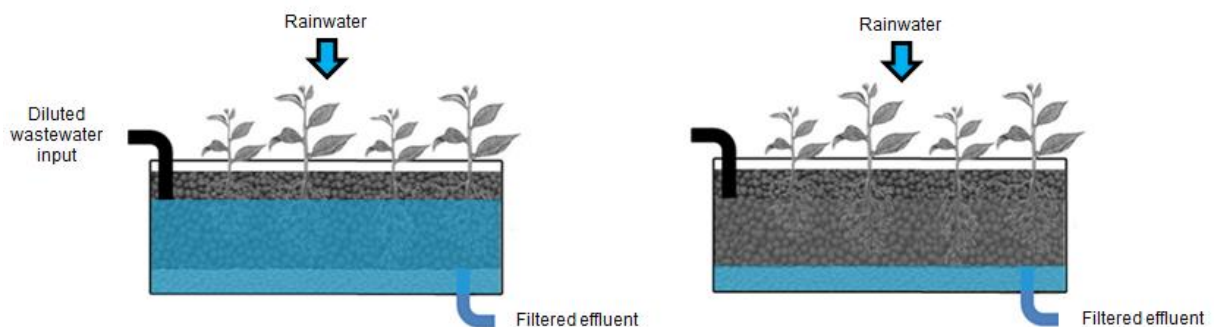


Figure 7: Filling and emptying the basins

Rainwater, quantified by a rain gauge, enters the pilot through the phytoremediation basins. The filtered water, by gravity, is collected in the buffer tank. The biological filtration and degradation processes that take place in the phytoremediation basins, carried out by aerobic microorganisms, remove some of the organic matter. Nitrogen is removed by nitrification, volatilization of ammonia

and adsorption by the roots and the filling material. Metals and phosphorus are adsorbed on the surface of the inert material. The macrophytes present in the two basins are as follows:

- *Paenia pivoine varie C1*
- *Canna X généralis*
- *Hibiscus moscheotus*
- *Mentha aquatica*
- *Petasite - Lytrum Salicaria*
- *Carex acutiformis*
- *Zantedeschia aetropica*
- *Hermerocallis*
- *Iris Pseudacorus*
- *Fuschia tom thumb*

3.1.2 Ozonation

Ozone is commonly used in the treatment of drinking water and wastewater because it quickly oxidizes organic and inorganic compounds without altering the smell and taste of the water.

The ozone generator used in the ReUse Pilot is supplied by the OZONE-SERVICE company and allows injecting doses of O_3 between 0,5 and 2,5 L/h. The generator produces O_3 sending an electric discharge to Oxygen flow. The oxygen is concentrated from ambient air. Disinfection efficiency is commonly measured using the concentration multiplied by time value (CT). The industrial ozone generator used is a CT 15 type, at low pressure and high frequency, for an ozone production from 2 to 16 g/h.

Ozone is generated directly on site since it is a highly unstable gas, in a standard environment it tends to turn into oxygen in about twenty minutes. The ozone rate is 1-3 g/m³. Since the solubility of ozone in water is very low, we need a highly efficient way of mixing them. Therefore, ozone is injected through a venturi tube (Figure 8).



Figure 8: Venturi tube photo

The difference in pressure between the high pressure at the inlet and the low pressure at the outlet generates a vacuum/suction effect that pulls the ozone gases into the water flow. Figure 9 presents a scheme of the venture functioning

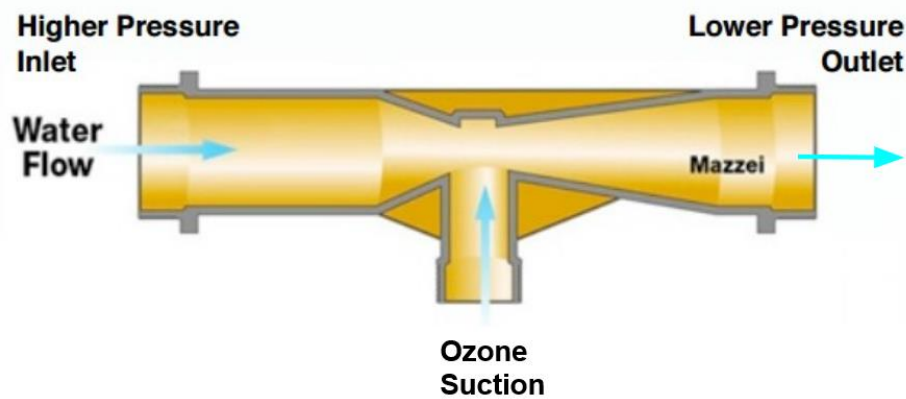


Figure 9: Scheme of the venture functioning. Source [43]

Immediately after the ozone injection, the water treated with ozone passes into a column. The ozone gases that are not transferred to the water go to the top of the column and are destroyed in a degasser. The contact time between water and ozone is less than 30 seconds. The water then reaches the micro-granular activated carbon (μ GAC) column (Figure 10).

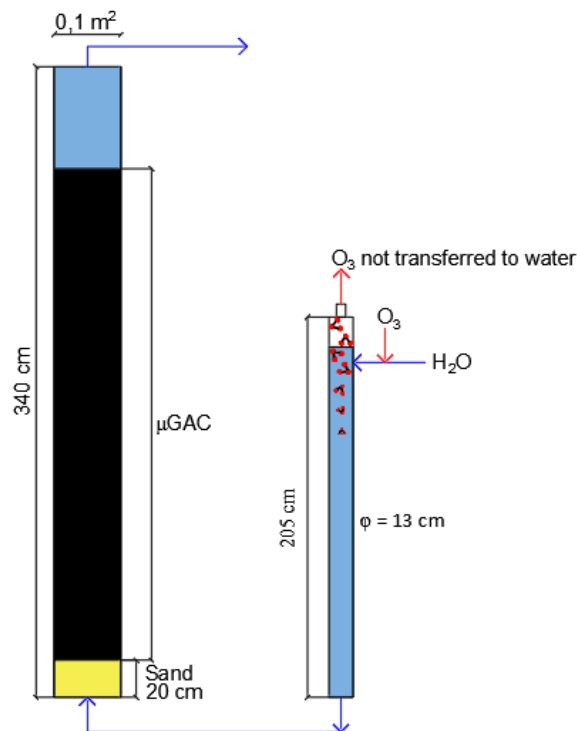


Figure 10: Ozonation and μ GAC filtration. Source: Veolia

Figure 11 shows the ozone concentrations upstream and downstream of the μ GAC column (OPACARB®FL). We can observe that the ozone residual is removed by the micro-granular activated carbon. This is important because ozone can cause damage to the UF membrane.

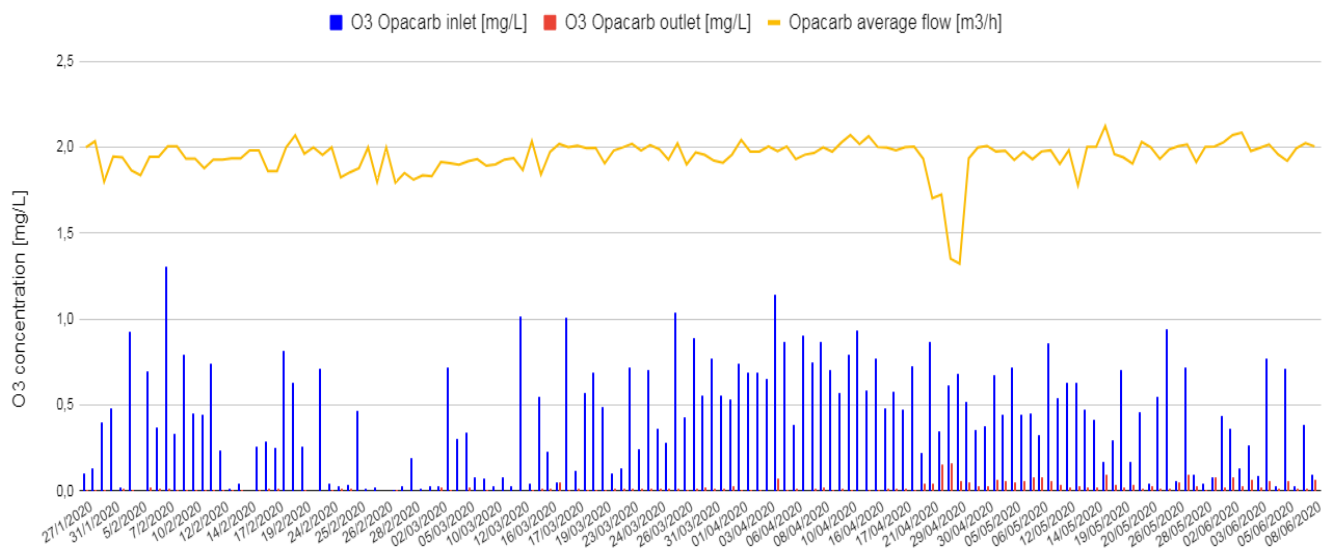


Figure 11: OPACARB®FL inlet and outlet ozone concentration

As we measure ozone at 10 am and at 5 pm we observe the same phenomenon every day. In the morning the concentration of ozone in OPACARB®FL inlet is higher than in the afternoon. Figure 12 presents the evolution of ozone concentration at OPACARB®FL inlet during the day. Since we arrive on site at 8:30 am and the pilot works 24 h per day, we believe that in the morning the water in the dilution tank is cleaner. During the day we consume water and produce wastewater. Therefore, the higher pollutants concentration in water consumes the ozone faster and we observe a decrease in ozone concentration during the day.

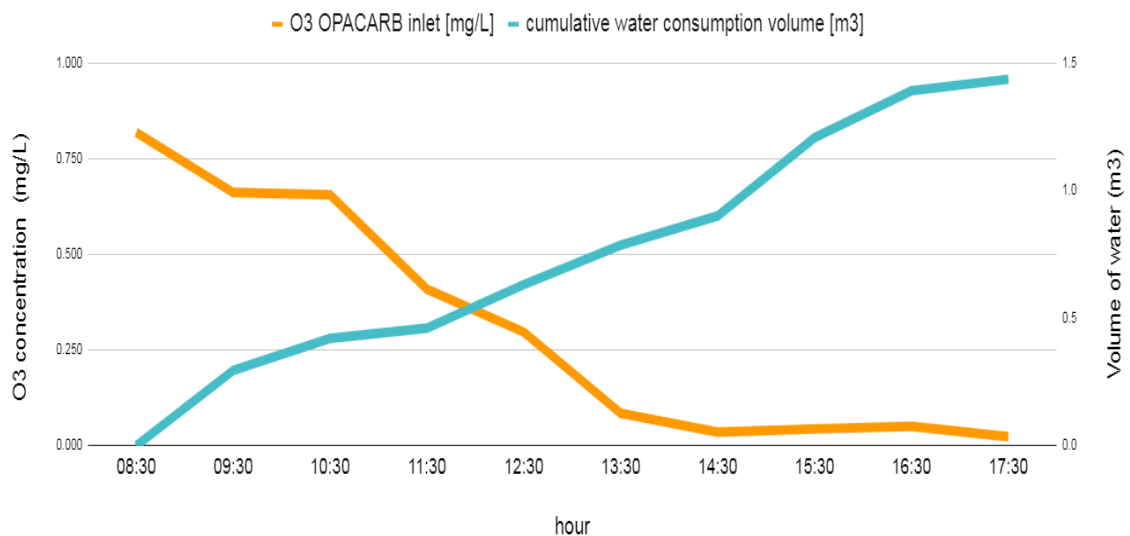


Figure 12: ozone concentration at OPACARB®FL inlet and water consumption on site during the day

3.1.3 Activated Carbon Adsorption (OPACARB®FL)

The most commonly used adsorbent material in the treatment of drinking water is activated carbon. With activation, a porous material with a high specific surface (450-1800 m²/g) and high affinity for

organic compounds is obtained. Activated carbon adsorption is used to remove micropollutants and organic molecules that give taste and smell to water.

OPACARB®FL is an upward flow reactor, made up of a fluidized bed of activated carbon in micro-grains (μ GAC) with which organic pollutants are removed by adsorption. After the ozone treatment, the water enters the micro-grain activated carbon filtration reactor, first passing through four nozzles (Figure 13) and then through a layer of 20 cm of sand.



Figure 13:OPACARB®FL nozzles

The upward flow of water allows a controlled expansion of the filling material based on the velocity of the feed water, allowing the adsorption of pollutants and dissolved organic substances. A layer of sand at the base of the column ensures a laminar flow of water through the medium (Figure 14). The expansion rate of activated carbon, for the same velocity, varies according to the temperature of the water, which affects the viscosity of the water and the characteristics of the activated carbon. Micrograins have a specific surface area smaller than powder, but larger than regular grains. Micrograins of active carbon do not require the addition of a chemical flocculant to deposit small carbon particles, as is common in drinking water treatment. We use the micrograin MICROSORB™ 400 R which has an average diameter of 650 μ m and a specific surface area of 900 m^2/g .

Opacarb®FL is equipped with systems to remove and to insert activated carbon in the column. The used activated carbon is sent to an external company that deals with its thermal regeneration.

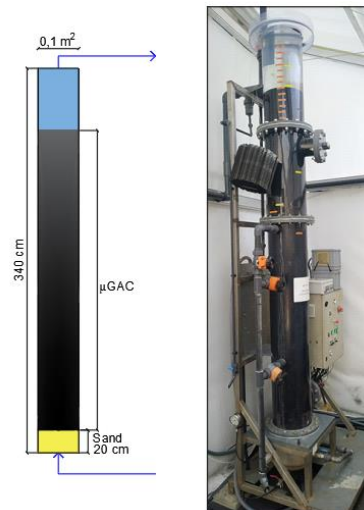


Figure 14: Opacarb®FL. Source: Veolia

At the outflow of the filtration column, the water proceeds towards the ultrafiltration system; at the exit of the Opacarb®FL column there is also a recirculation system towards the underground dilution tank, as shown in Figure 3. This recirculation system is used after the extraction of the used activated carbon and the introduction of the new carbon. When the column is put back into operation we want to prevent small particles of activated carbon from reaching the UF and clogging the membrane. Figure 15 shows the base skid dimensions of the Opacarb®FL.

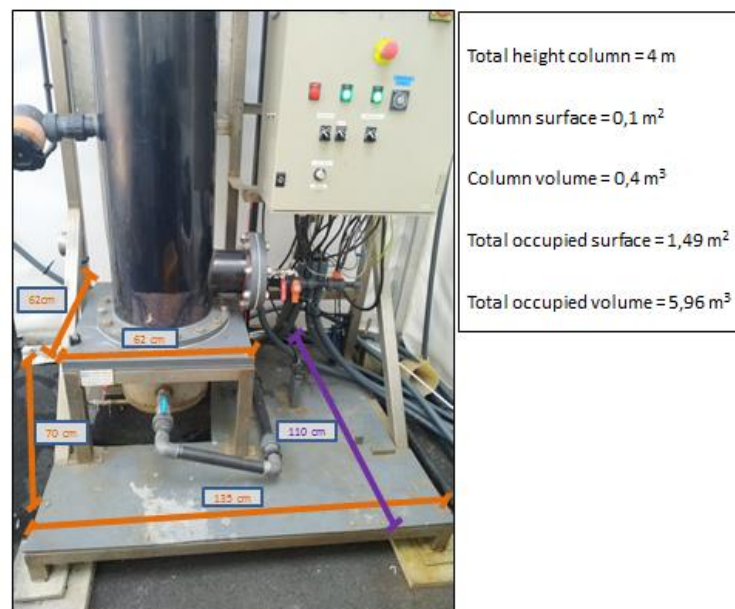


Figure 15: Opacarb®FL base skid dimensions

Operating parameters

The most important operating parameters for sizing the reactor are:

- Hydraulic Retention Time (HRT) [h]: time required for the passage of water through the entire system. Corresponds to the ratio between the volume (V) of the reactor and the flow rate of the feed (Q).

$$HRT = \frac{V}{Q}$$

- Empty Bed Contact Time (EBCT): The time during which the water to be treated is in contact with the adsorbent medium. It is the relationship between volume of the carbon empty bed (V_{EB}) and flow rate (Q).

$$EBCT = \frac{V_{EB}}{Q}$$

- Carbone Usage Rate (CUR): represents the amount of AC needed to treat a unit of volume of water. In our case, it is easier to measure this quantity by volume rather than by mass.

$$CUR = \frac{MassAC\ extract}{V_{treated\ water}} = \frac{VAC\ extract \cdot \rho}{Q_{treated\ water} \cdot t}$$

where:

ρ = water density = 1000 kg/m³

t = operating time [h]

Activated carbon renewal operations are performed once a week. The quantity of activated carbon to be extracted and replenished is assessed based on the volume of water filtered by the column, knowing that a treatment rate of 10 g/m³ is desired. Table 5 shows the values of the operating parameters calculated for the activated carbon column.

Table 5: OPACARB®FL operating parameters. Source: Veolia

Parameter	Value
μGAC	MICROSORB™ 400 R
Feed flow	2 [m ³ /h]
Flux	20 [m/h]
μGAC height at rest	180 [cm]
μGAC expansion height (T= 12 °C)	293 [cm]
HRT	10,5 [min]
EBCT	9 [min]
CUR	10 [g/m ³]
Expansion percentage	63%
AC Age	159

3.1.4 Ultrafiltration

Ultrafiltration is a process that uses a porous membrane as barrier during the filtration. The driving force is the pressure applied on the feed side and particles bigger than the pores are retained (size

exclusion principle). Ultrafiltration membranes have pores bigger than nanofiltration (NF) and smaller than microfiltration (MF). They are very efficient for turbidity and microorganisms removal and as pre-treatment for RO or NF.

The membrane used in the ReUse pilot is produced by MEMSTAR, a Chinese company. It is manufactured of polyvinylidene fluoride (PVDF) by a Non-solvent Induced Phase Separation (NIPS) technique. The total surface area is 38 m² and the average pore size is 40 nm. The module is hollow fiber and operates outside-in with a dead-end configuration. Figure 16 presents the specifications of the module informed by the supplier and Table 6 the module operating parameters.

MEMSTAR UF-0615ED HOLLOW FIBER MEMBRANE MODULE SPECIFICATIONS

MODULE SPECIFICATIONS

Membrane material	PVDF (NIPS)	
Pore size (μm)	0.04	
Filtration mode	Outside-In	
Housing material	UPVC/ABS	
Potting material	Epoxy/PU	
Filtration surface area (m ²) [ft ²]	40	[430]
Column volume (L) [gal]	15	[4]
Dry weight (kg) [lbs]	22	[49]
L1 (mm) [inches]	1386	[54.6]
L2 (mm) [inches]	172	[6.8]
L3 (mm) [inches]	1730	[68.1]
L4 (mm) [inches]	130	[5.1]
R (mm) [inches]	160	[6.3]
A	Influent/Discharge Port- DN32	
B	Concentrate Port- DN32	
C1	Permeate Port- DN32	
C2	Permeate Port- DN32	
D	Air Inlet Port- Φ12/9.5	

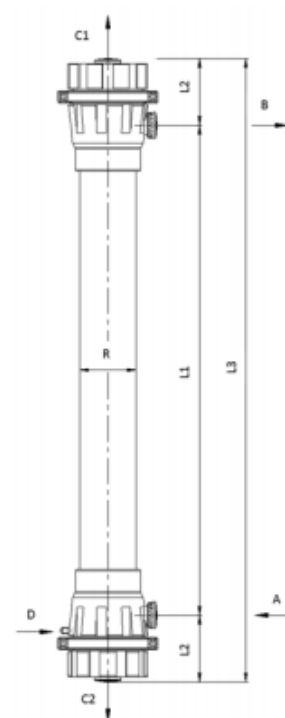


Figure 16: specifications of the UF module. Source [44]

Table 6: UF module operating parameters. Source [44]

MODULE OPERATING PARAMETERS

	Allowable Range
Operating temperature	5 – 45°C
Typical flux ¹	40 – 120 LMH
Instantaneous chlorine tolerance	2,000 ppm
Maximum lifetime chlorine tolerance	>500,000 ppm-hrs
Maximum feed turbidity ²	300 NTU
Maximum transmembrane pressure	1.5 bar (22 psi)
Maximum feed pressure ³	3 bar (44 psi)
Oil content in feed water	< 2 ppm
pH range	Operating: 1 – 10; Cleaning: 1 – 11
Allowed particle size in feed water ²	≤ 0.5 mm ≤ 0.12 mm for seawater feeds

Once released from the Opacarb®FL column, the water is collected in a 200-liter tank inside which there is a recirculation system towards the underground dilution tank. Figure 17 shows the UF system used in the ReUse Pilot. It is possible to observe both 200 L tanks, one for the feed and other for the permeate.



Figure 17: UF ReUse Pilot

A filtration cycle involves filtering the water for 15 minutes, followed by an air-scouring cleaning for 30 seconds and a final drain of 30 seconds. A double cleaning is performed every 5 filtering cycles. Figure 18 shows the air scouring diffuser.

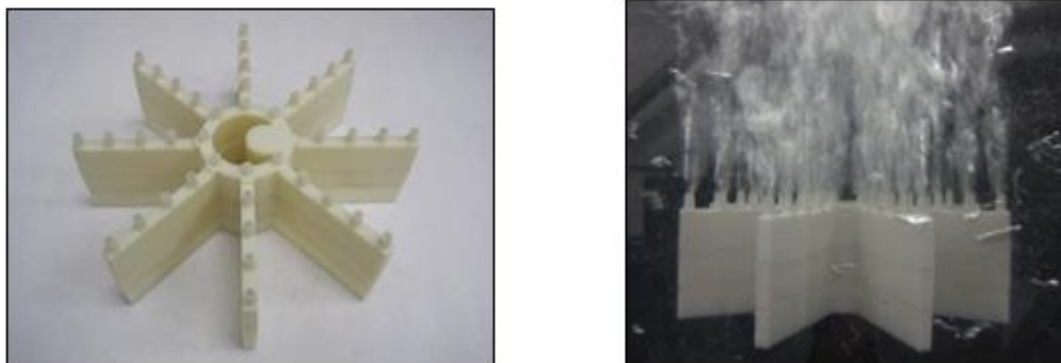


Figure 18: Air scouring diffuser

During filtration, the feed water valve and the filtrate valve are open and the feed pump is turned on. Figure 19 shows the fibers used in the hollow fiber module. We set the permeate flow at $1,6 \text{ m}^3/\text{h}$.



Figure 19: Fibers used in the hollow fiber module. Source [45]

The water treated with the UF membrane is collected in the second 200 liter tank and then sent to the final storage tank. From there, water can recirculate towards the underground dilution tank or it can feed the RO.

Definitions of key operating parameters

The most important operating parameters for the membrane are:

- Flow rate of the permeate: is the speed of the water passing through the membrane from the feed side to the permeate side. In our UF module it is possible to set this value, depending on the quality of feed water and the fouling in the membrane surface the feed pressure changes to reach this set value.
- Permeate flux: The permeate flux is the volume of filtered water that passes through a unit of the membrane surface over a specified period of time.
- Transmembrane pressure (TMP): The driving force of the filtration, it represents the difference in pressure between the feed and the permeate sides of the membrane. It is commonly measured in bars, psi or kPa. During filtration, solids deposited on the membrane surface will create resistance to filtration causing an increase in TMP. An adequate design filtrate flow is therefore required to control the rate of increase of the TMP. Physical and chemical cleanings are necessary to remove accumulated scale and reduce TMP. The maximum allowed TMP is 0.15 MPa.
- Normalized permeability: It is defined as the permeate flow by applied transmembrane pressure (differential pressure) corrected to a specified temperature, typically 20 or 25 degrees

Celsius. It is commonly measured in liters per hour per membrane surface per bar at 20 °C. Normalized permeability is one of the most important parameters used to measure membrane performance. In a properly designed and managed UF system, the normalized permeability will slowly decrease during the filtration cycles and return to previous levels after cleaning so that it remains substantially constant for long-term operation.

- Filtration cycle duration: depends on the quality of the feed water. An appropriate design value must be selected; the actual time must be adjusted according to the changes in the quality of the feed water. The typical duration of the filtration cycle is 20-60 minutes.

To evaluate the degree of membrane clogging, permeability is calculated every day as the ratio between the normalized flow at 20 °C and the transmembrane pressure. When the permeability drops below 50 L/(L·m²·bar@20°C), Recovery Cleaning is carried out. The TMP is calculated as the difference between the feed and the permeate pressure [bar]. Permeability is calculated with the following formulas:

$$P = J_{20}/PTM$$

$$J_{20} = K_T \cdot J$$

$$J = \frac{Q}{S}$$

$$K_T = e^{-0.0239(T-20)}$$

Where:

- K_T is a temperature correction factor to consider the variability of the parameters.
- J is the specific flow [L/(m²·h)] and represents the flow rate of filtered water per unit of membrane surface (S).
- J_{20} is the flow normalized at 20 °C.
- P is the permeability defined as the volume of water flowing through the membrane per unit of time, surface and pressure [L/(m²·h·bar@20°C)].

3.1.5 Reverse Osmosis

Unlike ultrafiltration, the reverse osmosis process uses a dense membrane. Only very small molecules, such as water molecules and some monovalent ions can pass through the dense membrane. Therefore, RO produces ultrapure water. To have a reasonable permeate flow despite the absence of pores it is necessary to apply a transmembrane pressure (driving force) higher than the one for UF or NF.

The module used in the ReUse pilot is the Sirion 200 Advanced by SOLYS, it can be seen in Figure 20. The membrane used is a polyamide thin-film composite and the maximum operating overpressure is 9,6 bar. We have an average permeate production of 96 L/h, a recovery rate of 66% and a salt rejection of 99,2%. The module needs a pretreatment since the maximum turbidity of feed is 1 NTU. This is not a problem for us because the turbidity of UF permeate is always below 1 NTU.



Figure 20: RO ReUse pilot

Currently the RO permeate is drained from the system. However, the next step is to remineralise the permeate and send it back to be used in the toilets on site. The RO concentrate is used to irrigate a small tomatoes plantation and the excess is collected and sent to the dilution tank.



Figure 21: Tomatoes plantation

3.2 Analytical Methods

Figure 22 shows the ReUse Pilot supply chain before the RO operation, highlighting the sampling points used for laboratory analysis since march 2019.

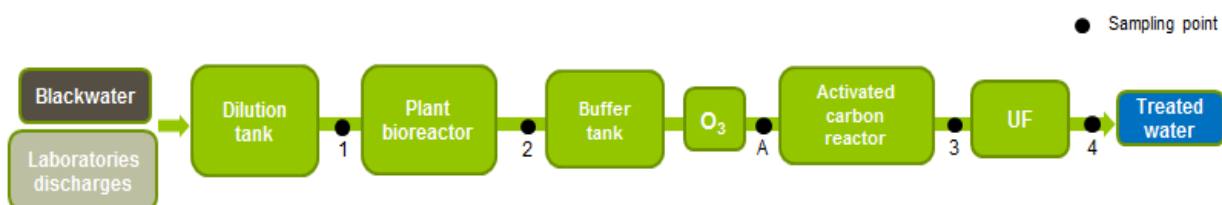


Figure 22: Sampling points in the ReUse Pilot

With reference to Figure 22, Table 7 reports the analysis carried out and their frequency.

Table 7: Sampling points and analyzes carried out

Sampling point	Analyses	Timing
1 and 2	UV abs, pH, T, Conductivity, COD, NH_4^+ , NO_3^- , NO_2^- , Ptot, PO_4^{3-} , DOC, Mn, Fe, NTU, Ntot	Twice per week, three campaigns for micropollutants, four bacterial campaigns
A	O_3	Twice per day
3	UV abs, pH, T, Conductivity, NH_4^+ , NO_3^- , NO_2^- , Ptot, PO_4^{3-} , DOC, Mn, Fe, NTU, Ntot, O_3	Twice per week, ozone twice per day, three campaigns for micropollutants, four bacterial campaigns
4	UV abs, pH, T, Conductivity, NH_4^+ , NO_3^- , NO_2^- , Ptot, DOC, Mn, Fe, NTU, Ntot, O_3	Twice per week, three campaigns for micropollutants, four bacterial campaigns

The analyses carried out and the methods to characterize and to monitor the water quality are the followings:

- **Turbidity**

Turbidity (NTU) gives information on the water cloudiness, the content of suspended particles. Particles in suspension can scatter a light beam focused on them. The equipment used, the turbidimeter HACH 2100N, has a detector positioned at 90° from the incident light. A higher number of particles in suspension scatter higher intensity of light that reaches the detector. Big particles settle

fast and may not be detected, the test is more efficient for colloidal suspensions. The results are given in NTU (Nephelometric Turbidity Unit). Calibration is done with control solutions (formazine).

- **Absorbance UV**

The Ultraviolet absorbance is an indirect measure of the amount of organic matter in water. Aromatic groups, very abundant within the macromolecules that form dissolved organic matter in the water, absorb UV light at 254 nm. The equipment used was the Spectrophotometer HACH DR 6000 and the results were given in m^{-1} .

- **Total Nitrogen**

Measured using LCK 138 LATON Hach kit. The kit is based in Koroleff digestion (with peroxodisulphate) and photometric detection with 2,6-dimethylphenol [32]. The measuring range is from 1 to 16 mg/L TNb. For digestion we used Hach Thermostat LT 200 and for the measurement the Spectrophotometer HACH DR6000 at wavelength of 345 nm.

- **Nitrate Nitrogen**

Measured using LCK 339 Hach kit with a measuring range of 0,23 - 13,5 mg/L NO_3^- -N. The kit is based on the reaction of nitrates with 2,6-diméthylphénol to form 4-nitro-2.6-dimethylphenol [33]. We used the spectrophotometer Hach DR6000 at a wavelength of 345 nm for the detection.

- **Nitrite Nitrogen**

Measured using LCK 341 Hach kit with a measuring range of 0,015 - 0,6 mg/L NO_2^- -N. The kit is based on the reaction of nitrites with primary aromatic amines in acidic solution to form diazonium salts. These combine with aromatic compounds that contain an amino group or a hydroxyl group to form intensively colored azo dyes [34]. We used the spectrophotometer Hach DR6000 at a wavelength of 345 nm for the detection.

- **Ammoniacal Nitrogen**

LCK 304 Hach kit with a measuring range of 0,5 - 5,0 mg/L NH_4^+ -N. The kit is based on the reaction of Ammonium ions with hypochlorite ions and salicylate ions in the presence of sodium nitroprusside as a catalyst to form indophenol blue [35]. We used the spectrophotometer Hach DR6000 at a wavelength of 694 nm for the detection.

- **Total Phosphorus/ orthophosphate**

Both were measured with the same LCK 348 Hach kit with a measuring range of 0,015 - 2,0 mg/L PO_4^{3-} -P. The kit is based on the reaction of phosphate ions with molybdate and antimony ions in an acidic solution to form an antimonyl phosphomolybdate complex, which is reduced by ascorbic acid to phosphomolybdenum blue [36]. We used the spectrophotometer Hach DR6000 at a wavelength of 880 nm for the detection.

- **Chemical Oxygen Demand (COD)**

COD is an indirect measurement of the amount of organic matter in a sample. With this test it is possible to measure virtually all organic compounds that can be digested by a digestion reagent.

It was measured using LCK 1414 Hach kit with a measuring range of 5 - 60 mg/L O₂. The kit is based on the reaction of oxidizable substances with sulphuric acid and potassium dichromate solution in the presence of silver sulphate as a catalyst. Chloride is masked by mercury sulphate. The reduction in the yellow coloration of Cr⁶⁺ is evaluated [37]. For digestion we used Hach Thermostat LT 200 and for the measurement the Spectrophotometer HACH DR6000 at a wavelength of 348 nm.

- **Dissolved Organic Carbon (DOC)**

can be measured directly by spectroscopy after sample filtration at 0.45 µm. However, spectroscopic measurement tends to include only the most complex OM molecules, including aromatic compounds. Thus, a low UV absorbance value does not necessarily mean a small amount of OM but usually a small amount of aromatic carbon. Moreover, the correlation differs for each type of resource, so it is necessary to establish it beforehand for each plant. Equipment used is TOC analyzer HACH QbD1200 and the results are given in ppm.

- **Total Manganese**

Measured using 8008 Hach kit with a measuring range of 0.015-2.0 mg/L Mn based on PAN Method. The used instrument is the same as for UV measurements.

- **Total Iron**

Measured using 8008 Hach kit with a measuring range of 0 to 0.7 mg/L Fe based on USEPA FerroVer Method. The used instrument is the same as for UV measurements.

- **Ozone**

Measured using LCK 310 Hach kit with a measuring range of 0,05 - 2,00 mg/L O₃. The kit is based on the reaction of Oxidizing agents with diethyl-p-phenylenediamine to form a red dye.[38]. We used the spectrophotometer Hach DR6000 at a wavelength of 552 nm for the detection.

4. Results and Discussion

4.1 Hydraulic Balance

Figure 23 presents the simplified hydraulic balance of the pilot. The objective is to have a closed loop system in the future, but currently we must monitor the entrance of wastewater and rainwater in the system to calculate the correct drainage volume. We consider the evapotranspiration in phytoremediation basins negligible. Therefore, every day the drainage should be equal to the wastewater effluent plus the rainwater that enters the system. The total volume of the system is 8000 L.

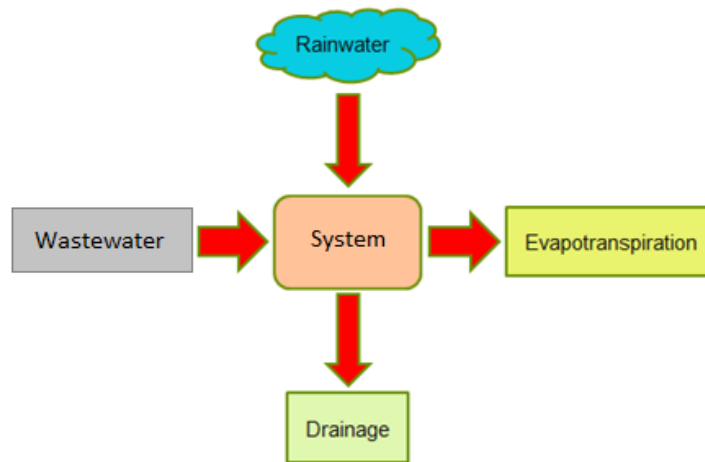


Figure 23: ReUse Hydraulic Balance

Until February 2020 the drainage was based on the level at the underground dilution tank. Treated water used to be drained a few times during the day in order to maintain the level constant. The volume of wastewater feeding the system used to be estimated as the volume of water drained minus the volume of rain during the day (calculated using a pluviometer). The problem with this approach is that it doesn't consider possible leakages or overflows.

In March 2020 a water volume meter was installed. Now it is possible to know the volume of water consumed on site and consequently the amount of wastewater sent to the Reuse pilot. The daily drainage is calculated to have the same volume as the wastewater feeding the system plus the volume of rain. In March, a system to automatically monitor the level in the dilution tank, the flow rate in Opacarb[®]FL column and flow rates of inlet and outlet of the phytoremediation basins was also installed.

At the end of June the RO unit started to operate. Currently the system is not a closed loop yet and the permeate of RO is completely drained. Figure 24 presents the data recorded per minute during one day for the level in the dilution tank and the flow rate at the Opacarb[®]FL column. It is possible

to see the stable functioning of the Opacarb[®]FL column even without people on site. The level in the dilution tank is stable when no one is present and it starts to rise at the beginning of working hours. The level drops when the RO pilot is in operation because the permeate is constantly drained from the system.

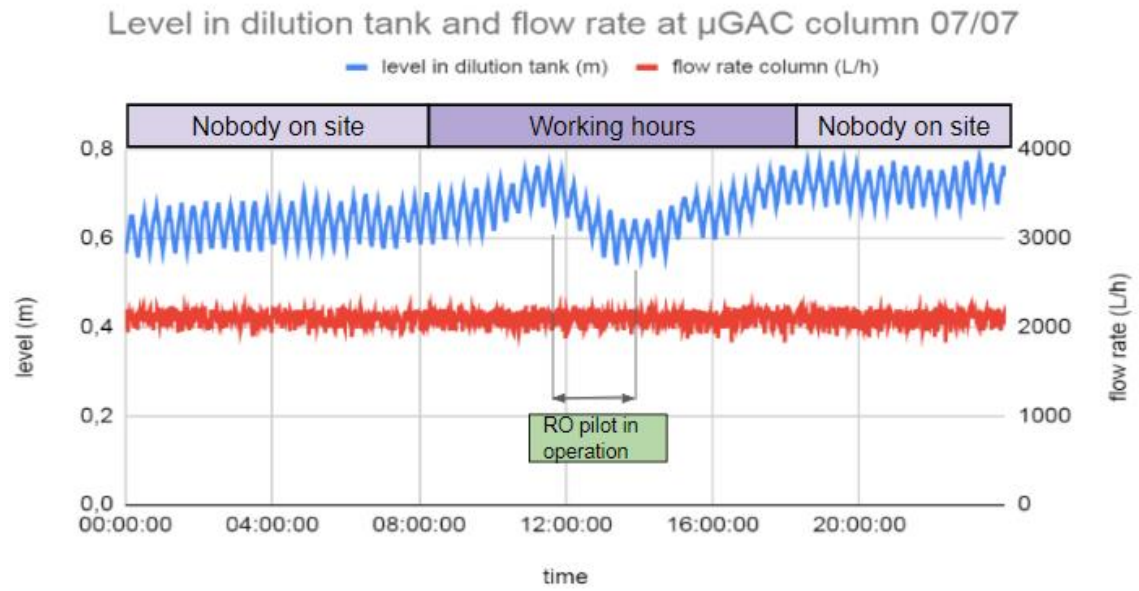


Figure 24: Level in dilution tank and flow rate at Opacarb[®]FL column (μGAC)

The level in the dilution tank has this oscillatory behavior because the pump that sends effluent from the tank to the phytoremediation basins doesn't operate in a continuous way. It's possible to observe inlet and outlet flow rates of the phytoremediation basins in Figures 25 and 26. The automatic monitoring system shows the behavior of the pilot per minute and allows us to detect any malfunctioning of the system.

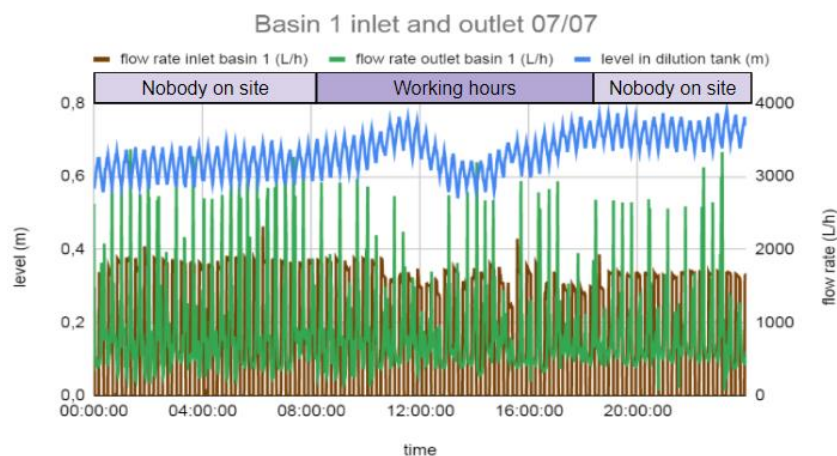


Figure 25: Inlet and outlet flow rates of the phytoremediation basin 1

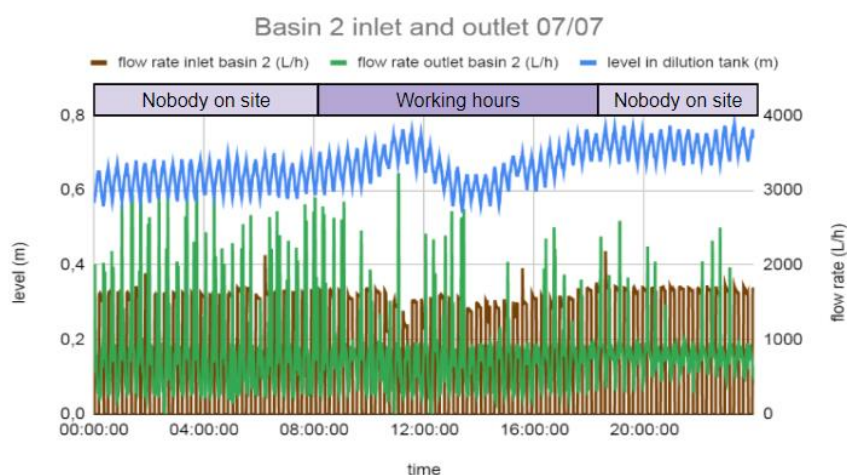


Figure 26: Inlet and outlet flow rates of the phytoremediation basin 2

Since the water volume meter and the automatic monitoring system were installed, the control of the hydraulic balance is more precise and the RO allows a more controlled method to purge the system. The result of this control can be seen in Figure 27 where the cumulative inlet and outlet volumes in the system are almost the same. Small differences in one day are compensated in the next without any damage to the system.

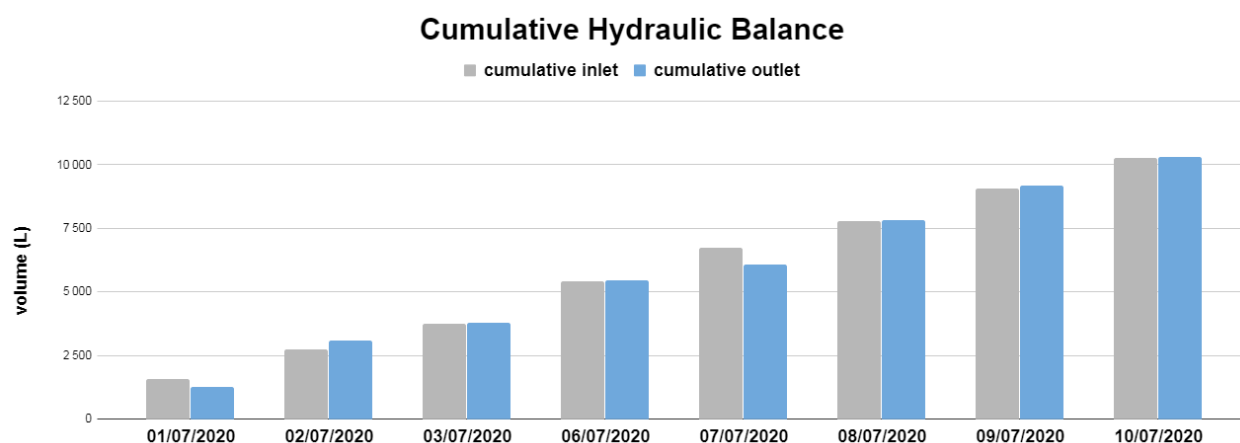


Figure 27: Cumulative hydraulic balance

This result shows that we have a controlled hydraulic balance therefore we are ready to take the next step and close the system.

4.2 Drinking Water Production: Water Quality

Tables 8 and 9 present the results of laboratory analysis of the feed wastewater present in the dilution tank and of the UF permeate. The legislation limit allows us to evaluate the water quality. Due to many changes in the reuse pilot we divided the results in two periods of time, table 10 presents the main differences between the two periods of time.

Table 8: Water quality evaluation from March until September 2019

Parameters	Feed	UF permeate			average removal	Legislation limit
	Average	Average	Max	Min		
NH ₄ ⁺ (mg/L)	0,201	0,031	0,46	0	84,6	0,1
NO ₃ ⁻ (mg/L)	26,9	26,4	66,43	2,08	1,9	50
NO ₂ ⁻ (mg/L)	0,5	0,13	1,6	0	74,0	0,5
Ptot (mg/L)	0,86	0,39	0,7	0,15	54,7	0,5
DOC (mg/L)	2,53	0,46	0,68	0,15	81,8	2
Mn (mg/L)	0,14	0,02	0,04	0,001	85,7	0,05
Fe (mg/L)	1,04	0,03	0,11	0	97,1	0,2
pH	-	7,21	7,9	6,7	-	6,5 - 9
Turbidity (NTU)	58,11	0,09	0,15	0,06	99,8	1
E. coli	43320	0	0	0	100	0 CFU/100 mL
Enterococcus	3576	0	0	0	100	0 CFU/100 mL
Spore	400	0	0	0	100	0 CFU/100 mL

Table 9: Water quality evaluation from October 2019 until June 2020

Parameters	Feed	UF permeate			average removal	Legislation limit
	Average	Average	Max	Min		
NH ₄ ⁺ (mg/L)	0,183	0,051	1,05	0	72,1	0,1
NO ₃ ⁻ (mg/L)	50,6	49,3	151,46	4,96	2,6	50
NO ₂ ⁻ (mg/L)	0,5	0,28	7,5	0	44,0	0,5
Ptot (mg/L)	0,81	0,66	1,85	0,03	18,5	0,5
DOC (mg/L)	2,22	0,69	1,24	0,3	68,9	2
Mn (mg/L)	0,04	0,03	0,08	0,002	25,0	0,05
Fe (mg/L)	0,1	0,01	0,07	0	90,0	0,2
pH	-	7,48	8	6,05	-	6,5 - 9
Turbidity (NTU)	2,84	0,08	0,45	0,02	97,2	1
E. coli	2851	0	0	0	100	0 CFU/100 mL
Enterococcus	782	0	0	0	100	0 CFU/100 mL
Spore	22	0	0	0	100	0 CFU/100 mL

Table 10: main differences between the two periods of time

	March until September 2019	October 2019 until June 2020
Ozonation	NO	YES
Coagulation FeCl ₃	YES	NO
μGAC column functioning	12/24 h	24/24 h
Carbon treatment rate	20 g/m ³	10 g/m ³
number of people on site	average 16 people (except September)	average 10 people (except June)

Currently there is no limit in French legislation for total phosphorus. However, predicting a possible change in the future, we decided to adopt a limit of 0,5 mg/L. It is interesting to notice that the feed wastewater comes from the dilution tank where wastewater is mixed with treated water. Hence, the quality of the feed is not bad and changes in the quality of the UF permeate can affect the quality of the feed. According to French legislation, we succeed in producing drinking water from wastewater reuse.

4.2.1 Turbidity removal

The removal of turbidity in the system was very good during the duration of the study and even the highest value found in UF permeate (0,45 NTU) is half of the legislation limit. The main responsible for such reliable removal is the UF membrane. Read section 4.3.1 Ultrafiltration Performance for more details

4.2.2 Dissolved Organic Carbon removal

The process which is mainly responsible for the removal of dissolved organic carbon (DOC) is the column of μGAC adsorption. There was effective removal throughout the study and even the highest value registered in UF permeate (1,24 mg/L) is below the legislation limit.

Following the sustainable principle of reducing quantities of chemicals and raw materials, we reduced the carbon treatment rate by half in the second period (October 2019 until June 2020). Although the average removal decreased from 82 to 69% the concentration of DOC in the second period is still below the legislation limit. It is likely that the average removal didn't drop more because in November 2019 we started to use ozonation to assist the μGAC adsorption. Ozonation can greatly increase adsorption efficiency .

4.2.3 Nitrogen pollution: Ammonium, Nitrites and Nitrates

The process mainly responsible for removal of nitrogen pollution are the phytoremediation basins. Although the average concentration of nitrogen pollution in UF permeate is below the legislation

limit, we observe that the maximum value obtained is above the limit. This implies that in some days the water was not drinkable. This happens due to the nature of phytupurification. As presented in Figure 28, the vegetation dies in cold months and grows in warm months. In winter the efficiency of phytoremediation decreases, hence we can observe higher concentrations of nitrogen pollution during the second period of the project.

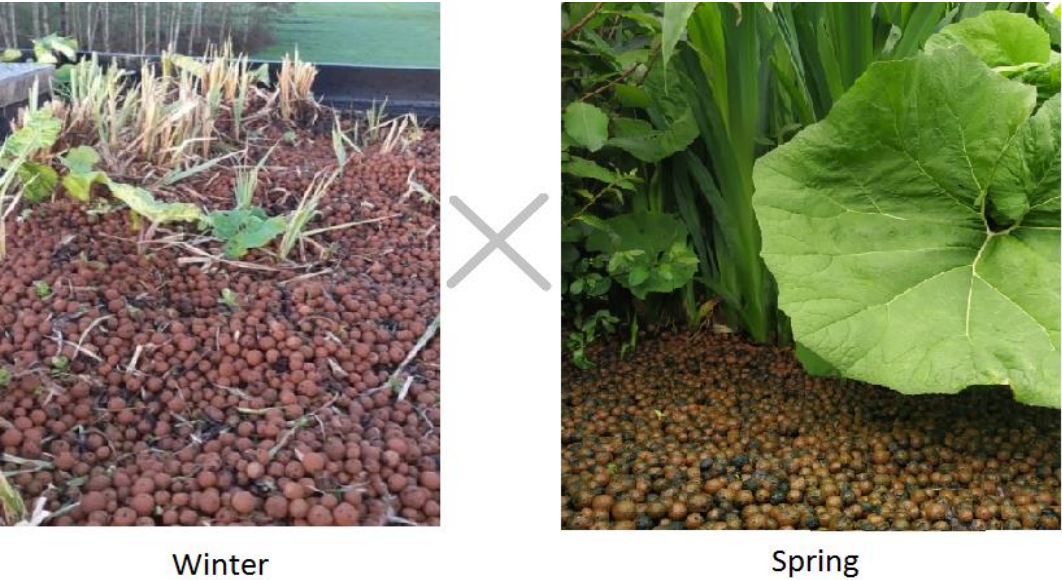


Figure 28: Vegetation growth in different seasons at phytoremediation basins.

Figure 29 shows the concentration of nitrates in the UF permeate compared with the temperature. The seasonality of nitrogen treatment is very clear in this graph. This is a big problem because when dealing with potable water production we must ensure the quality of water every day, otherwise we can cause damage to human health. This was one of the main motivations to add an additional treatment after the UF. In July 2020 we started the operation of a RO module after the UF.

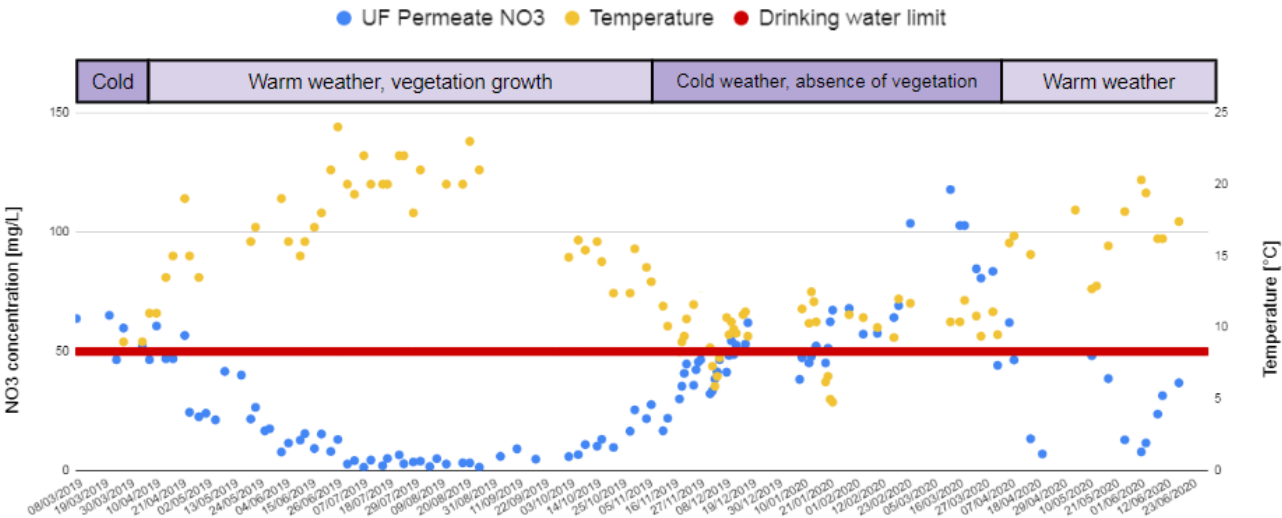


Figure 29: Seasonality of the nitrate ion

4.2.4 Phosphorus Removal

Until November 2019 the phosphorus was mainly precipitated with ferric chloride and then filtered in the phytoremediation basins. As we want a sustainable project with the minimum use of chemicals, we decided to stop the coagulant dosing on our pilot. The removal of phosphorus in the period of use of the coagulant is about 55%, while in the period after November it is about 19%. Figure 30 shows the variation of total phosphorus in the treated water (UF permeate). It is clear that the concentration of phosphorus has increased since the discontinuation of ferric chloride dosage.

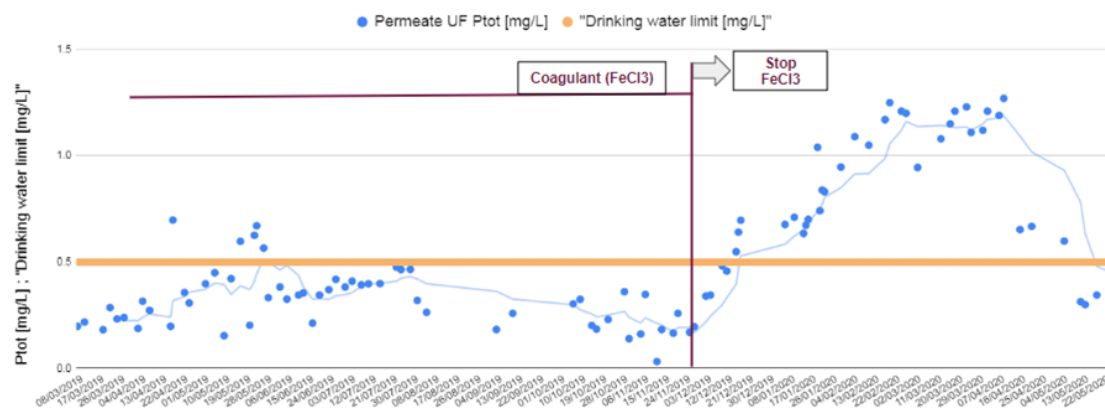


Figure 30: Permeate UF Total Phosphorus variation

The legislation does not provide a limit for this parameter. However, during the study of this project it was decided to set a limit equal to 0,5 mg/L. During the period of ferric chloride dosage, the average concentration of phosphorus in UF permeate was 0,4 mg/L and even during this period we found values above the limit. In the period without coagulant, on the other hand, the average concentration in treated water is 0,7 mg/L, beyond the limit established.

This was another motivation to add an RO module after the UF. It is expected that the RO will be more efficient than the coagulant in phosphorus removal with a lower consumption of chemicals. Phosphorus is one of the nutrients of plants, in fact it determines the development of roots, flowers and buds, strengthens the stem and also intervenes in some processes of chlorophyll photosynthesis. Therefore, we decided to irrigate a small tomato plantation with the concentrate from RO. Once the tomatoes grow, we will analyze them to ensure that the concentrations of metals and ions are not dangerous to human health.

4.2.5 Iron and Manganese Removal

The use of ferric chloride inevitably increases the concentration of iron within the system. About 50% of the iron present is eliminated during phytoremediation. From Figure 31 it can also be seen that the iron concentration decreases starting from the month of October 2019 (period of high rainfall); nonetheless, the iron concentration remains almost constant in the period following November 2019

when the ferric chloride is no longer dosed. Recalling that the iron limit value imposed by the legislation for drinking water is 0,2 mg/L, it is always respected.

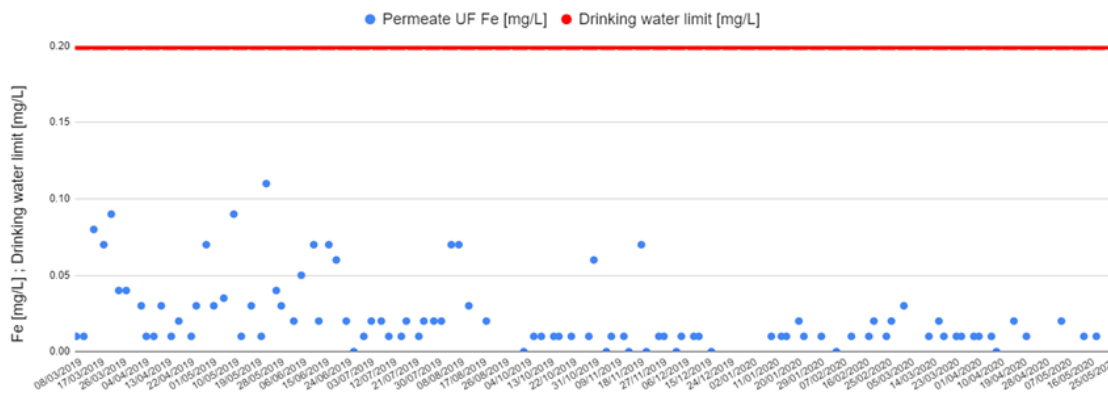


Figure 31: Iron concentration in UF permeate

The variation of manganese in the treated water is shown in Figure 32. With the use of ferric chloride there is also the supply of manganese in the system. However, unlike what was observed with iron, for the manganese there is not a clear reduction in concentration for the period without coagulant dosage. Therefore, we conclude that the coagulant has a more significant contribution to the concentration of iron in the system. Recalling that the manganese limit value for a drinking water is 0,05 mg / L, this is almost always respected. For the few days it was not respected we already have a solution: The RO.

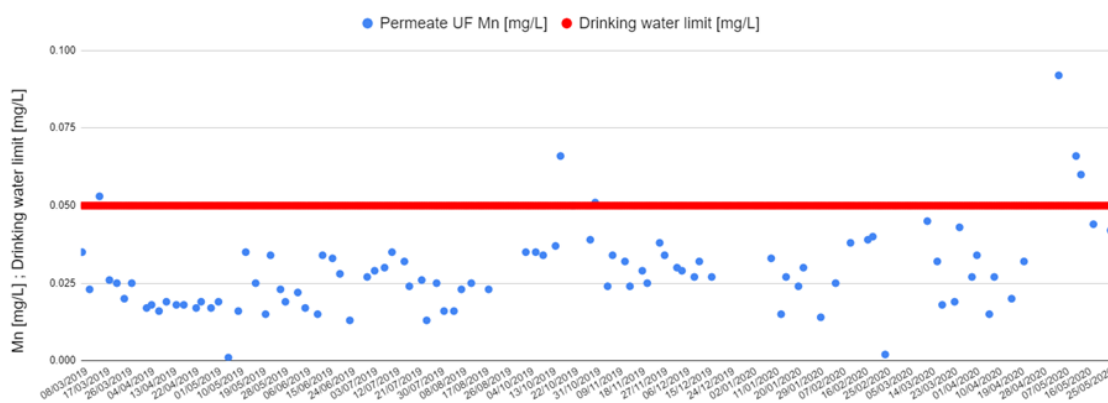


Figure 32: Manganese concentration in UF permeate

4.2.6 Micropollutants removal

In October 2019, a campaign for micropollutants was carried out through an external laboratory. A total of 471 substances belonging to different families were analyzed: Benzotriazoles and Benzothiazoles, Estrogenic Hormones, Pesticides, Pharmaceutical Compounds, Alkylphenols, Phthalates, Surfactants. Table 11 shows the number of molecules analyzed for each family of

micropollutants. Most of the molecules have been analyzed to anticipate a possible change in regulations in the event that wastewater is used directly for the production of drinking water.

Table 11: Number of micropollutant molecules analyzed

Family	Benzothiazoles and benzothiazoles	Estrogenic hormones	Pharmaceutical compounds	Alkylphenols	Phthalates	Pesticides	Synthetic fragrance	Surfactants
Number	7	2	54	13	12	378	2	3

The detected micropollutants are shown in Table 12. Of all the substances detected, the concentration in the UF permeate is below the detection limits and therefore cannot be quantified according to the current French legislation on drinking water. Since the results for treated water are below the detection limit, we decided to attribute a concentration equal to half the detection limit for calculation purposes (second column entitled treated water in the table).

Table 12: Micropollutants detected

Family	Micropollutants	LOR [$\mu\text{g/l}$]	OpacarbFL Inlet [$\mu\text{g/l}$]	Treated water [$\mu\text{g/l}$]	Treated water [$\mu\text{g/l}$]	Elimination %
Benzotriazoles and Benzothiazoles	1H-benzotriazole	0,03	0,86	< 0,030	0,015	98,26
Benzotriazoles and Benzothiazoles	5-methyl-1H-benzotriazole	0,03	2,93	< 0,030	0,015	99,49
Pharmaceutical compounds	Caffeine	0,01	0,17	< 0,100	0,005	97,06
Pharmaceutical compounds	Oxazepam	0,01	0,203	< 0,100	0,005	97,54
Pesticides	AMPA	0,05	0,315	< 0,050	0,025	92,06
Surfactants	Anionic Surfactants as MBAS	0,02	0,023	< 0,020	0,01	56,52

Of all the substances analyzed, only six molecules were detected in the raw water entering the Opacarb®FL. Figure 33 shows the concentrations of the micropollutants at the entrance and exit of the Opacarb®FL and their percentage of elimination. This result proves the efficiency of our micro-granular activated carbon adsorption for treatment of micropollutants.

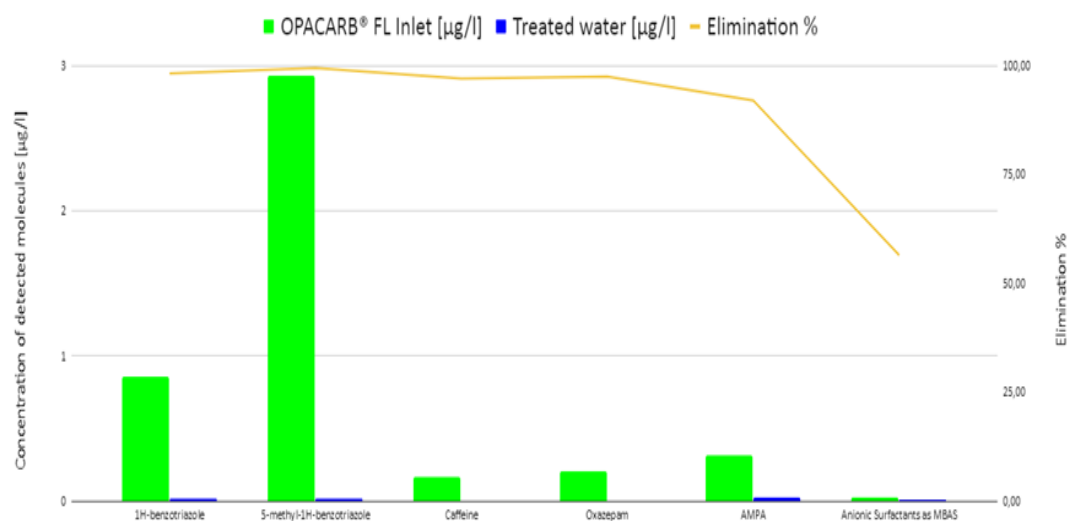


Figure 33: OPACARB®FL inlet and outlet detected micropollutants concentrations

It is noted that the detected molecules are present in very small quantities even in the feed water. The absence of quantification of practically all the analyzed micropollutants and the low concentration of the detected molecules in all samples are obtained thanks to the recirculation of the water which allows the dilution of the raw water with the treated water. Considering that the concentration of pesticides is below legislation limit (0,1 µg/L per single substance), we consider that we successfully remove micropollutants from our treated water.

4.2.7 Pathogenic microorganisms removal

Figures 34, 35 and 36 respectively show the concentration of intestinal *Enterococcus*, *Escherichia Coli* and anaerobic sulfur-reducing bacteria spores of 4 analyses performed by an external laboratory. Two bacterial analyses were carried out in 2019 before the operation of ozonation treatment and the other two analyses were carried out in January and June 2020 with ozonation treatment present.



Figure 34: *Enterococcus* concentration in ReUse samples



Figure 35: *Escherichia Coli* concentration in ReUse samples

There are no Enterococcus or E. Coli in the ultrafiltration permeate, therefore the limit imposed by the regulations is respected. The figures also show the quality limits of bathing water for Enterococcus and for E. Coli which are respectively 200 CFU/100 ml and 500 CFU/100 ml to have an idea of the quality of water during the stages of treatment. For drinking water the limit is 0 CFU/100 mL. We observe the efficiency of ultrafiltration for microorganisms removal in all the analyses. We also notice the disinfection function of ozonation decreasing the concentration of microorganisms in OPACARB®FL outlet. This is important because, although the UF membrane is very efficient for microorganisms removal, the microorganisms increase the fouling in the membrane surface, decreasing the membrane permeability (see section 4.3.1 UF performance). In addition, when dealing with potable water it is important to have a multi-barrier approach to ensure the quality of water.

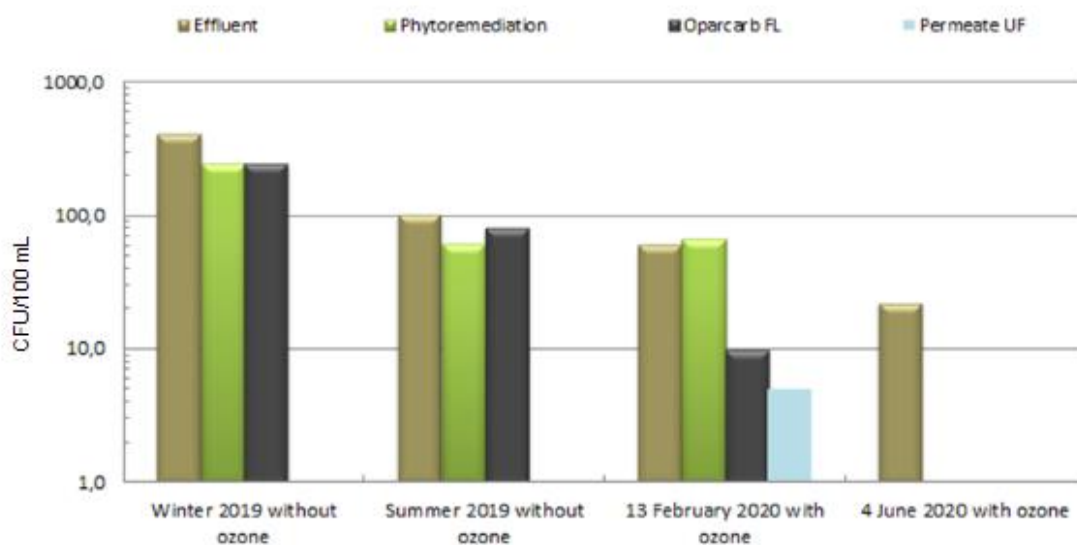


Figure 36: Anaerobic sulfur-reducing bacteria spores concentration in ReUse samples

For the Anaerobic sulfur-reducing bacteria spores we have similar results. However, in February a contamination was detected in UF permeate. As this is the only contamination detected in all the analyses of UF permeate, we believe this contamination occurred during manipulation or sample collection. We should keep monitoring to ensure that this is not an integrity problem in the membrane

4.2.8 Reverse Osmosis

The Reverse Osmosis (RO) operation started in July hence we have results from only two weeks to analyse. Table 13 presents the average results for the laboratory analysis during the first 2 weeks of RO operation. It is important to notice that for a new module in operation it is usual to have a period of adaptation. Therefore, it is possible that these numbers will change a little in the future.

Table 13: average results for the laboratory analysis of UF permeate, RO concentrate and RO permeate.

Parameters	UF permeate	RO permeate	% Removal	RO concentrate	Legislation Limit
NH ₄ ⁺ (mg/L)	0,006	0,001	80,0	0,03	0,1
NO ₃ ⁻ (mg/L)	19,04	6,02	68,4	51,37	50
NO ₂ ⁻ (mg/L)	0,33	0,12	64,6	2,42	0,5
P _{tot} (mg/L)	0,75	0,11	85,3	2,88	0,5
DOC (mg/L)	1,15	0,80	30,4	2,94	2
Mn (mg/L)	0,022	0,003	88,6	0,072	0,05
Fe (mg/L)	0,02	0,01	50,0	0,02	0,2
SO ₄ ²⁻	91,15	1,49	98,4	243,00	250
pH	8,25	7,76	-	8,18	6,5 - 9
Turbidity (NTU)	0,06	0,04	32,8	0,22	1
Conductivity (μS/cm)	767,00	47,15	93,9	2495,00	180 - 1000

We can observe that in RO permeate all the concentrations are below the legislation limit, making our production of drinking water more reliable. However, as the salt rejection is very efficient in the RO, the conductivity of the permeate is below the minimum limit. Therefore, a stage of remineralization of permeate is necessary and must be implemented in the future. After the results obtained with the RO we are confident of our capacity to produce drinking water from wastewater during the complete year.

4.3 System Stability and Performance

4.3.1 Ultrafiltration Performance

As explained in section 3.1.4, the permeability of the ultrafiltration membrane is calculated every day. Figure 37 presents the evolution of the permeability at 20°C during the year. It's visible that when the module started operating the permeability was very high (above 100 LMH/bar) and after a few days it stabilized around 85 LMH/bar. This is an usual behavior for new membrane modules since there is no cake layer at the beginning.

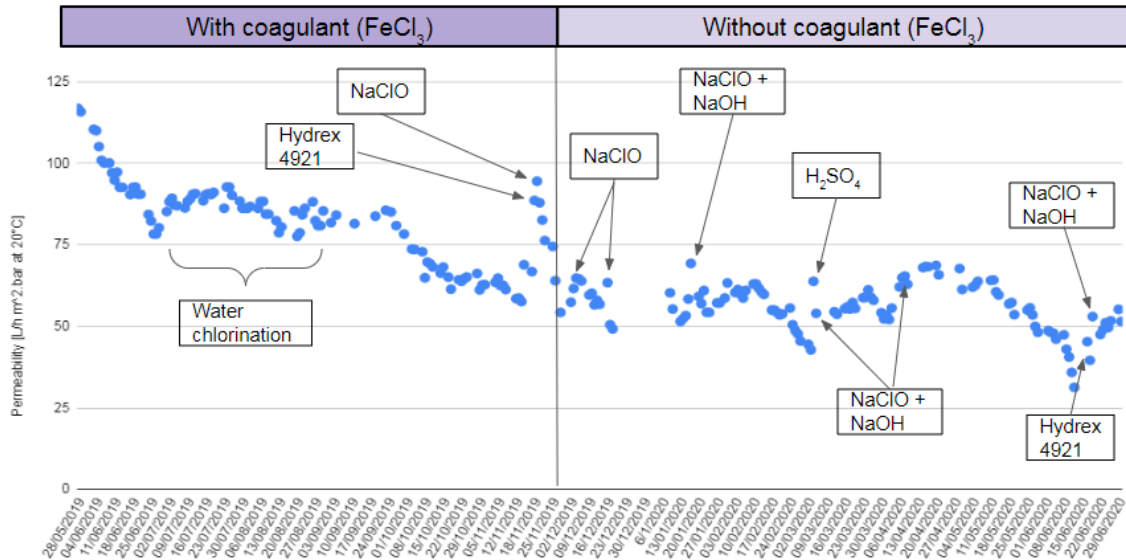


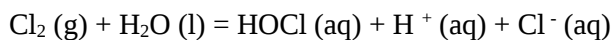
Figure 37: Ultrafiltration permeability at 20°C during the year

From June until the end of August 2019 we used the OXAQUA device for disinfection. French legislation states that potable water must have a free chlorine residual in order to ensure disinfection after it leaves the water treatment plant. We chose to make the chlorination before the ultrafiltration to reduce fouling and avoid chemical cleaning. The device is based on the principle of electrolysis of water. This technology does not require the addition of a chemical precursor, following the sustainable principle of reducing the use of chemicals. The chlorides naturally present in water are transformed into hypochlorous acid via the following equations:

Redox reaction



Hypochlorous acid formation



During the period with chlorination the permeability is stable around 85 LMH/bar without any chemical cleaning. This happens because the chlorine helps to decrease fouling. The ultrafiltration membrane is the main barrier to microorganisms in our system. Since we use a dead-end module, the microorganisms retained accumulate in the surface of the membrane and can proliferate there and

produce proteins and polysaccharides (membrane biofouling). The chlorine kills the microorganisms which decreases biofouling and improves membrane permeability [39].

The OXAQUA device produced a low concentration of free chlorine, between 0,08 and 0,17 mg/L. Since the membrane has an instantaneous free chlorine tolerance of 2 g/L, we believe that it didn't cause any damage to the membrane. However, French legislation requires that potable water must maintain a minimum free chlorine concentration of 0,3 mg/L at the outlet of a water treatment plant [40]. As the concentration obtained is below the minimum level established, when the OXAQUA device presented malfunctioning by the end of August 2019 we ceased the operation of the device.

Some time after that the permeability decreased (around 65 LMH/bar) due to increase in fouling and recovery cleanings were necessary. Each cleaning has a different purpose as explained in table 14. Due to concern regarding biofouling, most of the recovery cleanings included a NaClO step. The first cleaning with Hydrex 4921 was very efficient but the second one wasn't. A likely explanation is that the second cleaning was done during the period without coagulant dosage in the system, proving that we don't have metallic deposits in the membrane anymore.

table 14: Membrane cleaning agents

Product	Nature	Action	Utilization Condition
NaOH	Strong Base	Attacks organic fouling	pH 10 - 13
NaClO	Strong Oxidant	Prevents colonization by bacterial development. Oxidizes and reabsorbs certain organic molecules	pH 10 - 13
Hydrex 4921	Organic Acid	Solubilizes metallic deposits	pH 3 - 4
H ₂ SO ₄	Strong Inorganic Acid	Solubilizes deposits of metallic hydroxides or mineral salts	pH 2 - 3

The coagulant (FeCl₃) dosage that occurred until the end of November 2019 worked as a pre-treatment for the UF. The coagulation process removes part of the dissolved organic matter before the membrane and also agglomerates particles making them bigger than membrane pore. Hence, the number of particles trapped inside the pores of the membrane decreases [41]. However, we want to reduce the use of chemicals in our project. Therefore, by the end of November 2019 we discontinued the coagulant dosage in the pilot. After that, the permeability decreased reaching an average of 55 LMH/bar.

Another important parameter is the membrane integrity. Although we didn't perform any integrity test, it is possible to assume the integrity of the membrane due to the absence of microorganisms (results in section 4.2.7) and the low turbidity in UF permeate. Figure 38 shows the difference

between turbidity in UF inlet and outlet. It is possible to notice a reduction in inlet turbidity after the addition of ozonation before the μ GAC column. In every measurement the turbidity in UF permeate is below the legislation limit. This result and the absence of microorganisms in UF permeate prove that the performance of UF membrane is satisfactory and reliable.

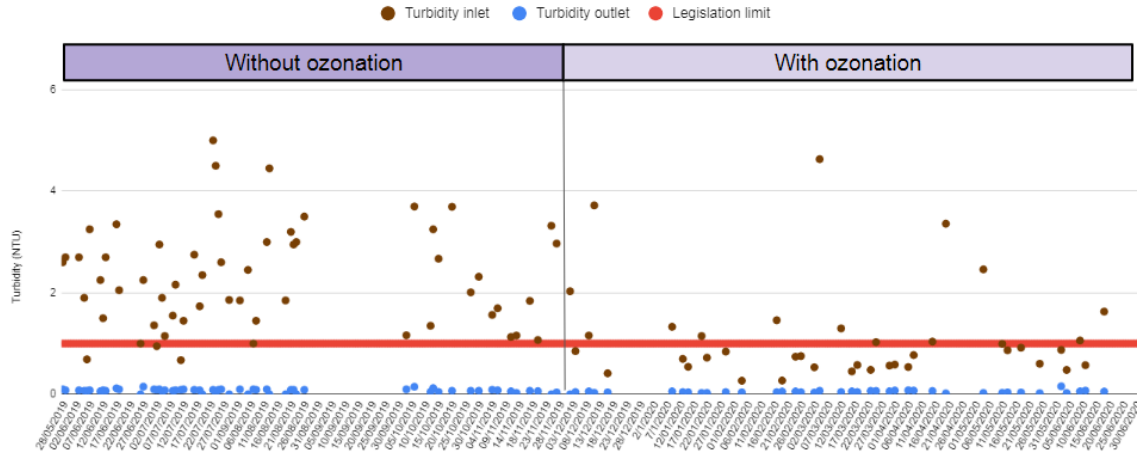


Figure 38: Turbidity in inlet and outlet of UF during the year

4.3.2 Reverse Osmosis Performance

Regular operation of the RO unit started in July hence we could only observe its performance for a short period of time. Table 15 summarises the main parameters provided by the RO operating system during the first weeks of operation. The high salt rejection and low permeate conductivity assure the membrane integrity.

Table 15: Main parameters provided by the RO operating system

Feed flow (L/h)	Permeate Flow (L/h)	concentrate Flow (L/h)	Recovery rate (%)	TMP (bar)	feed conductivity (μ S/cm)	permeate conductivity (μ S/cm)	Concentrate conductivity (μ S/cm)	salt rejection (%)
290	194	96	67	6,5	791	18	2280	99

Figure 39 compares the conductivity of feed and permeate. We can observe the reduction around 98% in all measurements, supporting the reliability of the membrane.

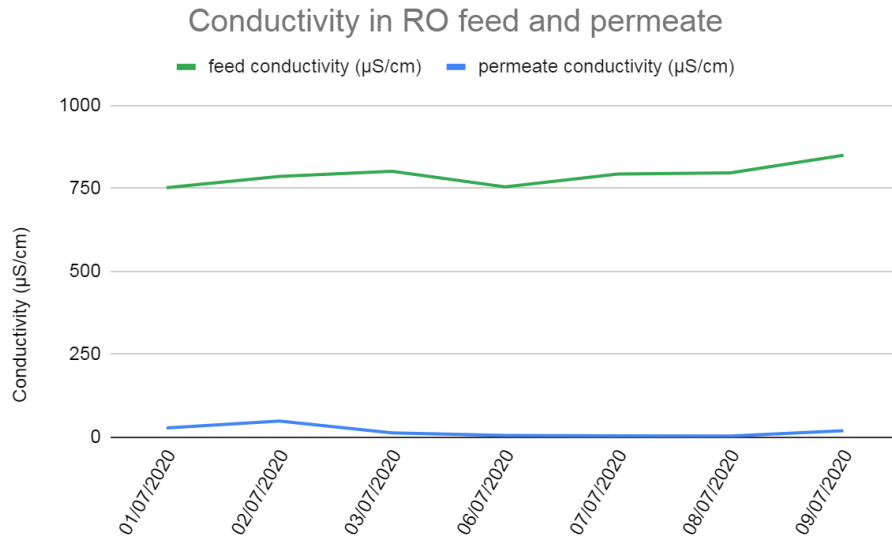


Figure 39: Conductivity in RO feed and permeate

It is possible to calculate the concentration factor using the following equations:

$$\text{concentration factor} = 1/(1 - \text{recovery rate})$$

$$\text{concentration factor} = \text{concentration of } A \text{ in concentrate} / \text{concentration of } A \text{ in feed}$$

Using the recovery rate (expressed in decimals) provided by the RO operating system in the first equation we obtain a concentration factor of 3,03. Using the concentrations obtained in laboratory analysis (see section 4.2.8) in the second equation we obtain an average concentration factor of 3,41. This difference is likely due to the fact that some of the concentrations were below the sensitivity limit of the analysis method, therefore the value may not be accurate. We consider the results consistent with the expected

4.4 Project Economic viability

After the technical success of the project, it is time to check the financial viability of it. The CAPEX for this project was 40000 euros. For the calculations, we considered a loan of 40000 euros to be paid in 20 years. To simplify the calculation, we assumed a constant interest rate of 1,44% according to the current French market [42]. Table 16 summarizes our annual expenses with the ReUse pilot.

Table 16: Annual expenses with the ReUse pilot.

OPEX	Energy	3154 €/year
	Activated Carbon	520 €/year
	Maintenance	1200 €/year
CAPEX loan repayment		2364 €/year
Total Expenses per year		7238 €/year

Currently, with 18 people on site working 8 hours per day, 5 days per week, we produce 1,1 m³ of wastewater per day. Considering that an year has an average of 253 working days in France, this gives us a production of 278,3 m³ of wastewater per year. However, the pilot works 24h per day, 7 days per week and we considered that for the energy and carbon consumption. If we have this type of Reuse treatment installed in a hospital or factory that works 24/7, it would be possible to generate more wastewater with the same energy cost. Assuming that in 24 hours it would be possible to generate 3 times more wastewater (3,3 m³/day) in a year (365 days) the wastewater production would be 1204,5 m³. Table 17 presents the cost per m³ of wastewater treated for both situations.

Table 17: Cost per m³ of wastewater treated for both situations

hours per day/days per week	Expenses (€/year)	Wastewater treated (m ³ /year)	Cost (€/m ³)
8/5	7238	278,3	26,01
24/7	7238	1204,5	6,01

As we aim to obtain sustainable development, we consider the possibility of installing photovoltaic panels. Nowadays, a 3kW photovoltaic panel costs between 5000,00 € and 6000,00 € in Europe [39], which in Brittany allows us to produce up to 3000 KWh per year. Table 18 presents the annual expenses of the ReUse pilot in this new scenario, with a CAPEX of 46000,00 €.

Table 18: Annual expenses with the ReUse pilot considering purchase of photovoltaic panels.

OPEX	Energy	2794 €
	Activated Carbon	520 €
	Maintenance	1200 €
CAPEX loan repayment		2724 €
Total Expenses per year		7238 €

The decrease in energy cost is just enough to compensate for the increase in loan repayment. Therefore, the cost per m³ of wastewater treated considering the solar energy is the same as without solar energy. The use of cleaner energy is an interesting option to improve public opinion regarding the ReUse project. In addition, we considered a constant price of energy. In the future, it's likely that the cost of energy will increase and photovoltaic panels will be cheaper and more efficient making this option even more attractive.

The cost of water in France is on average 5,00 €/m³. In our best scenario we have a cost of 6,01 €/m³ which means that currently our project is not financially viable. However, this calculation was made based on the wastewater production of 18 people in a small research center. If we could have a bigger scale of our pilot treating the wastewater in an hospital, factory or building, the increase in wastewater production would be much more significant than the increase in expenses per year. Scaling up is an efficient way to reduce cost and probably we would achieve economic viability under this condition. In addition, for regions with scarcity of water the chance to be autonomous in water supply is priceless.

5. Conclusions and Future Perspectives

The main objectives of this project are to produce potable water from wastewater, to operate in a closed loop system, to ensure reliability and performance of the process and to demonstrate financial viability.

The production of potable water was achieved. The average concentrations in UF permeate already respect french legislation for potable water (there is no limit for total phosphorus). However, due to the seasonal behavior of the phytoremediation process, this concentration limit was not respected every single day. Therefore, we recently added a RO module after the UF. Now we produce high quality water, as shown in table 19

Table 19: Quality of water produced compared to legislation limit

Parameters	RO permeate	Legislation
NH ₄ ⁺	0,001	0,1 mg/L
NO ₃ ⁻	6,02	50 mg/L
NO ₂ ⁻	0,12	0,5 mg/L
P _{tot}	0,11	0,5 mg/L
DOC	0,80	2 mg/L
Mn	0,003	0,05 mg/L
Fe	0,01	0,2 mg/L
SO ₄ ²⁻	1,49	250 mg/L
pH	7,76	6,5 - 9
Turbidity	0,04	1 NTU
Conductivity	47,15	180-1000 µS/cm

The next step is to remineralize the RO permeate. The RO salt rejection is high (99%) and water for human consumption must have a minimum concentration of minerals. Although we are avoiding the use of chemicals in our process, this next step is necessary and can be easily achieved with limestone dosage.

The closed loop system is not a reality yet. Currently, we extract all the RO permeate from the system. However, we have a very good hydraulic balance. In the first 10 days of July we had 10281 m3 of water entering the system and 10291 m3 extracted. This proves that we are ready to close the system and send the RO permeate to be used in toilet flushes. The current French legislation does not allow human consumption of water reused. We believe that projects like this one will provide technical

arguments to change this legislation in the future. Figure 40 presents the future perspective for ReUse pilot



Figure 40: ReUse pilot with closed loop. Source: Veolia

The reliability and performance of the process was also demonstrated. The system has been working for more than a year with satisfactory quality of treated water. Approximately 142,6 m³ of water have been treated and not even once the turbidity of UF permeate has reached 1NTU. The permeability of the membrane now is around 55 LMH/bar and recovery cleanings are performed when it drops below 50 LMH/bar. We believe that with the RO, an extra barrier, the system will be even more reliable.

The financial viability of the project is not as good as expected. In our best scenario, with people producing wastewater for the system 24h per day, 7 days per week, with the use of solar panels, the cost of treated water is 6,01 €/m³ while the average cost of water in France is 5 €/m³. However, this calculation was made based on the wastewater production of 18 people in a small research center. We believe that a scale up of the system to treat wastewater in an hospital, factory or building, will decrease the cost per m³ of water produced. In addition, for places with water scarcity the autonomy of water supply is an important advantage. With the climate changes and the increase in global population, this type of reuse technology will become even more necessary in the future.

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